早稲田大学大学院 環境・エネルギー研究科

博士学位論文

Development of Business Models for Effective Electric Power Management with Advanced Information Utilization

- For Sustainable Smart Grid Realization with Profitable Business Models -

情報の高度活用による新しいエネルギー管理と事業モデルの研究

－事業継続性を伴ったスマートグリッドの実現に向けて－

2015年1月

黒田　健
Ken Kuroda

早稲田大学大学院 環境・エネルギー研究科

博士学位論文

Development of Business Models for Effective Electric Power Management with Advanced Information Utilization

- For Sustainable Smart Grid Realization with
Profitable Business Models -

情報の高度活用による新しいエネルギー管理と事業モデルの研究

－事業継続性を伴ったスマートグリッドの実現に向けて－

2015年1月

早稲田大学大学院環境・エネルギー研究科
環境・電力システム研究

黒田　健
Ken Kuroda

Abstract

For the realization of “Smart Grid”, many and various demonstration projects have been conducted all over the world for several years. One of major purposes of Smart Grid is to realize optimal electric power system by the transition to the collaborative operation between power supply and demand using information communication technology (ICT). In order to enhance existing power system, which is already one of important social infrastructure, into Smart Grid, enormous and long term investment would be required, however, it looks the benefit of Smart Grid is unclear yet and related markets are not in rapid expansion. Therefore, it is necessary to clarify profitable Smart Grid measures and to promote investments and their recovery by many business enterprises for accelerating Smart Grid realization.

Therefore, this dissertation concerns critical components of Smart Grid including their implementation measures and technologies, provides various benefits and cost quantification methods, and proposes expected business models with these critical components and their evaluation methods. Thorough this study, the profitability of installation measures and effective utilization of ICT were focused to realize, continue and enlarge the critical components of Smart Grid.

As the result of the study, important challenges were clarified and their solutions were discussed. The followings are major clarifications. Firstly, the holistic optimization of power systems in demand-side was considered and proposed quantification methods for holistic and periodical installation effects of Smart Grid components. In addition, evaluation methods of Smart Grid components were proposed for the consideration of the near future power market in Japan. Secondly, two types of evaluation methods for Smart Grid components were proposed. The first one is the method which should prioritize profitability for business sustainability and expansion, and another one is the methods which should choose the best solution considering multi-objectives which have trade-off relations each other such as installation effects versus costs etc. Lastly, a value circulation model between power supply and demand sides was proposed and it was showed that value exchanges between them were possible virtually by the utilization of ICT, and environmental conditions which activated value creation were also provided.

Acknowledgements

Special thanks are due to my supervisor Professor Ryuichi Yokoyama, at Waseda University Graduate School of Environment and Energy Engineering, for his support, patience, and consistent encouragement throughout my doctorial study. His technical and academic advice was essential to the completion of this dissertation. I also would like to thank the other members of my review committees, Professor Masafumi Katsuta and visiting Professor Yosuke Nakanishi, at Waseda University, for their helpful comments during the thesis review process.

I want to thank Dr. Hideki Magori, invited researcher at the Yokoyama Laboratory. His expertise and advice have been extremely valuable, and without them this work would not have been possible. I would also like to thank the staff at the Yokoyama Laboratory, Professor Kenji Iba, visiting senior researcher (Meisei University), Dr. Daisuke Yamashita, junior researcher, for their a lot of precious advice, and special thanks to our administrative staff Mrs. Yuko Inaba and Mrs. Hiroko Kano for their support of this three year research work and guidance of the doctoral review procedures. I am also grateful to Mr. Yasuo Sato, ARK Information Systems for giving me his recommendations to the doctor course in Yokoyama Laboratory and many supports.

Over the past three years I have been extremely fortunate to receive both technical and financial support from Fujitsu Limited. I would like to thank Mr. Kenichi Yamagishi, the former head of Smart City & Energy Promotion Unit, and Teruyuki Sato, vice president of Smart City & Energy Promotion Unit, for giving me their recommendation of the doctor course entrance and this research opportunity in parallel with ordinary business activities. My profound gratitude goes to Dr. Tomiyasu Ichimura, senior director at Smart City & Energy Promotion Unit, for allowing me the opportunity to discuss research topics, problem definitions and solution methodologies in this work and without his support and lead, this work would not have been completed. I also wish to thank my colleagues in Fujitsu Limited and Fujitsu Laboratories Limited, Dr. Zhou Yicheng, Dr. Hideyuki Kikuchi, Mr. Yuichi Matsufuji, Mr. Tetsuya Kashiwagi, Mr. Yuji Mezaki and Mr. Daisuke Kobayashi.

Finally, my special thanks go to my friends and family, all of whom have given me endless encouragement and support throughout. This dissertation is dedicated to them.

Ken Kuroda
January 2015

Table of Contents

List of Tables

List of Figures

Abbreviations

ADE: Adaptive Differential Evolution

AODV: Ad hoc On-demand Distance Vector

AMI: Advanced Metering Infrastructure

AMR: Automated Meter Reading

BEMS: Building Energy Management System

B/F: Backward and Forward

CBM: Condition Based Maintenance

CEMS: Community Energy Management System

CEP: Complex Event Processing

CFA: Constriction Factor Approach

C&I: Commercial and Industrial

CPP: Critical Peak Pricing

CPU: Central Processing Unit

CT: Current Transformer

DA: Distribution Automation

DE: Differential Evolution

DFS: Depth First Search

DG: Dispersed Generation (Distributed Generation)

DMS: Distribution Management System

DOE: the United States department of Energy

DR: Demand Response

DSM: Demand Side Management

DSO: Distribution System Operator

EMA: Energy Management Application

EMS: Energy Management System

EPRI: The Electric Power Research Institute

ETP: European Technology Platform

EV: Electric Vehicle

FEMS: Factory Energy Management System

GA: Genetic Algorithm

GIS: Geographic Information System

HEMS: Home Energy Management System

HV: High Voltage

IBP: Incentive Based Program

ICT: Information Communication Technology

IHD: In-Home Display

I/O: Input and Output

IPESA: Improved Pareto Envelope based Selection Algorithm

ISO: Independent System Operator

ISONE: Independent System Operator New England

IT: Information Technology

IWA: Inertia Weight Approach

JIS: Japan Industrial Standard

JRC: Joint Research Centre

KCL: Kirchhoff’s Current Law

KVL: Kirchhoff’s Voltage Law

KVS: Key Value Store

LED: Light Emitting Diode

LV: Low Voltage

MDMS: Meter Data Management System

MEMS: Mansion Energy Management System

METI: Ministry of Economy, Trade and Industry

NEDO: New Energy and Industrial Technology Development Organization

MOEA: Multi-Objective Evolutional Algorithm

MOPSO: Multi-Objective Particle Swarm Optimization

NIST: National Institute of Standards and Technology

NYISO: New York Independent System Operator

OLSR: Optimized Link State Routing

OMS: Outage Management System

OPF: Optimal Power Flow

PAES: Pareto Archived Evolution Strategy

PBP: Price Based Program

PCS: Power Conditioning System

PESA: Pareto Envelope based Selection Algorithm

PEV: Plug-in Electric Vehicles

PJM: Pennsylvania New Jersey Maryland Interconnection

PLC: Power Line Communication

PPS: Power Producer and Supplier
PSO: Particle Swarm Optimization
PTR: Peak Time Rebate
PV: Photovoltaic
PX: Power eXchange
RES: Renewable Energy Source
RF: Radio Frequency
ROI: Return On Investment
RTO: Regional Transmission Organization
RTP: Real Time Pricing
SAIDI: System Average Interruption Duration Index
SAIFI: System Average Interruption Frequency Index
SCADA: Supervisory Control And Data Acquisition
SME: Small and Medium Enterprises
SPEA: Strength Pareto Evolutionary Algorithm
SVC: Static Var Compensator
SVR: Step Voltage Regulator
TBM: Time Based Maintenance
TOU: Time Of Use
UPS: Uninterruptible Power Supply
U.S./US: United States
VAR: Volt-Ampere Reactive
VT: Voltage Transformer

(Unit of Measurement)
GB (Byte): GigaByte
GHz (Hertz): GigaHertz
min.: minute
p.u.: per unit
sec.: second
USD: United States Dollar
V, kV (Volt): Volt, kilo-Volt
kW, MW (Watt): kilo-Watt, Mega-Watt
Wh, kWh, GWh (Watthour): Watthour, kilo-Watthour, Giga-Watthour

Chapter 1 Introduction

In this chapter, the background and the goal of this dissertation are described. In the description, “Smart Grid”, which is the subject of this study, is defined because there is no unique common definition and many definitions by various organizations exist. Then the direction and the investigation flow of this dissertation are described by showing the structure of this dissertation.

1.1. Background and Context to This Study

Several years have passed since the term “Smart Grid” became widely used all over the world, and many pilot and/or demonstration Smart Grid projects have been conducted. In addition, some incentive plans or subsidy systems have been implemented to promote Smart Grid in many countries or regions.

However, it looks that only a few verified and commercially deployed Smart Grid technologies with clear benefits exist. The reason might be Smart Grid benefit is still unclear because Smart Grid realization requires restructurings of various existing power supply systems and their components, and these should need a large scale expense, while many expectations by Smart Grid realization exist, such as improvement of power supply reliability, reduction of environmental burdens and expansion of the number of employees working for new energy related businesses etc. One of the reasons might be major Smart Grid expected achievements such as advanced demand control and a large scale installation of small size renewable energy sources (RESs) are mainly on technology improvements in demand-side. Because most current Smart Grid technologies are based on the existing technologies for large size and small number of equipment, and these would require high cost if such technologies would be deployed to small size and large number of equipment in demand-side. In addition, many new technologies in demand-side are proposed such as power selling using photovoltaic (PV) generation systems, power saving by energy management systems (EMSs) and dynamic pricing and demand response (DR) programs. However it is difficult for most of them to recover their installation and operation costs at present. For example, electric power selling using RES generation is not profitable without subsidies, and various support programs are required to recover their service installation and operation cost only with their small cost reduction effect in most countries and regions.

In order to solve these challenges, high value production Smart Grid components should be developed with their quantification method. Moreover, it is necessary to clarify the profitability of Smart Grid measures as businesses, and many business organizations should join to various Smart Grid projects and make investment continuously. Expansion of information communication technology (ICT) utilization is one of expected areas for these challenges and it should contribute not only to efficiency improvement of existing power system technologies but also to value production using various and huge information, which can be collected by the recent information technology evolution. However the fact is that ICT applied areas to power systems are limited at present.

On the above mentioned background, it should be necessary to clarify critical component technologies and measures to realize Smart Grid, to quantify their installation effects and to propose evaluation methods of their optimal implementation into Japanese market in the aspect of business profitability and effective utilization of ICT for these technologies and measures.

1.2. Smart Grid and Advanced Power System

Firstly, Smart Grid definition in this dissertation is described because Smart Grid is a wide-ranging concept and a unique definition does not exist.

Smart Grid concept is defined at various organizations all over the world and such various definitions of Smart Grid reflect individual characteristics and constraints of organizations, regions or countries these Smart Grid concepts defined. For example, the National Institute of Standards and Technology (NIST), which is United States (U.S.) standard setting organization, defines Smart Grid as follows [1-1].

"A modernized grid that enables bidirectional flows of energy and uses two-way communication and control capabilities that will lead to an array of new functionalities and applications. Unlike today's grid, which primarily delivers electricity in a one-way flow from generator to outlet, the smart grid will permit the two-way flow of both electricity and information."

As another example, European Technology Platform (ETP) defines Smart Grid as follows. [1-2]

"An electricity network that can intelligently integrate the actions of all users

connected to it - generators, consumers and those that do both - in order to efficiently deliver sustainable, economic and secure electricity supplies. A smart grid employs innovative products and services together with intelligent monitoring, control, communication, and self-healing technologies in order to:

- *Better facilitate the connection and operation of generators of all sizes and technologies*
- *Allow consumers to play a part in optimising the operation of the system*
- *Provide consumers with more information and better options choosing their energy supplier*
- *Significantly reduce the environmental impact of the whole electricity supply system*
- *Maintain and improve the existing high levels of system reliability, quality, and security of supply*
- *Maintain and improve the existing services efficiently*
- *Foster the development of an integrated European market."*

On the other hand, in Japan which is the targeted market of this study, the Ministry of Economy, Trade and Industry (METI) defines the Smart Grid as follows [1-3] and Figure 1-1 is the Smart Grid overview by METI [1-4].

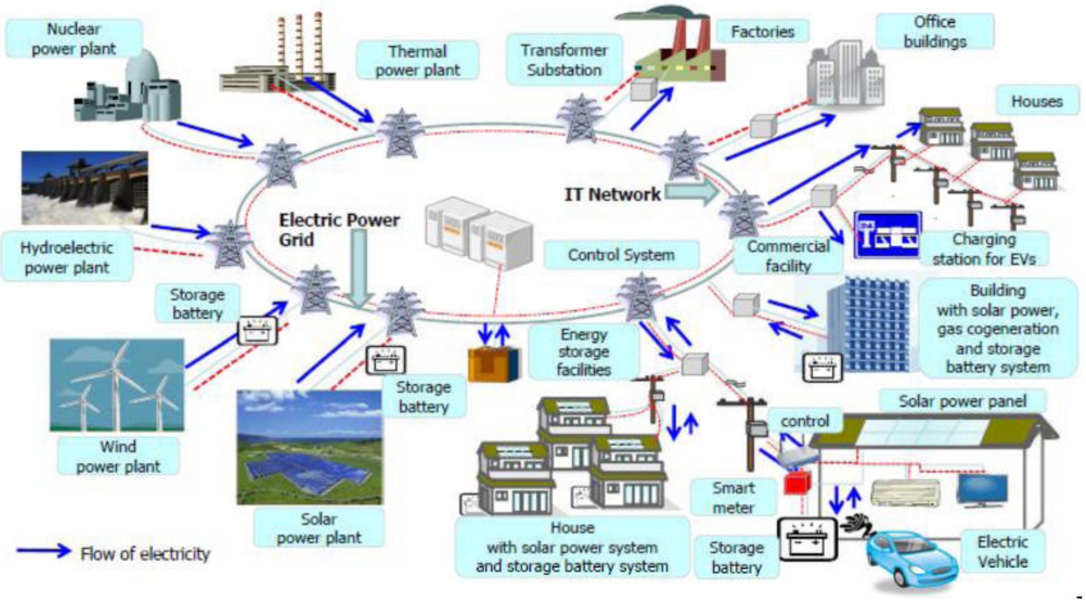


Figure 1-1 Smart Grid Overview by METI [1-4]

"Next generation energy system, as it is called Smart Grid is the concept of next

generation power systems corresponding to challenges related to power supply and demand using state-of-art information technologies (IT). Generally, for large scale installation of dispersed generations such as renewable energy, it is aimed to realize high efficiency, high quality and high reliability power systems by the integration and utilization of information from dispersed generations, energy storages and demand side using high-speed communication network technologies, as well as combined operation with existing large scale power sources and transmission and distribution networks."[1]

In addition, various standard setting organizations and industries define their own Smart Grid and they are organized in [1-5]. Referring to these various Smart Grid definitions, it is found that the following words are used commonly.

- Intelligent Power Supply Network
- ICT Utilization
- Two-way (bidirectional)

These three features are outlined as follows.

(1) Intelligent Power Supply Network

Smart Grid is a power supply network and not existing power supply system but is composed of new equipment which has advanced technologies from power generation assets to power consumption appliances. In addition, this power supply network has something "intelligent" mechanisms, such as optimal operation function or automatic recovery in case of failure etc.

(2) ICT Utilization

Smart Grid provides "intelligent" features described in 1.2(1) by the utilization of all information which are generated at all points from power generations to power utilization points which compose Smart Grid. Therefore, information transferring, processing and utilizing mechanisms which can treat huge amount of data from a large number of equipment should be essential.

(3) Two-way (Bidirectional)

Smart Grid is two-way power supply network. Two-way has two means and the first is power flow direction and the second is information utilization flow direction. As for the

---

[1] Original definition is in Japanese and attached as Appendix B

power flow aspect, power flow direction would be two-way from existing one-way power flow from centralized large generators to consumers, because consumers would have their own generators and excess generated power should be injected into power supply network for selling. As for the information utilization flow aspect, the supply and demand balancing method would be two-way. While power companies are adjusting their supply electric power corresponding to electric power demand in the current power supply system, in the Smart Grid, consumers would control their demand considering power supply capacity, or power companies might control consumers' electric power demand by providing dynamic price programs corresponding to power companies' supply capacity using information of both supply and demand sides.

Because the targeted market of this study is the power market in Japan, this dissertation adopts the METI's Smart Grid definition as the base definition and detailed discussions will be conducted focusing on above mentioned three features of Smart Grid definitions.

1.3. Aims of This Study

This study aims to contribute to the realization of Japanese Smart Grid which is an improved power system in all aspects of security, safety, ecology and economy compared with existing power systems. In order to realize Japanese Smart Grid, many Smart Grid related projects have been conducted and various new technologies such as dispersed generations (DG) including RES generations, electric storages, smart meters and so on also have been installed. However, it is not Smart Grid yet but just a power systems limited number of above mentioned new technologies connected. Because new technologies such as PV and wind turbine are environment friendly but unstable in the aspect of generation capacity, roughly speaking the same amount of reserved power such as power storages would be required if there are no any control mechanisms. Therefore, the collection of power systems' state information and optimal controls of new technologies using such information are essential in order to increase RES amount and reduce the number of power storages. However ICT utilization in power systems is still very limited at present and this might be one of the reasons why the amount of RES would not be expanded while power quality is very high. Therefore, the expansion of ICT adapted areas in power systems maintaining power quality is one of most important topics in the study, as well as clarification of critical new Smart Grid technologies and measures. Although power storage and its effective management are also important topics to realize Smart Grid, these topics are out of the scope because the consideration of effective ICT utilization is focused in this study.

In addition, while installation effect of these Smart Grid technologies such as DG, EMS etc., have been studied, most are stand-alone effects estimation and earning models as business models have not been considered. As mentioned in 1.1, the realization of Smart Grid requires installations of various technologies and measures, and these require a lot of investment. That means it is necessary that many companies should enter the new electricity market and provide many investments to the market continuously. In order to realize such situations, clear benefit is essential and thus this dissertation focus on profitability of Smart Grid business models and another important objective is to clarify these effective business models for Smart Grid elemental technologies and measures.

The followings are major items what this study should clarify.

- Critical component technologies and measures to realize Smart Grid
    - To clarify areas where especially ICT application increases production values
- Business profitability and sustainability by the quantification of installation effect for critical technologies and measures for Smart Grid
    - To provide versatile evaluation methods and tools for the first stage of Smart Grid activities in order to support potential entrants into this new power market
- Evaluation methods of technologies and measures installed into Japanese power market in the aspect of business profitability.
    - To propose sustainable model without dependence on subsidies because most of subsidy projects are evanescent and ended with demonstration projects

1.4. Structure of This Paper

In order to achieve aims of this study, the dissertation is composed of seven chapters as follows.

Here, the background and the goal of this study are defined and provides the direction and the investigation flow of this study by showing the structure of this dissertation.

Chapter two explores critical components of Smart Grid by researches, analyses and reorganization of activities in Smart Grid demonstration projects worldwide. In the consideration, candidates of Smart Grid critical component technologies and measures are extracted focusing on their benefit in order to consider profitability of these technologies and measures. In addition, selected candidates are evaluated whether ICT utilization can contribute effectively and then Smart Grid critical component technologies and measures in this study are selected.

From chapter three to chapter five, reorganizations of component measures, effect quantifications of countermeasures and proposals of effective business models are conducted for Smart Grid critical components defined in chapter two.

Chapter three deals with optimal power generation technologies and measures in demand-side and explores effect evaluation and quantification methods of DG installations. In the chapter, optimal location and size of DGs for the power loss minimization are considered and also an evaluation method of installation effect of PV generation systems which are expected as future main RES generation system is considered and proposed.

Chapter four deals with optimal power consumption technologies and measures in demand-side and explores EMS and DR which are receiving big attention in Japan recently. In the chapter, implementation effect formulation and evaluation of these measures are conducted and also effective business models are proposed.

Chapter five deals with optimal power supply and demand balancing in demand-side, and effective information utilization models for power distribution area are proposed. As the first model, a distribution network monitoring system considering a large number of PV installed environment, which is one of important issues in the near future power systems in Japan. As the second model, outage detection system using smart meter data is proposed because data sensing devices in low voltage distribution systems are not installed sufficiently at present. In the system, the fault information of smart meter data transfer is used because data transfer would be faulted in case of outage.

Chapter six, evaluation methods for the installation effect of technologies and measures which are considered from chapter three to chapter five are proposed. Firstly, value converting methods for periodical amount and equivalent monetary value are proposed because business profitability should be evaluated on periodical basis such as month, quarter, half year and year with same comparable units. Then, two types of evaluation methods for the installation effect of Smart Grid critical technologies and measures are proposed. The first one is a method of profitability priority approach and the second one is a method of multi-objective optimization approach because most power system optimization problems are constrained multi-objective optimization problems which includes trade-off relation multiple objectives such as measure implementation effects versus their cost etc.

Chapter seven describes overall conclusion of this study with regard to the "Sustainable Smart Grid Realization" which means advanced power systems in aspects of safety, economy, environment and security and has effective business models with profitability. Firstly the coverage of research topics in this study for critical components of Smart Grid selected in chapter two are reviewed and then the value circulation model is provided because produced values of technologies and measures explored in this study are related among each other and the relation should be considered when effects and expenses of these technologies and measures would be evaluated.

Figure 1-2 shows the structure of this dissertation.

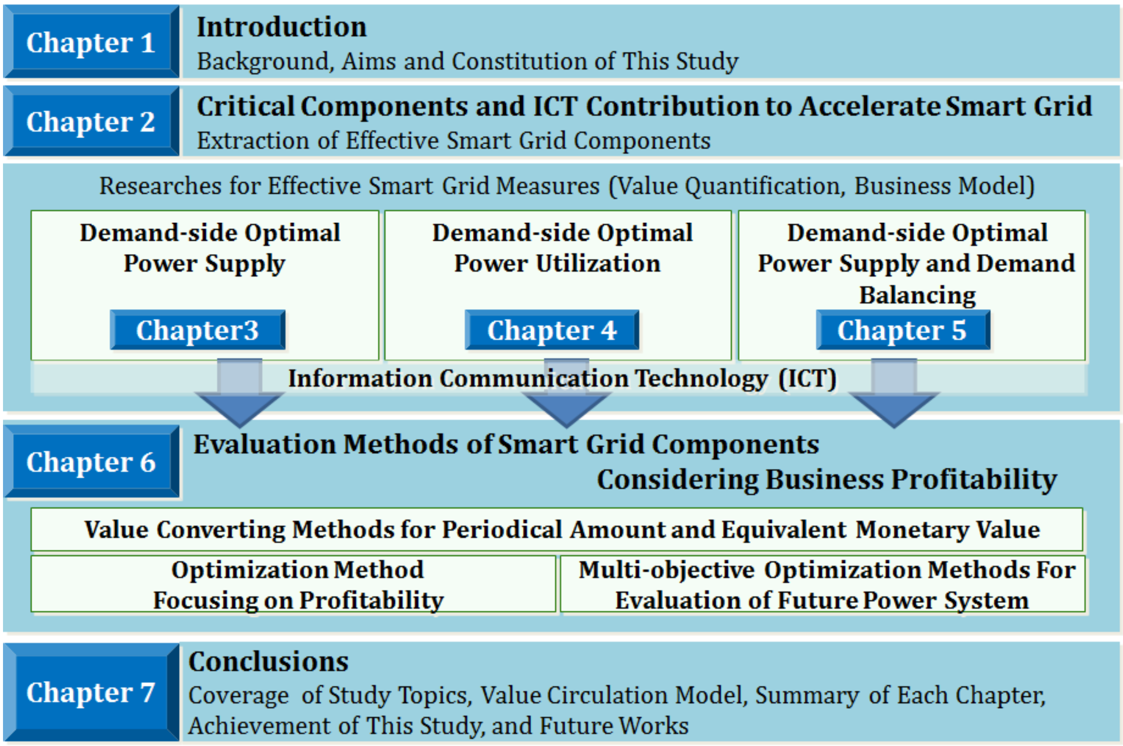


Figure 1-2 Structure of This Dissertation

Chapter Reference

[1-1] "Smart Grid: A Beginner's Guide," National Institute of Standards and Technology's (NIST) web site. Available at: http://www.nist.gov/smartgrid/beginnersguide.cfm

[1-2] "What is Smart Grid?," The European Technology Platform (ETP) web site. Available at: http://www.smartgrids.eu/ETPSmartGrids

[1-3] "次世代エネルギーシステムに係る国際標準化に向けて (International Standardization on Next Generation Energy System)," Report by the Study Group on International Standardization for Next Generation Energy Systems, January 2010 (in Japanese) [Online]. Available at Ministry of Economy, Trade and Industry web site: http://www.meti.go.jp/report/downloadfiles/g100129d01j.pdf

[1-4] T. Goda, "Japan's Challenge for a Standardiszation of Inverter Technology," NEDO High Penetration PV Workshop, October 2012 [Online] Available at: http://iea-pvps.org/index.php?id=153&eID=dam_frontend_push&docID=1487

[1-5] M. Shabanzadeh and M. P. Moghaddam, "What is the Smart Grid? - Definitions, Perspectives, and Ultimate Goals," The 28th International Power System Conference, November 2013

Chapter 2 Critical Components to Realize Smart Grid and Contribution of Information Communication Technology

In this chapter, critical components of Smart Grid are considered by surveys, analyses and reorganizations of activities in Smart Grid demonstration projects mainly in the United States (U.S.). In the consideration, candidates of Smart Grid critical component technologies and measures are extracted focusing on their benefit to consider profitability of these technologies and measures. The extracted technologies and measures are considered and discussed in the aspect of information communication technology (ICT) effectiveness, and then Smart Grid critical component technologies and measures in this study are selected.

2.1. Smart Grid as Future Power Systems

Firstly, approaches for Smart Grid realization as future power systems are researched and basic ICT roles are considered in this section.

2.1.1. Smart Grid Demonstration Projects

Many and various Smart Grid projects have been conducted all over the world centering on the U.S. and European Union (EU) countries, and their plans, results and effects have been reported in various publications. For major examples, the U.S. department of Energy (DOE) awarded 9 Smart Grid demonstration projects to promote Smart Grid in 2008 and the Electric Power Research Institute (EPRI) conducted a framework development project to estimate benefits and costs of Smart Grid projects and introduced 10 steps which organized Smart Grid elements, functions, and benefits [2-1]. EPRI also has provided reports for these advanced projects' status continuously [2-2][2-3][2-4][2-5]. In addition, [2-6] considers Smart Grid benefits and costs by utility sectors such as transmission, distribution and customers, and Joint Research Centre (JRC) in EU and DOE provided the joint report for assessment of Smart Grid benefits and costs [2-7]. In many of these reports, criteria and metrics to assess Smart Grid benefits and costs are provided. In this chapter, critical components and ICT contribution for accelerating

Smart Grid realization are discussed and selected using these various projects information and their evaluation reports.

2.1.2. Smart Grid and ICT Solutions

In order to realize Smart Grid, various approaches have been tried and verified in many countries and regions for various purposes such as customer benefit improvement, optimal installation of dispersed generation (DG) installation, power grid reliability improvement, efficient power assets operation and new electric power market establishment [2-8].

For the realization of most new services by Smart Grid, establishment of information communication networks between service providers and their customers are essential at first. However many challenges exist in implementation and operation of the access network (as it is called last mile network) which connects power companies and their customers and also power supply and consumption equipment. Therefore, a new network solution for these challenges is required. Secondly, a new energy management functions using ICT is necessary because Smart Grid requires power supply and demand balancing utilizing both sides information at the same time as providing new value-added services such as power demand reduction and leveling (peak cut or peak shift etc.) etc.

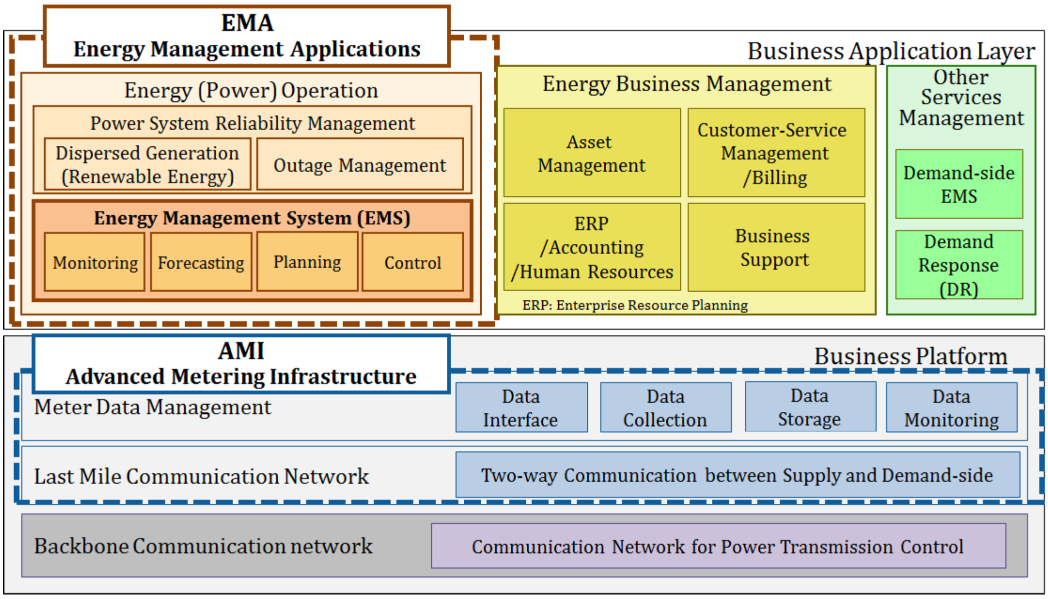


Figure 2-1 ICT Based Smart Grid Solution Concept

Therefore, in consideration of Smart Grid from the aspect of ICT, it can be considered that various advanced services by Smart Grid realization are established on these two base concepts. The former is called advanced metering infrastructure (AMI), composed of smart meters, access networks and data management systems, which is implemented as the first step of typical Smart Grid Project. The latter is called Energy Management Applications (EMA) in this paper, composed of various kinds of energy management systems (EMSs) for the realization of power supply and demand collaboration controls.

Figure 2-1 shows ICT based Smart Grid solutions concept from the viewpoint of power companies referring to the concept in [2-9] to illustrate holistic Smart Grid solutions and the relation between AMI and EMA. Business platform consists of communication networks and their data management systems and the AMI solution is one of platform solutions. Business applications such as energy operation and energy business management are provided on the platform solutions. Energy operation area includes applications for power system operation and control, and is traditionally the area for machine control systems and little ICT contribution area at present. EMS is one of base energy operation solutions for supporting new requirement in Smart Grid. On the EMS solution, solutions for power system reliability such as renewable energy source (RES) management and outage management are provided. Energy business management area includes applications for power companies' efficient business management, and service provision business area is for additional diversified service business area for power companies and other service business providers.

2.2. Clarification of Smart Grid Critical Components

In this section, effective procedures to decide critical components to promote Smart Grid and their measures are proposed. As mention in the introduction, in this study it is assumed that possible reasons which prevent Smart Grid realization might be its necessity of enormous investment under the unclear benefit, and ICT utilization should create new additional values and contribute to clarify these values. The followings are proposed procedures to clarify critical components to promote Smart Grid.

2.2.1. Clarification Approach of Smart Grid Critical Components

Clarification approaches to clarify critical components to promote Smart Grid are provided below.

(1) Analysis of Expected Benefits by the Realization of Smart Grid

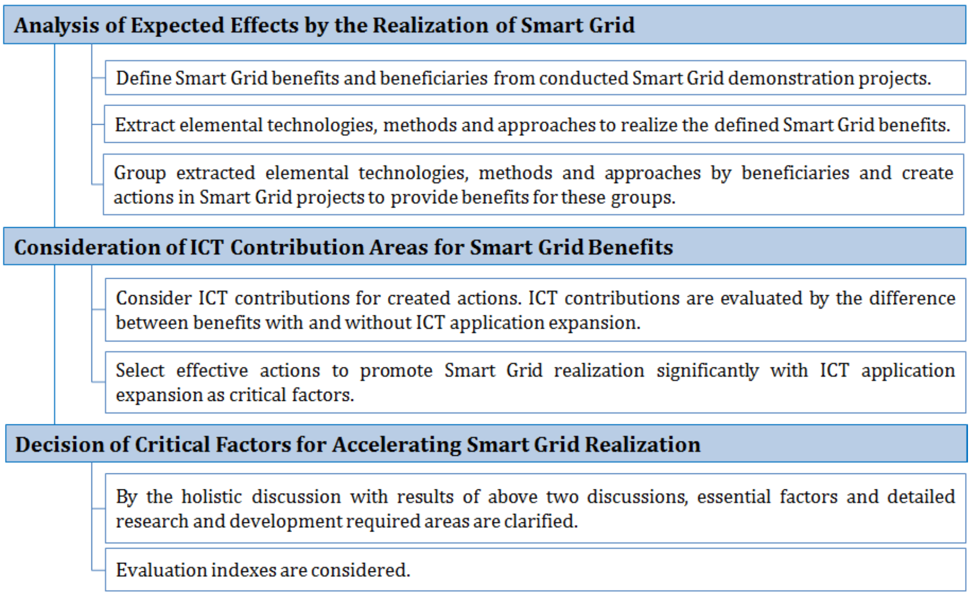
Firstly this study describes expected benefits by the realization of Smart Grid through survey analysis of Smart Grid demonstration projects in the U.S. The analysis focuses on benefit of Smart Grid, because it is necessary to generate profits or values for both power companies and consumers to realize Smart Grid which requires enormous investment and cost. Technological measures to realize the Smart Grid benefits are extracted from the demonstration projects, and then extracted measures are grouped. After that, actions in Smart Grid projects to provide benefits for these groups are considered and created.

(2) Consideration of ICT Contribution Areas for Smart Grid Benefits

Secondly, ICT contribution areas to these Smart Grid benefits and some actual realization measures are discussed. ICT contributions are evaluated by the difference between benefits with and without ICT application. Then, effective actions to promote Smart Grid realization significantly with the expansion of ICT applications are considered and created.

(3) Decision of Critical Components for Accelerating Smart Grid Realization

From the results of above two discussions, critical components and required areas for detailed research and development are discussed and concrete research topics accelerating Smart Grid are provided.



Analysis of Expected Effects by the Realization of Smart Grid
- Define Smart Grid benefits and beneficiaries from conducted Smart Grid demonstration projects.
- Extract elemental technologies, methods and approaches to realize the defined Smart Grid benefits.
- Group extracted elemental technologies, methods and approaches by beneficiaries and create actions in Smart Grid projects to provide benefits for these groups.

Consideration of ICT Contribution Areas for Smart Grid Benefits
- Consider ICT contributions for created actions. ICT contributions are evaluated by the difference between benefits with and without ICT application expansion.
- Select effective actions to promote Smart Grid realization significantly with ICT application expansion as critical factors.

Decision of Critical Factors for Accelerating Smart Grid Realization
- By the holistic discussion with results of above two discussions, essential factors and detailed research and development required areas are clarified.
- Evaluation indexes are considered.

Figure 2-2 Clarification Procedures of Critical Components to Promote Smart Grid

Figure 2-2 shows clarification procedures of critical components to promote Smart Grid which summarize above mentioned three steps. In accordance with the procedures, critical components and their countermeasures are considered in this section.

2.2.2. Definition of Smart Grid Benefits and Beneficiaries

Firstly, benefits and their beneficiaries by the Smart Grid realization are defined. Although various definitions exist regarding Smart Grid benefits, benefits and beneficiaries defined in [2-1] are used in this study as the base definition because these benefits and beneficiaries are based on actual Smart Grid projects and the definition should obtain the consensus among many Smart Grid project concerned parties.

Table 2-1 Summary of Reorganized Smart Grid Benefits Defined in [2-1]

Benefit Category	Benefits	Typical Beneficiary
Economic	Electricity cost savings	Consumer
	Reduced generation costs from improved asset utilization	Utility(G) Utility(G)
	Deferred Generation Capacity Investments Reduced Ancillary Service Cost	Utility(G) Utility(G) Utility(G)
	Reduced transmission congestion costs	Utility(T)
	Deferred Transmission Capacity Investments	Utility(T) Utility(T)
	Deferred Distribution Capacity Investments	Utility(D) Utility(D)
	Reduced Transmission Equipment Failures	Utility(T)
	Reduced Distribution Equipment Failures	Utility(D)
	Reduced Transmission Equipment Operation & Maintenance Cost	Utility(T) Utility(T)
	Reduced Distribution Equipment Operation & Maintenance Cost	Utility(D) Utility(D)
	Reduced Transmission losses	Utility(T)
	Reduced Distribution losses Theft reduction Reduced Meter Reading Cost	Utility(D) Utility(R) Utility(R)
Reliability and Power Quality	Reduced cost of power interruptions Reduced costs from better power quality Reduced Sustained Outages and Major Outages	Utility(D) Consumer Consumer
Environment	Reduced damages as a result of lower greenhouse gas /carbon emissions Reduced damages as a result of lower SOx, NOx, and Particulate Matter emissions	Society in general Utility(C)
Energy Security	Greater energy security from reduced oil consumption	Society in general Utility(C)
	Reduced widespread damage from wide scale blackouts	Society in general Consumer

Note: Gray colored cells are outside scope of this study.

In the definition, benefits are categorized by “Economic”, “Reliability and Power Quality”, “Environment” and “Energy Security”, and “Utility”, “Consumer” and “Society” are used as beneficiaries. With regard to “Utility” as beneficiary, sub category such as G: Generation, T: Transmission, D: Distribution, R: Retail and C: Common are used in order to clarify targeted business organizations in this study.

Table 2-1 shows reorganized Smart Grid benefits and beneficiaries defined in [2-1] by above mentioned four categories, and some benefits are divided to define beneficiaries clearly. Although

Table 2-1 shows many benefits to various beneficiaries expected by the realization of Smart Grid, this study focuses on some major areas as the viewpoint of Smart Grid rapid promotion.

One of the big differences in Smart Grid compared with existing power supply systems is small-medium size DGs exist in demand-side (distribution area) and in economic, reliability and environmental aspects, optimal power delivery and consumption would be achieved by collaborated control between supply and demand sides. In order to realize these, various technology improvements are required in demand-side.

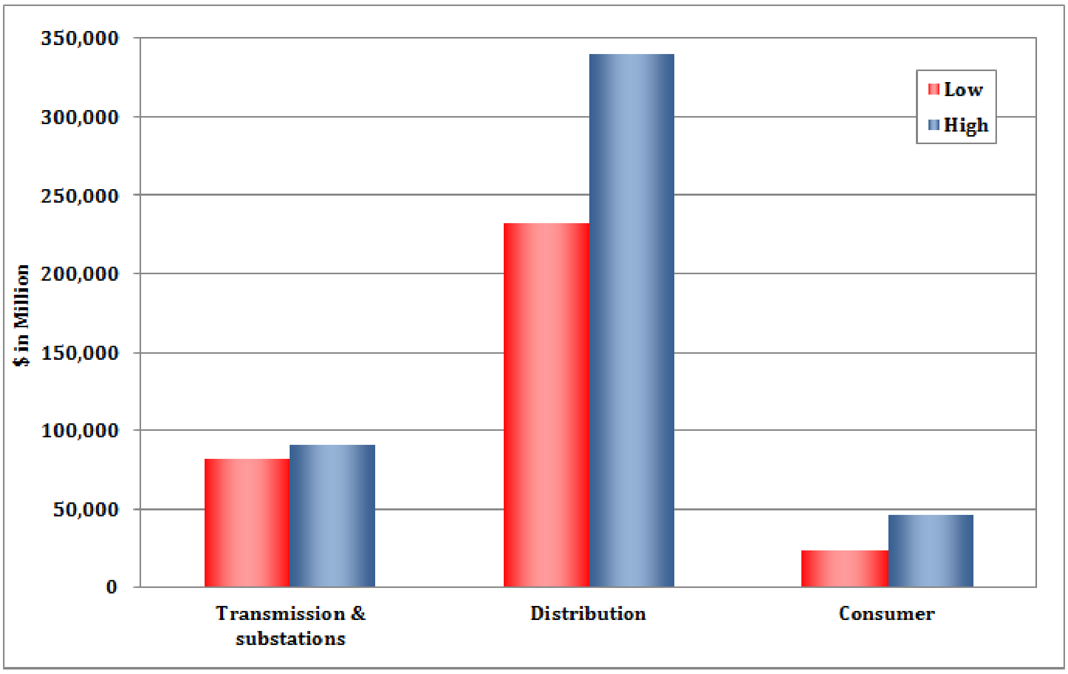


Figure 2-3 Total Smart Grid Cost [2-6]

Figure 2-3 shows total costs to enable a fully functioning Smart Gird showed in [2-6], and the report estimates that 309-403 billion U.S. dollars (USD) investment to distribution system area would have been provided for twenty years. This shows center area of Smart Grid investment is distribution system area (demand-side). Therefore, benefits which beneficiaries are Utility (D) and Consumer and also benefits which contribute to demand-side power source such as DG and batteries are focused on as major objects in this study. Because benefits which beneficiary is "Social" should be provided as philanthropy, business ethics and compliance for regulations etc., these are not adequate benefits considered by their profitability. Therefore, these benefits are out of scope in this study. However, it would be essential to consider environment, safety and security related matters in the discussion of economic and reliability related benefits achievement.

2.2.3. Technological Measures to Realize Smart Grid Benefits

Next, related technologies, methods and approaches to realize Smart Grid are considered for each selected Smart Grid benefits from major demonstration projects and related research reports and papers.

(1) Electricity Cost Savings

This benefit is that electricity price down or rebate receipt in consumers by behavior changes in themselves. It includes contract modification by load leveling, incentives from power companies for consumer's peak cut, autonomous energy saving operation by smart appliances and cost reduction by changing various electricity price programs [2-7][2-10][2-11]. The followings are Smart Grid technological measures which realize this kind of benefit.

- Technologies for EMS in demand-side such as Factory (FEMS), Building (BEMS) and Home (HEMS)
  - Visualization of power consumption, appliance and equipment control, demand forecast and simulation etc.
- Various electricity price programs including demand response (DR)
  - Time of Use (TOU), Real Time Pricing (RTP), Critical Peak Pricing (CPP), Peak time Rebate (PTR) etc.
- Smart Equipment, Smart Appliances

(2) Deferred Generation Capacity Investments

Although this benefit means deferred investment for large scale and centralized generation plants generally, the benefit is considered in this study because it might be considered that some demand-side control such as DR programs or DG installation etc., can contribute to the deferment of the investment for large scale generation plants [2-10]. Therefore, only demand-side control methods by DG and DR etc., are focused as sources of this benefit.

- DG and RES installation
- DR and demand-side management (DSM)
- Peak reduction and energy saving by EMS

(3) Reduced Ancillary Service Cost

In this study, ancillary service cost is defined as the cost which is paid for the power supply stability by power companies connecting their plants with power transmission or distribution systems, to the organization such as independent system operator (ISO). In order to reduce ancillary service cost under the near future environment where a large number of RES generators are installed, highly accurate forecast of generation capacity and power demand in a target area, and also real-time rapid control systems which use the forecasted information might contribute to effective management of distribution systems. Community EMS (CEMS), which provides power supply and demand balancing functions for a certain area, has been studied and developed and it is expected that CEMS provides advanced supply and demand control functions including efficient ancillary service provision.

- CEMS
    - High accuracy forecast of generation capacity and power demand
    - Real-time rapid control system
    - Ancillary service provision

(4) Deferred Distribution Capacity Investments

Power demand peak reduction is necessary as a method for deferment of distribution equipment investment. In order to achieve that, similar measurements in 2.2.3(1) and 2.2.3(2) are required. In other word, actions for load reduction in demand-side lead to deferment of distribution asset investment, and demand-side DG installations would make same effect. Therefore, these load reduction effects might lead to price reduction or incentives provision by power companies.

(5) Reduced Distribution Equipment Failures

By the detailed status monitoring of distribution systems, power flow with abnormal current and/or voltage injected into distribution equipment would be preventable. Also, by the collection of detailed status data from equipment in distribution systems, signs of equipment failure can be detected. The followings are technological measures to realize them.

- CEMS
    - High accuracy forecast of generation capacity and power demand
    - Optimal system control algorithms and simulations using electricity generation and load forecast.
- Asset and equipment state monitoring
    - For reliable operation and rapid failure detection
    - For improved asset maintenance methods such as equipment condition based maintenance.

(6) Reduced Distribution Equipment Operation & Maintenance Cost

The expansion of autonomous control areas contributes to operation and maintenance cost reduction. Also, equipment status monitoring makes condition based maintenance (CBM) possible from conventional time based maintenance (TBM), and CBM can reduce some inspection works which are not necessary from the viewpoint of asset health. This change is beneficial operation not only for the aspect of work volume reduction but also of human error reduction. The followings should be technological measures to realize above these functions.

- Autonomous wide area asset monitoring
- Autonomous asset control
- Asset maintenance methodologies such as CBM, TBM etc.

(7) Reduced Distribution Losses

In the conventional power supply model that electric power generated by large-scale centralized power plants is transmitted and distributed to demand areas, one of significant problems is power loss which is caused by impedance of power transmission and distribution lines. Because power loss depends on the distance from a power plant to demand points, adequate DG and other equipment installation and system reconfiguration in demand-side would be key points in order to reduce power loss [2-12][2-13][2-14][2-15]. Therefore, the followings should be technological measures.

- Installation and optimal allocation of DGs.
- Distribution system reconfiguration

- Reactive power and voltage control (Static Var Compensator (SVC) or Step Voltage Regulator (SVR) installation and optimal allocation)

(8) Theft Reduction

Power theft reduction would be achieved by detecting abnormal usage through continuous power consumption monitoring. Generally, theft reduction is one of important benefits of AMI.

- AMI (Smart Meter, communication network (last miles network) and data collection and management system (meter data management system (MDMS))

(9) Reduced Meter Reading Cost

As well as 2.2.3(8), this is one of important benefits of AMI installation. Historically meter reading is operated by metering staffs every month or every year etc. By AMI, efficient, frequent and accurate metering would be achieved.

- AMI

(10) Reduced Cost of Power Interruptions

Cost of power interruptions is the expense for countermeasures of power interruptions required in power companies. In order to reduce the cost, reduction of outage, rapid detection and islanding of outage sections are required and also rapid restoration from outage by using autonomous control, remote control and alternatives should be necessary. The followings should be required technological measures.

- Wide area distribution system and equipment monitoring
- Detection of outage section
- Autonomous control, remote control (Islanding and restoration)
- Collaborative operation with alternatives such as DGs and power storages including electric vehicles (EVs).

(11) Reduced Costs from Better Power Quality

This benefit means cost reduction for damages in demand-side from momentary outage, voltage sag and swelling or harmonics. In order to reduce the cost, some hardware devices such as stationary power battery for short term outages and adaptive protection circuits are required.

(12) Reduced Sustained Outages and Major Outages

Sustained outages and major outages make significant damages to actions in power consumers and it is necessary to avoid. Basically, same actions in 2.2.3(10) are required and also power consumers should corporate peak cuts and peak shifts to avoid wide-area outages or major power interruptions considering consumers' profitability.

2.2.4. Creating Actions in Smart Grid Projects

Here, extracted technological measures are grouped by their similarity and actions in actual Smart Grid projects are considered for each group.

a. Selection of Critical Benefits Which Need Further Discussion

Before the grouping, focusing technologies and measures are selected considering the purpose of this study. Countermeasures for 2.2.3(8) "Theft reduction" and 2.2.3(9) "Reduced Meter Reading Cost" would be achieved by autonomous and frequent power consumption data collection using AMI. AMI is one of the base infrastructures for Smart Grid and it also takes important roles from the viewpoint of ICT utilization. However AMI for general purposes such as theft reduction and reduced meter reading cost would be out of scope in this study because some countries and regions have already installed smart meters for these purposes. (Utilization of data collected by AMI for other purposes is scope of this study.) In addition, countermeasures for 2.2.3(11) "Reduced Costs from Better Power Quality" should be achieved by mainly hardware and thus benefit it is also outside the scope of this study.

b. Categorization of Critical Technologies, Methods and Approaches in Selected Critical Benefits

Here, selected critical benefits are reorganized by the similarity in their characteristics, objectives or required technologies. All countermeasures can be related to improved power supply, power consumption or control between power supply and consumption in a certain region or area. Therefore, extracted technological measures are categorized by "optimal power supply", "optimal power utilization" and "optimal power supply and demand balancing" and these three major categories are defined as critical areas to promote Smart Grid penetration in this study. Table 2-2 shows actions for critical components in actual Smart Grid projects and their objectives which are needed to be achieved. In other word, items in this table show critical elements for the realization of

Smart Grid and it is necessary that this study need to provide effective measures for the realization of these items.

Table 2-2 Actions for Critical Components in Smart Grid Projects and Their Objectives

Critical Components Technological Countermeasures	**Actions in Smart Grid Projects**	**Objectives**
(1) Optimal Power Supply - DG - Optimal volt- ampere reactive (VAR) control (SVR, SVC Installation) - Network reconfiguration - Autonomous control	- Optimal DG installation. - Optimal SVR, SVC installation - Optimal distribution network reconfiguration - Generator operation and maintenance optimization (Asset management Asset life cycle cost management)	- Peak power cut/shift - Power loss reduction - Total generation cost reduction - RES capacity expansion - Stable voltage/current - Ancillary service cost reduction - Operation and maintenance Cost reduction - Life time cost reduction
(2) Optimal Power Utilization - Demand-side efficient energy management (Visualization, device control, demand forecast,) - Various electricity price program including DR - Smart equipment and Smart appliance (Autonomous control)	- EMS (BEMS, HEMS, Mansion EMS (MEMS) and FEMS) - Demand response (DR) and Various electricity price system - Smart equipment and appliance Autonomous control -	- Electricity saving - Electricity peak cut - Electricity cost saving - CO_2 emission amount reduction - Optimal electricity price program -
(3) Optimal power supply and demand balancing - Wide area energy management - Wide area system, asset and device status management - Outage area specification - Distribution automation (Automatic and remote control) - Supply and demand forecasting and adjusting (DG, Battery, Power storage including electric vehicle (EV), Stationary Power storages, Uninterruptible Power Supply (UPS), DR)	- EMS (CEMS, Wide Area EMS) - Outage management - Asset condition monitoring, - Distribution automation - EV integration - System control - Aggregator services (BEMS, DR, MEMS etc.)	- Real-time supply and demand balancing - Outage indexes minimization - Operation and maintenance cost reduction - Deferred asset investment - Deferred inspection interval - Efficient management for Small and many loads and power supply asset such as dispersed generators and power storages.

2.3. ICT Contribution Areas for Smart Grid

In this section, ICT contribution for challenges in critical components and technological measures selected and categorized in previous section is considered.

2.3.1. ICT Value Provision Model

Figure 2-4 shows the value provision model of ICT which illustrates relationship between Smart Grid realization elements and Smart Grid benefit from the viewpoint of ICT.

ICT should play several important roles in every element in order to provide Smart Grid benefits from data generation to value proposition as follows.

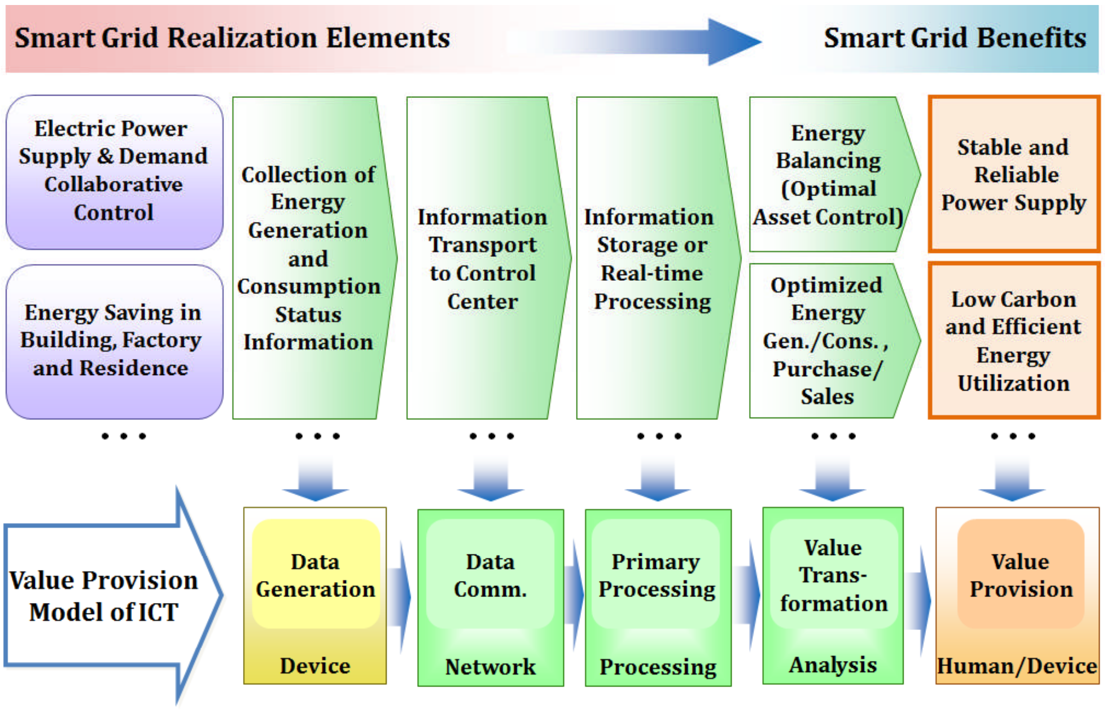


Figure 2-4 Value Provision Model of ICT

From the diagram, the followings are technologies which especially require ICT contribution.

- Advanced network technology which communicates data between meters or sensors in demand-side and data center systems in two ways
- Advanced data collection technology for enormous and frequently generating data from a large number of smart meters and sensors.
- On-memory based rapid data processing technology for real-time data utilization.
- Advanced data storage technology for rapid big data analyses for efficient data processing.
- Value transformation technology which creates new values and benefits for end users or control devices.

Smart Grid realization should be promoted if above these ICT advantages could be effectively applied to critical Smart Grid elements selected in the previous section.

2.3.2. ICT Contribution Areas for Value Provision

As mentioned in above, ICT applications to power systems are limited and most are utilization of communication network (Network function) or standalone data processing (Processing function) for limited business objectives generally. Although all these ICT related technologies are essential for the realization of Smart Grid, this study focuses on “Value transformation technology” because this is the collaboration required area between electrical technologies and ICT while other four elemental technologies are achieved by mainly information processing and network technologies.

By the engineering innovations related to sensor technology, many measuring devices including smart meters should be installed in many and various areas, and various enormous data could be collected through information networks. As new value added areas utilizing various information, the following areas should be promising considering ICT utilization advantages.

(1) Specific and Total Optimization

In most of utilizing measures and technologies for power supply, historical and experimental knowledge has been utilized. These are small risk and safe but might not be optimal. On the other hand, the application of optimization approaches has been still very limited because of various constraints such as small number and inaccurate data, low computer performance and intractability of problems needed to solve. However, recent ICT innovation is removing some of such constraints and a current small PC has the same performance as a mainframe computer in several years ago. Therefore, various optimization techniques using ICT have possibilities for changing profitability of power companies’ and consumers’ business.

(2) Interoperability and Collaborative Operation

While the conventional power supply model is a one way power flow model from large-scale centralized power plants to demand areas, advanced power supply model in Smart Grid should be a two-way power flow model which can execute more effective collaborative operation between supply and demand sides. In order to realize the new two-way model, detailed and frequent information utilization for both sides is necessary and real-time processing should be required. By the improvement of this area, optimizations of regional power utilization including local power production for local consumption and power interchanges within the region could be realized.

(3) Integrated and Automatic Control

ICT has contributed to the automation of human works recently and that lead to better productivity. Next step should be ICT contribution to equipment automatic control utilizing information and wide-area network. Generally, it has been difficult to use wide-area networks for the automatic control of equipment because of their low response time and lack of reliability so far. However recent ICT innovation is steadily realizing automatic equipment control.

2.3.3. Relation between Smart Grid Critical Areas and ICT Contribution

In the consideration of Smart Grid critical components in 2.2, all countermeasures to realize Smart Grid were categorized by “optimal power supply”, “optimal power utilization” and “optimal power supply and demand balancing” and these three major categories were defined as critical areas to promote Smart Grid penetration in this study. Therefore, ICT should contribute to these three critical areas and provide values and benefits utilizing technological advantages described in above.

One of the data collection mechanisms of Smart Grid is the AMI and thus the base data for new added values and benefits should be the data collected by AMI. Therefore AMI is one of key base components. In addition, the value and benefit transformation using collected data should be realized by computer applications. Because all three critical areas are related to the power optimization, computer applications for advanced power management should be another key base component and these applications are EMAs.

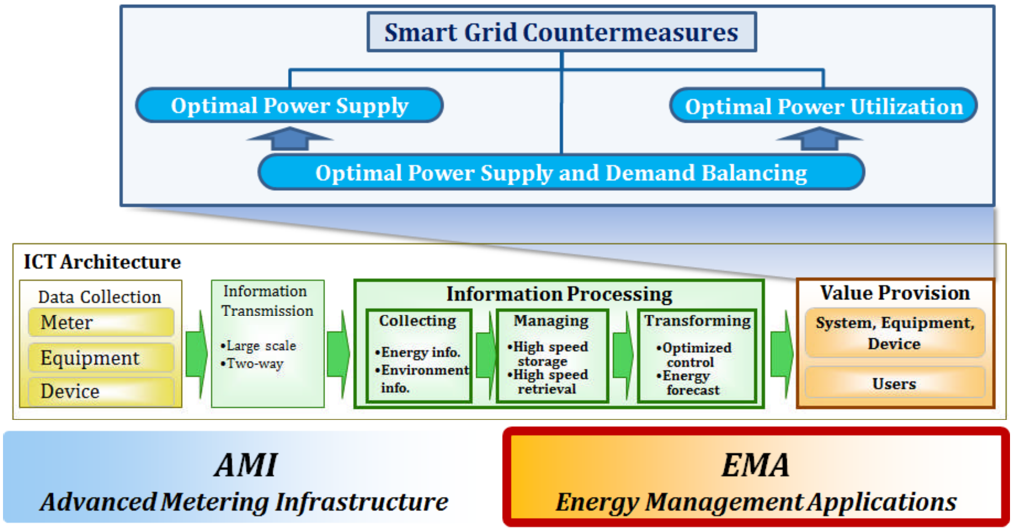


Figure 2-5 Relation between Smart Grid Critical Areas and ICT Contribution

Figure 2-5 shows the relation between Smart Grid critical areas and ICT contributions. Data collected by smart meters are transferred to center system and stored and processed by various information systems to generate new added values. It means that the main objective of this study is to explore advanced and effective EMAs which realize critical Smart Grid measures utilizing data collected by smart meters.

2.4. Base ICT Smart Grid Technologies

Before further consideration of EMAs, AMI and EMS which are key foundations of EMAs are described as the base Smart Grid technologies. In the aspect of ICT applications, most Smart Grid projects start with AMI implementation and new services are provided based on the EMS. Because there are various kinds of EMSs such as BEMS, FEMS and FEMS etc, this type of EMS is called CEMS collectively in this study.

2.4.1. AMI Solution as Smart Grid Infrastructure

In this study, AMI is a premised ICT infrastructure and not a target solution for further considerations. However, it is very important to understand AMI's specific features for effective EMAs considerations because most of data collected by AMI should be the input data for EMAs. Therefore, this study provides basic features of AMI solution.

Table 2-3 Challenges for the Network Establishment in AMI

AMI Implementation Phase	
Category	Challenges, Expectations
System configuration and registration of meters and related equipment.	Enormous management works are generated in addition to current meter management items. ➔ Related communication equipment (gateway, repeater etc.) management, interfacing to backend systems such as billing system etc.
Network design.	Long term (several years) network installation term. ➔ It is almost impossible to design suitable network considering several ~ over ten years later environment.
AMI Operation Phase	
Category	Challenges, Expectations
Environmental change	Requirement of Network re-designing ➔ Network redesign in later implementation stage
Trouble shooting and maintenance	Requirement of rapid failure discovery ➔ Difficult to detect failures before customer's discovery at present

AMI has been installing for field trial, pilot and commercial deployment around the world as the first step of Smart Grid implementation. Typical differences of AMI network compared with current network infrastructure are its vast amount of connected devices and long implementation term, and both influences to the network establishment.

Table 2-3 shows challenges for the network establishment in AMI. In the AMI implementation, it is difficult for current general network technologies to solve these challenges with reasonable cost. Because it is not practical to install new wired network, generally power line communication (PLC) and/or Radio frequency (RF) mesh network are adopted as communication technologies for AMI [2-16].

PLC utilizes existing distribution networks and is cost effective measure because no need to prepare specific communication line. Therefore PLC is one of effective technologies for auto meter reading with low frequency data collection. However high speed PLC should be necessary considering requirements of AMI or future Smart Grid infrastructure and the high speed PLC utilization outside is unauthorized in Japan. Therefore, this paper describes RF mesh technology's possibilities as an AMI establishment technology.

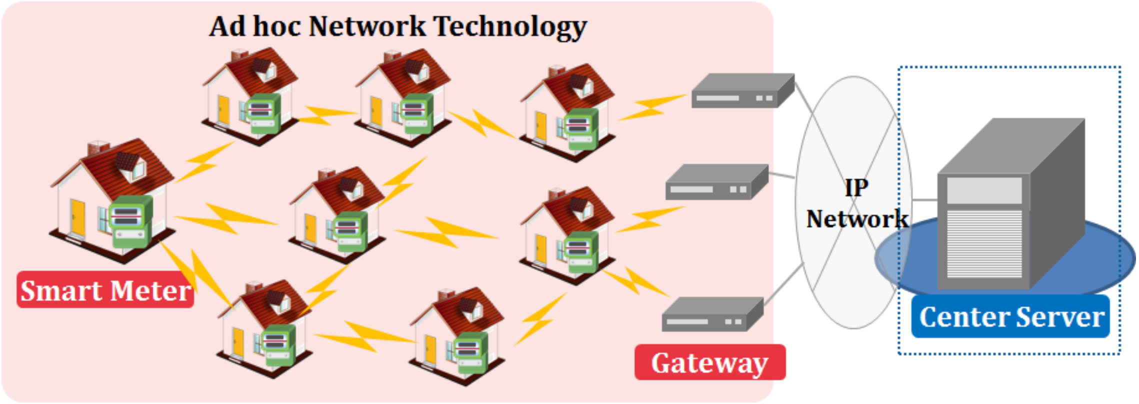


Figure 2-6 Ad−hoc Network Technology in AMI

RF mesh network consists of distributed autonomous nodes communicated each other and each node passes their data through the network. This is also called "ad-hoc network" and can be established only with installation of nodes and some wireless communication equipment, illustrated in Figure 2-6. Both PLC and RF mesh do not need communication line but require data concentration equipment such as concentrator, gateway, evaluation points between them should be technological performance and total cost.

(1) Challenges of RF Mesh Network for AMI

There are two major types for communication routing in RF mesh network, which are the reactive type (AODV: ad hoc on-demand distance vector) and the proactive type (OLSR: optimized link state routing), illustrated in Table 2-4.

In the reactive type, control packets for route search are broadcasted at every communication. Therefore, this type is suitable for frequent communication route change network such as mobile communication. However, these control packets are increased and communication performance is degraded in response to the number of communication modules in the network. This is the one of major issues for difficulty of large scale wireless network establishment.

In the proactive type, control packets are broadcasted periodically and a communication route is decided. This connection routing information is shared among communication modules. Although this method reduces communication packets, control packets are broadcasted for whole network and still it is difficult to establish large scale network. Also, the update frequency of communication quality information is low because of periodical route establishment.

Table 2-4 Major RF Mesh Routing Methods

Routing Type	Reactive type	Proactive type
Description	Route setting at every communication	Route setting prior to communication by sending periodical control packets
Advantage	Real time re-routing can be performed upon environmental change	Equalizing traffic by sending control packets periodically
Dis-advantage	Causes heavy traffic (packet)	Inability of real time re-routing
Good for…	Small Size Network Mobile Communication Network	Medium Size Network

(2) Technology to Solve These Challenges

In order to solve current challenges for AMI in RF mesh, it is necessary to reduce control packets as much as possible and provide rapid recovery method from communication failure. The following ad hoc network technology has succeeded to reduce control packets dramatically by communicating connection and route information with only neighbor communication modules [2-16]. In addition, unnecessary packets are reduced by adopted “depth first search (DFS)”. Table 2-5 shows brief description of the ad hoc technology. In the communication quality aspect, rapid route switch can be executed in case of failure by the restoration of several alternative routes in each communication module.

Table 2-5 Proposed Ad-hoc Technology

Routing Type	Improved Proactive Type
Description	Searching based on leaned routing information without sending unnecessary control packets
Advantage	Control packets reduction and real-time re-routing capability
Suitable Network	Large size fixed network

By the adoption of this method, only one gateway can collect data from 1,000 communication modules logically and the large scale RF mesh network with over 10 million communication modules can be established. Because this network can re-establish its network route automatically based on the network quality, it is very flexible for environmental changes over time and high reliability. Figure 2-7 shows major features of the RF mesh technology.

Automatic Connection in Large Scale Network

- No complicated Network setting
- About 1,000 Smart Meters per Gateway

Flexible and High Reliability

- Automatic re-routing in case of failure/congestion occurred for stable and secured data transmission.

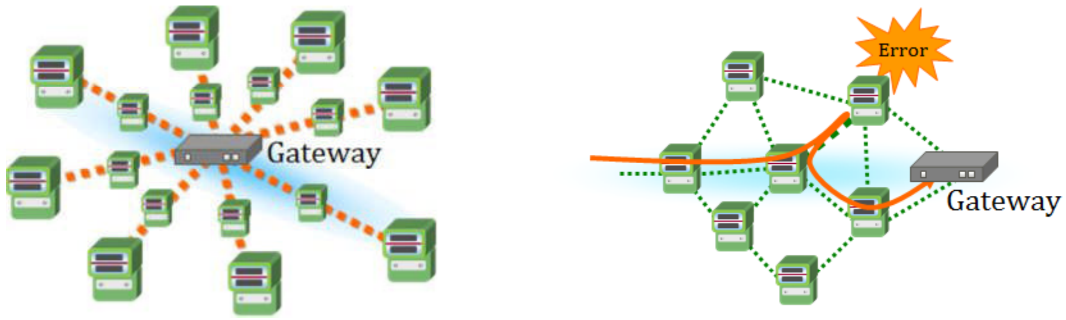


Figure 2-7 Major Features of the RF Mesh Technology.

(3) Collaboration between RF Mesh Network Technology and Center System

Because sometime obstacles might enter into wireless communication route, it is almost impossible for wireless network to use clear communication environment at any time. Therefore, it should be considered recovery methods for the occurrence of data collection failures over several million metering.

Although it is necessary to recollect metering data in case of data collection failures, an execution of simple data collection retry might make data flood in case of power outage because all meters in a certain outage area are retried metering data collection. Therefore, a center server system has a measure for multiple metering data collection at one time, so it is not necessary to retry data collection only with one data collection failure. If some metering data recollection were required, a recovery specified data collection measure is executed periodically for preventing concentration of data collection.

In addition to above methods, on-demand metering which collects metering data by an individual request from the center server is also provided. Although general control systems are center management type which the center server issues commands to control devices, this AMI center system can solve data amount and traffic issues to distribute roles with both center server and communication modules.

(4) AMI Utilization as Smart Grid Infrastructure

Although AMI is one of important elements of Smart Grid infrastructure, it is not realistic at present that AMI would be the ultimate Smart Grid infrastructure because it is difficult to use AMI as various data collection network for realizing power supply and demand balancing considering its band width and security related issues. However, the above mentioned ad-hoc network technology is expected as a future sensor network technology and might be the best technology for Smart Grid because of the following reasons.

- Network is established only with communication module installation (No communication cables)
- No network design (Each sensor communicates each other and establish network automatically.)
- Large scale network establishment (1 gateway for 1,000 communication modules, possible to establish large network with over 10 million communication modules.)

Actually, this network technology has been adopted various industries in addition to electric power industry. Table 2-6 shows some applicable areas of the ad-hoc technology. In order to realize Smart Grid, it is essential to utilize various kinds of information in addition to electric power related information. Network in various industries are constructed and the interconnection of these networks realize various and enormous data collection and these data should contribute to the realization of high accuracy EMAs and EMSs.

Table 2-6 Ad-hoc Technology Applicable Areas

Industry	Support Area	Collection Data
Agriculture	Work Schedule, Status Confirmation	Temperature, Moisture, Illuminance Soil component etc.
Process Industry	Operation Management Maintenance Support	Operation status, consumables, firmware version etc.
Beverage	Sales Planning Delivery Order	Merchandise Inventory, change, sales status etc.
Logistics	Traffic Support Delivery Status	Location information, Engine rotation etc.
Utility	Metering Support Demand Control	Consumption, Supply and demand balancing.

2.4.2. CEMS as a Smart Grid Infrastructure

Although the main objective of this study is to explore advanced and effective EMAs, all these applications are provided based on CEMS providing power flow balancing mechanisms between supply and demand sides. Historically, electric power from large concentrated generations is supplied corresponding to continuously varying demand. On the other hand, energy management in the Smart Grid concept is characterized in that demand-side concerns with efficient power utilization for providing benefit for both supply and demand sides. In this study, CEMS is defined as the second base infrastructure of Smart Grid for power supply and demand collaboration system in distribution area and basic functions and enabling technologies are described.

(1) Required Functions [2-18]

The main target of the CEMS is to provide optimized operation programs for power supply and consumption equipment in order to provide benefits for both supply and demand sides. In order to realize that, the following forecasting and planning features are required.

- Forecast accurate amount of power supply and demand in each calculation time frame
- Develop optimized target power supply and demand plans
- Shift power demand targeting for the developed demand plans
- Supply power corresponding to the developed supply plans

Table 2-7 CEMS Required Functions

Category	Function Group	Functions	Function Outline
Forecasting and Planning	Supply and Demand Forecasting	● Forecast (Total generation, Total demand, Response rate (Recommendation) ● Data Interface (Control center, Power exchange (PX), Weather information, Other EMSs etc.)	● Frequent and Rapid Forecast - Total power supply amount by both utilities and dispersed generation assets - Total demand - Branch level supply and demand forecast considering photovoltaic (PV), EV and battery installation. ● Variation Forecast
	Supply and Demand Balancing	● DR and DSM Program Development ● Generation Dispatch ● Notification PV(Power Conditioning System (PCS)) Battery, EV charge, charging,) ● Data Interface ● Power flow calculation	● Power Demand Control by DR and DSM ● Renewable Energy Prioritization by the Movement of Decarbonizing ● Local Production for Local Consumption in Electric Power - For disaster resilient power systems
	Supply and Demand Scheduling	● DR and DSM Recommendation provision ● Generation Dispatch ● Notification PV(PCS), Battery, EV ● Data Interface ● Power Flow Calculation	● Demand Shift for Achievement of Target Demand plan (e.g. Optimized operation program provision for each device, PV disconnect from the system for stable power supply etc.) ● Consumer Voluntary Demand Reduction (e.g. TOU provision, etc.)
Monitoring and Control	Equipment Monitoring	● Real-time System Situation Monitoring ● Real-time System Status Monitoring ● Backup Generation Monitoring	● Existing Supply Equipment Monitoring ● Power Supply Equipment Monitoring in Demand-side ● Data Storage for Future Advanced Equipment Control
	Equipment Control	● Control Message Transformation ● Interface Existing Process Computers	● Developed Schedule Reflection to Existing Power Supply Equipment. ● Disconnection of Demand-side DG, battery etc. from Power Systems ● Operation Support for Reserve Generations

Also the following monitoring and control features are required once optimized power supply and demand plan is determined.

- Monitor power supply and consumption equipment status
- Control power supply and demand equipment for the achievement of optimized targeted power supply and demand plan

Table 2-7 shows detailed description of above mentioned features in CEMS.

(2) Technologies Required to Provide CEMS Functions

In order to realize above mentioned CEMS functions, various advanced technologies are required to execute enormous data high speed processing because of dealing with a large amount of distribution assets and residential equipment data. Here, some applicable technologies are introduced.

a. Advanced Technical Calculation

Power flow calculation and optimization are essential measures to estimate power supply and demand amount and to create efficient power supply plans. Although various power flow calculation methods has been studied, one of the main objectives of the CEMS should be to provide rapid calculation algorithm for the environment that many DGs (mainly PV generation) are installed and a lot of information can be collected and processed, considering the power supply environment in the near future in Japan. Therefore, it is expected that power flow calculation method can deal with a lot of DGs as well as a large number of power consumers (load points) and can set various optional attributes. This means the power flow calculation need to deal with enormous data incomparably larger than ever before, so it is required to have a rapid processing algorithm.

b. Enormous Information Collection and Delivery

Because many and high density PVs installation might influence power stability by reverse power flows, voltage sags or voltage rises etc., some functions are required to monitor power system situation and status information, and execute adequate actions to avoid instability statuses. Therefore, it is assumed that the CEMS needs to collect (or calculate) power status data such as voltage and current. Also, data from RES generation in demand-side should be all collected, as well as data from reserved generations for back-up and other related equipment. These data would be integrated and processed to create optimized operation programs in CEMS and these programs reflect to the targeted equipment.

Furthermore, metering data from AMI, process data from supervisory control and data acquisition (SCADA), distribution management system (DMS) and other related data such as weather and PX data etc., are assumed to be integrated in CEMS, and these data and calculation results should be utilized for the improvement of optimized programs calculated by EMAs.

c. High Speed Data Processing

The CEMS is required to process huge power supply and demand related data and provide optimized operation plans rapidly. Therefore, high speed mechanisms from the viewpoint of information processing should be adopted, as well as consideration of high speed algorithm or processing logics. In the baseline of the CEMS concept, the application of the complex event processing (CEP), in-memory database and the key value store (KVS) has been studied to meet data process requirements as Smart Grid information infrastructure. Table 2-8 shows outline of these technologies and examples of their adopted area in CEMS.

Table 2-8 Rapid Data Processing Methods in CEMS

Adopted Technology	Description	Adopted Area
CEP (Complex Event Processing)	Rule based data processing by judgment of monitoring event context	Real-time system information visualization
In Memory Database	Database management system of on-memory data storage	Power Flow calculation
KVS (Key Value Store)	Simple and rapid data storage method by Key and Value	System asset management

Figure 2-8 shows the holistic overview diagram of CEMS concept. Various information from supply and demand sides, other organizations such as service provides, PX etc., are gathered using various networks. Data collection/delivery interfaces interpret data property and transfer the data to CEP. In the CEP, the data are distributed to adequate processing units or data storages using scenarios stored in the CEP. Processed data by the above mentioned rapid data processing method are returned to supply and demand equipment for optimal control and/or returned to operators and consumers for the optimal energy management.

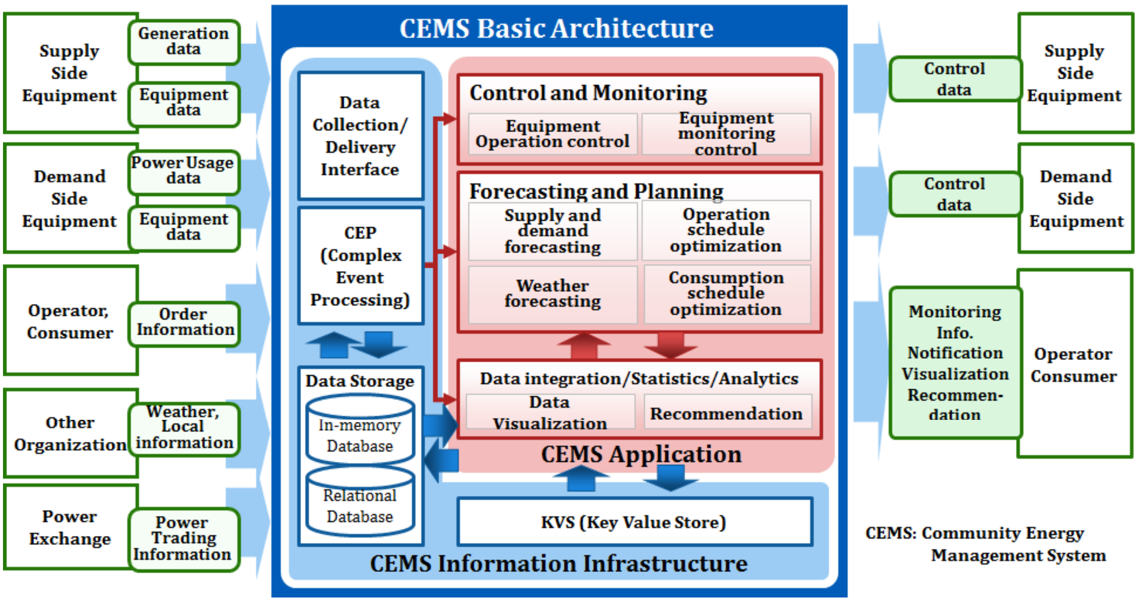


Figure 2-8 Supply-side EMS Concept Overview

2.5. Key Technical Research Topics for Realizing Smart Grid

At the end of this chapter, key technical research topics are described and research directions and expectations are defined. Here, it is necessary to clarify for whom these research topics would be conducted because benefit or profit, focused in this study, depend on the position of entrants in power markets. Therefore, the position of beneficiaries in this study is also clarified.

2.5.1. Key Research Topics

Key technical research topics including concrete challenges for selected ICT contribution topics are described for the critical areas of Smart Grid realization selected in 2.2.

(1) Optimal Power Supply

In this category, main research topic is optimal installation of distributed equipment such as DG for efficient and reliable power supply. The major purposes of this topic are cost and power loss reduction by locating generators near demand, RES increase for the reduction of CO_2 emission and quick power supply recovery from a disaster.

(2) Optimal Power Utilization

In this category, major research topics should be to provide effective demand-side EMSs for optimal energy utilization and to develop effective price programs including DR for optimal power companies' operation. In order to provide both effective EMS and price programs provision including DR, control methods of customers' equipment or appliances should be considered and clarified.

(3) Optimal Power Supply and Demand Control

In this category, the most critical challenge is to maintain reliability of the future advanced power systems considering a large number of RES generation connected environments, including power supply and demand balancing, voltage and current management, and outage management in a target system using both supply and demand sides information.

From above considerations, Table 2-9 describes ICT contribution topics for critical technological measures to realize Smart Grid. Therefore this study defines that Smart Grid elemental technologies in "Optimal Power Supply", "Optimal Power Utilization" and "Optimal Power Supply and Demand" should be keys to Smart Grid realization and the expansion of ICT application to these technologies should accelerate the realization.

Table 2-9 ICT Contribution Topics for Critical Technological Measures for Smart Grid

Category	ICT Contribution Topics
Optimal Power Supply	**Optimal asset installation for efficient power supply, such as DG etc.** - Optimal allocation of DG, SVR and SVC - Benefit and cost evaluation of RES
Optimal Power Utilization	**Benefit realization of demand control measures such as efficiency energy consumption (Consumer EMS) and various price program** - Benefit and cost evaluation by demand-side EMSs - Benefit and cost evaluation by power companies' price programs including DR
Optimal Power Supply and Demand Control	**Effective methods to maintain power supply reliability in a targeted area** - State monitoring for distribution system with a large number of PVs - Outage management for smart meter installed environment

2.5.2. The Stance of This Study for Business Profitability

This study explores critical Smart Grid measures from the viewpoint of business profitability and thus the stance for the business profitability of this study should be clarified because the business profitability varies depending on market participants' business. For example, PV system installation is beneficial for PV system vendors and system installed customers can get benefit from PV generations (by power selling or consumption). On the other hand, PV systems might cause reverse power flow and reduce power supply reliability in distribution systems from the viewpoint of distribution system operator (DSO).

The reason why this study focuses on business profitability is that it promotes market expansion and generates additional investment continuously by the market entrants, and it is assumed that this movement should realize Smart Grid. Therefore, the stance of this study for business profitability is the standpoint of competitive service providers such as power generation companies, power retail companies and electricity related service companies.

2.6. Summary

In this chapter, Smart Grid benefits and their related technologies which can accelerate Smart Grid realization by the effective utilization of ICT was discussed assuming that possible reasons which prevent Smart Grid realization might be its necessity of enormous investment under its unclear benefit, and ICT utilization should create new additional values and contribute to clarify these values. In the discussion, several areas and component actions which had high possibility to accelerate Smart Grid realization by the effective utilization of ICT were selected as future expected business areas, and some effective development topics were provided.

As the result, most of critical components of Smart Grid are installations of new technologies and measures in power demand-side, and these were able to be categorized by "optimal power supply", "optimal power utilization" and "optimal power supply and demand". In the consideration of the achievement of these Smart Grid critical components from the aspect of ICT, information collection by the establishment of AMI is the premise and effective business models based on EMAs running on the AMI and CEMS would be essential. Also the value of ICT utilization is to convert collected data (information) into values and thus it is necessary to consider solving challenges for the realization of measures in Smart Grid critical areas by the data utilization. In other words, the most important objective in this study should be to clarify concrete and effective EMAs running on AMI and CEMS, and their business models with well-documented figures.

Also, the business profitability discussing in this study is the one from the viewpoint of competitive power service providers, because it is assumed that such business profitability for these players should promote market expansion and investment increase for Smart Grid realization.

Chapter References

[2-1] EPRI (Electric Power Research Institute), “Methodological Approach for Estimating the Benefits and Costs of Smart Grid Demonstration Projects,” EPRI, January 2010

[2-2] EPRI (Electric Power Research Institute), “Smart Grid Demonstration Initiative Two-Year Update,” EPRI, August 2010

[2-3] EPRI (Electric Power Research Institute), “Smart Grid Demonstration Initiative Three-Year Update,” EPRI, July 2011

[2-4] EPRI (Electric Power Research Institute), “Smart Grid Demonstration Initiative Four-Year Update,” EPRI, July 2012

[2-5] EPRI (Electric Power Research Institute), “Smart Grid Demonstration Initiative Five-Year Update,” EPRI, August 2013

[2-6] EPRI (Electric Power Research Institute), “Estimating the Costs and Benefits of the Smart Grid – A preliminary Estimate of the Investment Requirements and the Resultant Benefits of a Fully Functioning Smart Grid,” EPRI, March 2011

[2-7] V. Giordano and S. Bossart, “Assessing Smart Grid Benefits and Impacts: EU and U.S. Initiatives,” Joint Report EC JRC – US DOE, 2012

[2-8] Y. Serizawa, “ICT Trends in Smart Grid Projects and Promising Solutions of Communications Network for TIPS (Smart Grid プロジェクトにおける ICT の動向と次世代グリッド(TIPS)のための通信ネットワークの課題),” R08028, CRIEPI Report, June 2009 (in Japanese)

[2-9] Fujitsu, Smart Grid Solution, [Online]. Available at Fujitsu Limited web site: http://www.fujitsu.com/global/solutions/business-technology/smartgrid/outlook/

[2-10] M. H. Albadi and E. F. El-Saadany, “Demand Response in Electricity Markets: An Overview,” IEEE Power Eng. Soc. General Meeting 2007, IEEE, pp.1-5, June 2007

[2-11] K. Kuroda, T. Ichimura and R. Y , “An effective evaluation approach of demand response programs for residential side,” Advances in Power System Control, Operation and Management (APSCOM 2012), 9th IET International Conference, pp.1-6, November 2012

[2-12] N. Acharya, P. Mahat and N. Mithulananthan “An analytical approach for DG allocation in primary distribution network,” Electrical Power and Energy Systems, vol.28,no.10, pp.669–678, December 2006

[2-13] D. Q. Hung, N. Mithulananthan, and R. C. Bansal, “Analy l Expressions for DG Allocation in Primary Distribution Networks,” IEEE Transaction on Energy Conversion, vol.25, no.3 pp.814–820, September 2010

[2-14] O. I. Elgerd, “Electric energy system theory: an introduction”, McGraw-Hill, 1971

[2-15] A. G. Marinopoulos, M. C. Alexiadisb and P. S. Dokopoulos, “Energy losses in a distribution line with distributed generation based on stochastic power flow,” Electric Power System Research, vol.81, no.10, pp.1986-1994, October 2011

[2-16] M. Miyashita, S. Morimura, O. Ogawa, and M Kikuchi, “Physical Network Architecture and Technical Issues for Demand-Area Secure Communication Network (需要地系セキュア通信ネットワークの物理網構成と技術課題),” R10012, CRIEPI Report, May 2009 (in Japanese)

[2-17] Y. Takahashi, K. Kawashima, Y. Nakaya, T. Ichikawa, “Network Technology Supporting an Intelligent Society: WisReed,” FUJITSU Scientific & Technical Journal, no.4, October 2011

[2-18] K. Kitagawa, D. Matsumoto, K. Amano, “Fujitsu's Approach to Realization of Energy Management System (エネルギーマネジメントシステムの実現に向けた富士通の取組み),” FUJITSU, vol62, no.6, pp.651-658, November 2011 (in Japanese).

Chapter 3 Demand-side Optimal Power Supply

In this chapter, technologies and measures for demand-side optimal power supply which were discussed in chapter two as one of critical components of Smart Grid are considered with profitable business models. In the aspects of general versatility, optimal dispersed generation (DG) allocation and renewable energy sources (RES) expansion are selected as major topics in this category.

3.1. Expectations for Demand-side Optimal Power Supply Technologies

In chapter two, “Optimal power supply” was selected as one of critical areas for Smart Grid realization and some key technical research topics were also decided. Here, expectations of these topics are confirmed and detailed research topics considered in this chapter are decided. The followings are selected two topics to be considered in this chapter.

(1) Optimal Allocation of Power Asset

With respect to the installation of distribution assets for stable power supply such as DG, step voltage regulator (SVR) and static var compensator (SVC) etc., poor selections of location and size of these asset installations lead to unstable or inefficient power supply compared with no these asset installations. Therefore, challenges and their countermeasures to identify the optimal location and size of distribution asset are selected as the first research topic for the demand-side optimal power supply.

(2) Benefit Evaluation of Renewable Energy Source

Recently, a large scale expansion of RES DG installation is expected especially all over the world. However, it is difficult to recover their installation and operation cost with the cost reduction from effective power utilization and surplus power sales, and this tendency would be more likely to be in small size consumers such as small companies and households. Therefore, apparent benefits or incentives for power consumers should be necessary in order to promote RES penetration, and RES installation benefits for power companies such as peak cut and shift, CO_2 reduction and power loss reduction, should be passed on DG owners and consumers to expand power consumers’ benefits. Therefore, benefit evaluation of RES is selected as the second research topic for demand-side optimal power supply.

3.2. Optimal Power Asset Allocation in Demand-side for Advanced Power Supply

An optimal allocation of DG is one of the most promising approaches for engineering innovation in the near future to realize low-carbonate power system because DG is one of important methods to install renewable energy generation and also installation of DG with optimal location and size can reduce power loss in power systems dramatically.

Against this background, various studies for optimal allocation of DG in distribution systems have been implemented recently and these are the study of the problem solution to decide the optimal location and size of single or multiple DGs for minimizing power loss in the targeted distribution systems. In this study, DG is used as an asset for reducing active power loss in a targeted distribution system and this means DG is a device which can provide active and reactive power. Therefore, the proposed solution method can be applied to various power system control assets such as SVR and SVC etc.

In the problem to minimize power loss, it is required to solve non-linear discrete optimization problem called “Discrete optimal power flow (OPF) Problem” under constraints such as power flow laws, voltage upper and lower limits, and apparent current upper limit etc. However, Discrete OPF has individual intractability for the solution and thus approximate solutions such as analytical and metaheuristic methods have been adopted to decide optimal location and size of DG. On the other hand, it is difficult to ensure that the solution by such approximate methods is optimal and also such approximate methods are difficult to understand overall characteristics for active power loss minimization by various installation conditions of DG. In addition, these methods are difficult to apply to the multiple DGs installation problems.

The author’s group has studied optimal allocation of DG problems with the approach using an exact solution from above mentioned methodological aspects, and proposed new approaches for optimal allocation of DG in simple pilot system model using an enumerative method in [3-1][3-2][3-2]. While the enumerative method has many advantages such as consideration of complex constraints, applicability for multi-objective problems and qualitative analysis capability for whole solutions, it has the critical challenge which combinatorial explosion tends to occur. In order to solve this challenge, this study proposes a new approach which reduces the number of combination by the adoption of some practical constraints, and the proposed method is evaluated by the simulations with multiple DGs installations using both a simple pilot model and a real size distribution system model.

3.2.1. Studies and Approaches for Power Loss Reduction

Many studies for power loss reduction of distribution networks have been reported and various network reconfiguration approaches by switching and capacitor placement have been proposed. In [3-4], power loss reduction and load balancing technology was developed by network reconfigurations. Various metaheuristics approaches such as genetic algorithm (GA), simulated annealing and improved Tab Search had been applied to network reconfiguration for power loss reduction [3-5][3-6][3-7]. With respect to capacitors installation for power loss reduction, [3-8] provides the well-known “2/3 rule” that optimal capacitor size to minimize power loss into a feeder with uniform load is 2/3 of the total load, and optimal location is 2/3 of the total distance. Also, [3-9][3-10] described that the impact on feeder losses of DG can be analyzed with something similar with the 2/3 rule, and [3-10] proposed an analytical method for the optimal DG location and size to minimize power loss for four DG types – Injecting *P* (active power) only, Injecting *Q* (reactive power) only, Injecting *P* & *Q* and Injecting *P* and consuming *Q*. The proposed approach in [3-10] and [3-11] used the real power loss expression popularly known as “exact loss” formula [3-12] as follows.

$$P_L = \sum_{i=1}^{N}\sum_{j=1}^{N}\left[\alpha_{ij}\left(P_iP_j + Q_iQ_j\right) + \beta_{ij}\left(Q_iP_j + P_iQ_j\right)\right] \tag{3-1}$$

where

$$\alpha_{ij} = \frac{r_{ij}}{V_iV_j}\cos\left(\delta_i - \delta_j\right), \beta_{ij} = \frac{r_{ij}}{V_iV_j}\sin\left(\delta_i - \delta_j\right) \tag{3-2}$$

$r_{ij} + jx_{ij} = Z_{ij}$ are (*i,j*)th entry of [*Z* bus] matrix.

Also, P_i, P_j are the active power injections at the *i* th and *j* th buses, Q_i, Q_j are the reactive power injection at the *i* th and *j* th buses and *N* is the numbers of buses.

3.2.2. Approach to Recognize Optimal Location and Sizing of DG Installation

In this subsection, a new approach using an exact solution method for obtaining an optimal location and size of DG in a simple distribution system model is provided.

(1) Utilization of the Enumeration Method as an Exact Solution Method

Among some exact solution methods such as “branch and bound” and “dynamic programing” which divides a complex problem into partial problems for efficient calculation, the enumeration method which enumerates solutions for every possible combinations is used in this study. If all possible combinations of the problem would be enumerated, the optimized solution was able to be selected from them. This is a very simple and reliable approach and versatile. However possible combinations of location and size for DG should be enormous in the problem (called “Optimal DG installation problem”) generally and the number of calculations would increase dramatically if additional variables such as attributes of DG would be added. Therefore, it is generally considered that the utilization of enumeration method for the “Optimal DG installation problem” is not practical. However, the enumeration method for the problem might be possible if the numbers of possible combinations for calculation would be reduced by using a simple power system model and adding constraints for the DG location bus and the injecting power type.

Therefore, this research uses the enumeration method for the “Optimal DG installation problem” on condition that it would applied to a simple distribution system model with some constraints so that possible combination numbers of DG installation are limited to around several dozes.

(2) Definition of the Simple Distribution System Model

In this research, 6-buses and no branched simple system is used as the simple distribution system model illustrated in Figure 3-1. In this figure, Bus1 is the slack bus and resistance r_i and reactance x_i (i=1, 2,⋯,5) are considered in each branch.

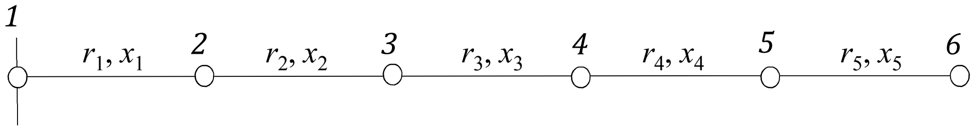


Figure 3-1 Simple Distribution System Model

(3) Formulation of Optimal DG Allocation Problem

In this research, minimization of active power loss in whole targeted distribution networks is defined as an objective function, and firstly the formulation of optimal DG allocation problem is implemented. In the formulation, allowable DG locations are buses in the targeted system model and 0-1 variable *y* is utilized for showing whether DG is installed or not at the targeted bus. As constraints, power flow law and cardinalities which reduce the number of combinations for DG location candidates are considered but voltage and apparent current constraints are not considered. If simulation results would excess these unconsidered limits, new constraints would be considered. Based on these conditions, the problem for optimal allocation of DGs is formulated as follows.

$$\min \sum_{i \in M} Ploss_i \tag{3-3}$$

Subject to

$$\dot{S}_j + \dot{G}_j = \dot{V}_j \dot{I}_j{}^* \quad (j \in N) \tag{3-4}$$

$$y_k \in \{0, 1\} \quad (k \in K) \tag{3-5}$$

$$x_k \in \{0, 1, \ldots, n_k\} \quad (k \in K) \tag{3-6}$$

$$\sum_{k \in K} size[x_k] \le S_{\max} \tag{3-7}$$

$$K_{\min} \le \sum_{k \in K} y_k \le K_{\max} \tag{3-8}$$

where

K	:	Set of candidate DG locations
n_k	:	Number of allowable DG sizes at candidate DG location *k* (*k*∈*K*)
$size[]$	:	Allowable DG sizes for each candidate DG location (P- or Q-values)
y_k	:	1 if candidate DG location *k* is selected, 0 otherwise (*k*∈*K*)
x_k	:	Decision variable for DG size at candidate DG location *k* (*k*∈*K*), 0 if y_k=0
$S_{\max}$	:	Total allowable capacity of installed DG's (P- or Q-value)
$K_{\min}$	:	Minimum cardinality for the number of installed DG's
$K_{\max}$	:	Maximum cardinality for the number of installed DG's
M	:	Set of grid branches : {1,2,..., m}
N	:	Set of grid buses : {1,2,..., *n*}
$\dot{S}_j$	:	Complex power load at grid bus-*j* (nonpositive value)
$\dot{G}_j$	:	Complex power generation at grid bus-*j* (nonnegative value) See Table.1 how to specify $\dot{G}_j$ at the bus corr. to the candidate DG location *k*. *A*ssume that $\dot{G}_j = 0$ at all load buses before placing the DGs.
$\dot{V}_j$	:	complex voltage obtained by power flow at grid bus-*j*
$\dot{I}_j$	:	Complex injected current obtained by power flow at grid bus-*j* $[[\dot{I}_j] = [\dot{Y}][\dot{V}_j]$ ($[\dot{Y}]$: Admittance matrix)
$Ploss_i$	:	Active power loss obtained by power flow at grid branch-*i*

(3-3) is the objective function which represents overall active power loss minimization in the targeted system. (3-4)-(3-8) are constraints. (3-4) is the power flow constraint. (3-5) is 0-1 variable which represents status whether DG is installed or not at the targeted bus. (3-6) is the integer constraint for discrete variable x which decides discrete capacity in DG in each location. As input data for DG location candidates, bus number, group number, DG type and the number of considered capacity and its discrete values are defined. (3-7) is the capacity constraint for total DGs so as not to exceed the value of $S_{\max}$. (3-8) is the constraints for total number of DGs.

The DG type considered at each candidate location bus is *PQ* type – injecting both active and reactive power, and capacity of each installed DG is defined. Table 3-1 shows DG type and defined discrete capacity values for the DG.

Table 3-1 Types and Capacity of DGs

DG type	Bus Specification	Input Values	Used in Power flow
PQ Type: Both active and reactive power injecting DG	*PQ* Bus	P_1~P_{nk}, P/Q ratio or Power Factor	Re($\dot{G}$), Im($\dot{G}$)

(4) Solution Procedure of the "Optimal DG Installation Problem"

In this research, an optimal DG installation is defined as the DG installation which minimizes the power loss of a targeted distribution system and its decision procedure is provided. In the procedure, one DG installation into any one bus from Bus2 to Bus5 in the simple distribution system model is considered (Bus1 is the slack bus). In order to find the DG location and its size to minimize power loss in the simple system model, the amount of power loss in case of DG installation into every one bus is calculated by a power flow calculation method. As the method of power flow calculation, the backward and forward (B/F) method is used in the research. The reason is that the B/F method is considered as a suitable power calculation method for a radial distribution system which is the Japanese typical distribution system style and its computational speed is fast compared with the Newton-Raphson method which is used for power flow calculation commonly [3-13].

The procedure of the B/F method is provided as follows. A dot on the top of the character denotes complex numbers and an asterisk on the right hand side denotes complex conjugate.

1) Predefine the voltage $\dot{V}_i\,(i = 1,2,\ldots,n\ (= 6 \text{ in the system model}))$ for each bus.

2) Calculate the injecting current $\dot{I}_i\,(i = 1,2,\ldots,n)$ for each bus using the following formula.

$$\dot{I}_i = \left(\dot{S}_i / \dot{V}_i\right)^* \quad \dot{S}_i : \text{Load of bus } i \tag{3-9}$$

3) Sum up injecting currents for each bus and set the each branch current by the following manner. (Backward sweep)
4) Calculate the sum of currents for each bus following the Kirchhoff's current law (KCL) starting from every end bus (Bus6 in the pilot system) to the slack bus (Bus1 in the simple distribution system) sequentially (Bus6 → Bus5 → … → Bus1 in the pilot system).

$$\dot{I}_{sr} \leftarrow \dot{I}_r \quad (s\text{: sending end bus, } r\text{: receiving end bus}) \tag{3-10}$$

$$\dot{I}_s \leftarrow \dot{I}_s + \dot{I}_r \tag{3-11}$$

5) Calculate the voltage drop for each bus by the following manner. (Forward sweep)
6) Execute the voltage drop calculation following the Kirchhoff's voltage law (KVL) using the calculated current $\dot{I}_i$ by the Backward Sweep, starting from the Slack bus (Bus1) to the every end bus (Bus6) sequentially (Bus1 → … → Bus6).

$$\dot{V}_r = \dot{V}_s - \dot{Z}_{sr}\dot{I}_{sr} \quad (\dot{Z}\text{: Impedance, } s\text{: sending end bus, } r\text{: receiving end bus}) \tag{3-12}$$

7) Calculate the voltage difference between the calculated voltage $\dot{V}_i$ and the previous voltage $\dot{V}_{iold}$ for each bus and execute the following convergence test.

$$\left\| \dot{V}_i - \dot{V}_{iold} \right\| < \varepsilon \quad \left(\dot{V}_{iold}\text{ : Previous voltage} \quad \varepsilon\text{ : Convergence criterion} \right) \tag{3-13}$$

8) Repeat 2) to 5) using the voltage $\dot{V}_i (i = 1,2,\ldots,n)$ obtained by the Forward Sweep until meeting the condition (6).
9) Calculate the power loss of the targeted system in comparison of the total injected power with the total load. (The difference is the power loss.)

(5) Preparation Works

Here, preparation works for optimal allocation of DG are described such as definition of assumption, initial settings and base calculation.

a. Assumptions and Initial Settings

Assumptions in the calculation are as follows.

- Only one DG is installed into any one bus of the simple distribution system model except for the slack bus.
- Three types of DGs capable of injecting active power (*P*) only, reactive power (*Q*) only and both active and reactive power (*P* & *Q*) are considered. DG's injecting power is set from 0 to 1 with 0.05 increments. In case of injecting both active and

reactive power, the size of reactive power is set at 1/2 of active power considering a general power factor (0.89).

- Load of each bus is uniform (except for the slack bus)
- No susceptance is considered.
- Initial values of voltage V_0, active power P_0, reactive power Q_0 for each bus are showed in Table 3-2, and resistance R and reactance x values of each branch are showed in Table 3-3. The data of amplitude are all per unit (p.u.)

Table 3-2 Bus Data

Bus	P_0	Q_0	V_0	Remarks
1	-	-	1.0	Slack bus
2	-0.1	-0.05	1.0	
3	-0.1	-0.05	1.0	
4	-0.1	-0.05	1.0	
5	-0.1	-0.05	1.0	
6	-0.1	-0.05	1.0	

The data of amplitude are all p.u.

Table 3-3 Branch Data

Branch	R	x	Remarks
Bus 1-2	0.02	0.01	r_1, x_1
Bus 2-3	0.02	0.01	r_2, x_2
Bus 3-4	0.02	0.01	r_3, x_3
Bus 4-5	0.02	0.01	r_4, x_4
Bus 5-6	0.02	0.01	r_5, x_5

The data of amplitude are all p.u.

b. Base Calculation

Table 3-4 shows the power flow calculation results for the simple distribution system model without DG to obtain the power loss without DG placement.

Table 3-4 Power Flow Calculation Result without DG

Bus	P (Load)	Q (Load)	Re V	Im V	Re I	Im I	P	Q
1			1.0000	+0.0000	0.5147	-0.2573	0.5147	0.2573
2	-0.1000	-0.0500	0.9871	+0.0000	-0.1013	0.0507	-0.1000	-0.0500
3	-0.1000	-0.0500	0.9768	+0.0000	-0.1024	0.0512	-0.1000	-0.0500
4	-0.1000	-0.0500	0.9690	+0.0000	-0.1032	0.0516	-0.1000	-0.0500
5	-0.1000	-0.0500	0.9638	+0.0000	-0.1038	0.0519	-0.1000	-0.0500
6	-0.1000	-0.0500	0.9612	+0.0000	-0.1040	0.0520	-0.1000	-0.0500
					Power Loss ➔		**0.0147**	0.0073

The data of amplitude are all p.u.

The result shows the active power loss of the system model without DG is 0.0147. The accuracy of this calculation result is confirmed by the power mismatch between the defined and the calculated active and reactive power of each bus is sufficiently small. (The max mismatch is 4.637e-009 in this calculation).

3.2.3. Simulations and Consideration of the Simulation Results

Power loss calculation results for three types of DG (*P* only, *Q* only both *P* & *Q*) installation are provided in this subsection. Power loss calculation results by DG installation into any one bus of the system model are enumerated using the B/F method, and then the optimal solution is selected from them.

(1) Consideration 1: Installation of DG Capable of Injecting Active Power Only

Firstly, installation of the DG capable of injecting active power (*P*) only is considered. Table 3-5 shows the power loss calculation result with the installation of the DG injecting active power only and Figure 3-2 shows the loss reduction effect by the size of the DG for each installation bus.

Table 3-5 Power Loss Calculation Result with DG Capable of Injecting Active Power

DG Size (*P*)	Bus2	Bus3	Bus4	Bus5	Bus6
0.0500	0.0136	0.0128	0.0122	0.0118	0.0116
0.1000	0.0127	0.0112	0.0101	0.0094	0.0092
0.1500	0.0119	0.0098	0.0083	0.0075	0.0073
0.2000	0.0112	0.0086	0.0068	0.0060	0.0060
0.2500	0.0106	0.0076	0.0057	0.0049	0.0052
0.3000	0.0101	0.0069	0.0049	0.0043	0.0049
0.3500	0.0097	0.0063	0.0044	**0.0040**	0.0051
0.4000	0.0094	0.0060	0.0042	0.0042	0.0058
0.4500	0.0093	0.0058	0.0044	0.0048	0.0070
0.5000	0.0092	0.0059	0.0048	0.0058	0.0087
0.5500	0.0092	0.0062	0.0055	0.0071	0.0107
0.6000	0.0093	0.0066	0.0065	0.0088	0.0133
0.6500	0.0095	0.0073	0.0078	0.0108	0.0162
0.7000	0.0098	0.0081	0.0093	0.0133	0.0196
0.7500	0.0102	0.0092	0.0112	0.0160	0.0234
0.8000	0.0107	0.0104	0.0133	0.0191	0.0275
0.8500	0.0114	0.0118	0.0157	0.0225	0.0321
0.9000	0.0121	0.0134	0.0183	0.0263	0.0370
0.9500	0.0129	0.0152	0.0212	0.0303	0.0423
1.0000	0.0138	0.0171	0.0243	0.0347	0.0480

The data of amplitude are all p.u.

The calculation result shows a certain size of injected active power to minimize the power loss exists in each bus and the power loss for each bus shows a convex downward quadratic curve. The result also shows that suitable location of the DG is Bus5 and adequate size of injecting active power (*P*) is 0.3500. In this case, the power loss is dramatically reduced to 0.0040 (from 0.0147) and its improvement rate is about 72.8%

compared with the no DG case.

Here, applying the “2/3 rule” to the system model, the approximate best answer is that the location would be 0.3333 from Bus4 toward Bus5, and the injecting active power would be 0.3333. Considering possible DG installation locations are buses of the simple system model, it is possible that this calculation result nearly follows the “2/3 rule”.

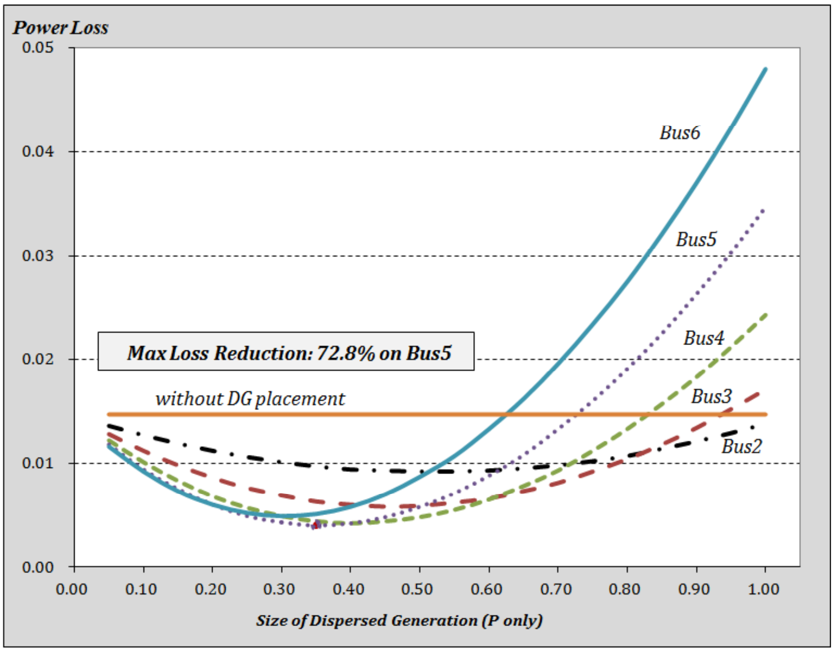


Figure 3-2 Loss Reduction Effect by the Size of DG for Each Installation Bus (Injecting Active Power Only)

(2) Consideration 2: Installation of DG capable of Injecting Reactive Power Only

Secondly, installation of the DG capable of injecting reactive power (Q) only is considered. Table 3-6 shows the power loss calculation result with the installation of the DG injecting reactive power only and Figure 3-3 shows the loss reduction effect by the size of the DG for each installation bus. The calculation result shows a certain size of injecting reactive power to minimize the power loss exists in each bus and the power loss for each bus shows a convex downward quadratic curve as well as the consideration 1. The result shows that suitable location of the DG is Bus5 also, and adequate size of injecting reactive power (Q) is 0.2000. In this case, the loss reduction effect is small compared with the consideration 1, the power loss reduced to 0.0120 (from 0.0147) and its improvement rate is about 18.4% compared with the no DG case. (Although Table 3-6 shows there are three cells which have the minimal power loss value of 0.0120 (i.e., injecting 0.1500 and 0.2000 reactive power at Bus5, and injecting 0.2000 reactive power at Bus4), the value of them with six decimal are 0.011992 (0.1500, bus5) , 0.011971 (0.2000, Bus5) and 0.011978 (0.2000, Bus4) respectively. With regard to the “2/3 rule”, this calculation result nearly follows the “2/3 rule” also.

Table 3-6 Power Loss Calculation Result with DG Capable of Injecting Reactive Power

DG size(*Q*)	Bus2	Bus3	Bus4	Bus5	Bus6
0.0500	0.0142	0.0138	0.0135	0.0133	0.0133
0.1000	0.0138	0.0131	0.0127	0.0124	0.0124
0.1500	0.0135	0.0127	0.0122	**0.0120**	0.0122
0.2000	0.0133	0.0124	**0.0120**	**0.0120**	0.0124
0.2500	0.0133	0.0124	0.0121	0.0124	0.0132
0.3000	0.0133	0.0126	0.0126	0.0132	0.0145
0.3500	0.0134	0.0130	0.0133	0.0144	0.0163
0.4000	0.0137	0.0136	0.0144	0.0161	0.0187
0.4500	0.0140	0.0144	0.0157	0.0181	0.0215
0.5000	0.0144	0.0153	0.0174	0.0206	0.0249
0.5500	0.0150	0.0165	0.0194	0.0235	0.0287
0.6000	0.0156	0.0179	0.0217	0.0267	0.0330
0.6500	0.0163	0.0195	0.0242	0.0303	0.0378
0.7000	0.0172	0.0213	0.0271	0.0344	0.0430
0.7500	0.0181	0.0233	0.0302	0.0388	0.0487
0.8000	0.0191	0.0255	0.0337	0.0435	0.0549
0.8500	0.0203	0.0279	0.0374	0.0487	0.0616
0.9000	0.0215	0.0305	0.0414	0.0542	0.0687
0.9500	0.0228	0.0332	0.0457	0.0601	0.0762
1.0000	0.0243	0.0362	0.0503	0.0663	0.0842

The data of amplitude are all p.u.

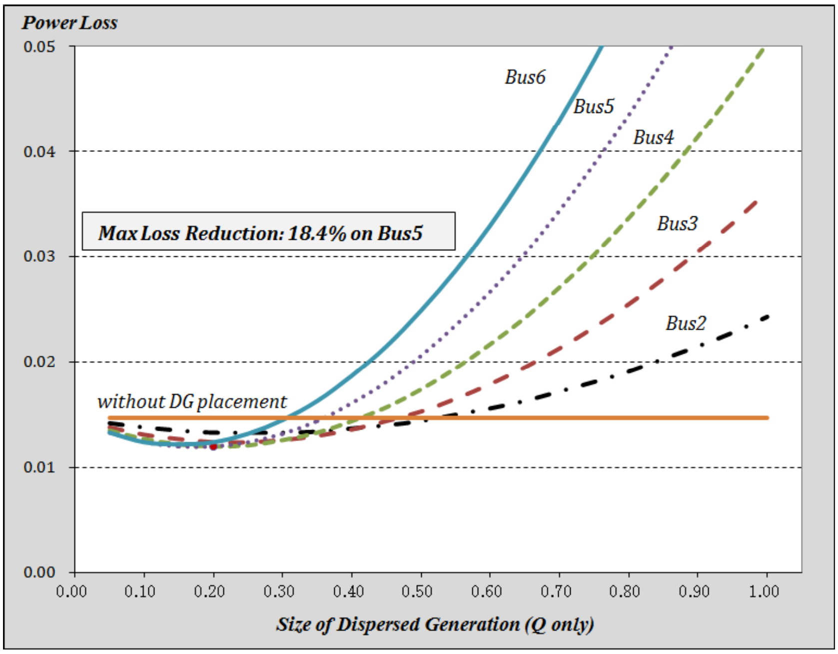


Figure 3-3 Loss Reduction Effect by the Size of DG for Each Installation Bus (Injecting Reactive Power (*Q*) only)

(3) Consideration 3: Installation of DG Capable of Injecting Both Active and Reactive Power

As the last consideration, installation of the DG capable of injecting both active and reactive power (P & Q) is considered. Table 3-7 shows the power loss calculation result with the installation of the DG injecting both active and reactive power and Figure 3-4 shows the loss reduction effect by the size of the DG for each installation bus.

Table 3-7 Power Loss Calculation Result with DG Capable of Injecting Both Active Power and Reactive Power (P & Q)

DG size(P)	Bus2	Bus3	Bus4	Bus5	Bus6
0.0500	0.0134	0.0124	0.0116	0.0111	0.0109
0.1000	0.0122	0.0103	0.0089	0.0081	0.0078
0.1500	0.0112	0.0086	0.0067	0.0057	0.0055
0.2000	0.0104	0.0071	0.0049	0.0039	0.0039
0.2500	0.0096	0.0059	0.0036	0.0026	0.0029
0.3000	0.0090	0.0050	0.0026	0.0018	0.0025
0.3500	0.0085	0.0043	0.0020	**0.0015**	0.0028
0.4000	0.0082	0.0039	0.0018	0.0017	0.0037
0.4500	0.0079	0.0037	0.0019	0.0024	0.0051
0.5000	0.0078	0.0038	0.0025	0.0036	0.0071
0.5500	0.0079	0.0041	0.0033	0.0052	0.0096
0.6000	0.0080	0.0047	0.0046	0.0073	0.0127
0.6500	0.0083	0.0055	0.0062	0.0098	0.0162
0.7000	0.0087	0.0066	0.0081	0.0127	0.0202
0.7500	0.0092	0.0079	0.0103	0.0161	0.0247
0.8000	0.0098	0.0094	0.0129	0.0198	0.0297
0.8500	0.0106	0.0111	0.0157	0.0239	0.0350
0.9000	0.0114	0.0131	0.0189	0.0284	0.0409
0.9500	0.0124	0.0153	0.0224	0.0332	0.0471
1.0000	0.0135	0.0177	0.0262	0.0384	0.0537

The data of amplitude are all p.u.

The calculation result shows the loss reduction effect for each bus shows similar characteristics of the consideration 1 and the optimal location of the DG is Bus5 also, and adequate size of injecting active power (P) is 0.3500 (reactive power (Q) is 0.1750). In this case, the power loss is dramatically reduced to 0.0015 (from 0.0147) and its improvement rate is about 89.8% compared with the no DG case. In the effectiveness of the power loss reduction, this case is the best among these three cases. In addition, the result nearly follows the “2/3 rule” as well as the consideration 1 and 2.

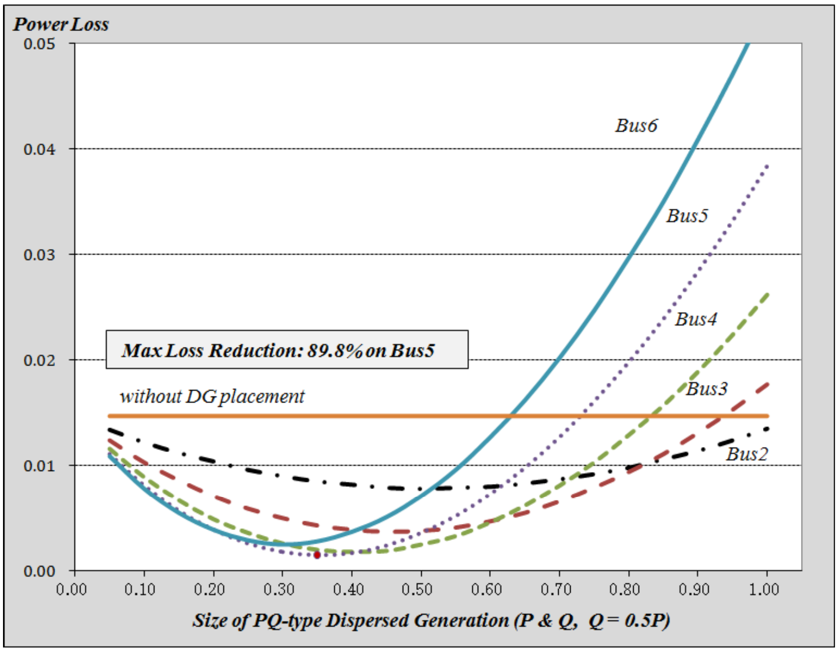


Figure 3-4 Loss Reduction Effect by the Size of DG for Each Installation Bus (Injecting Both Active and Reactive Power (*P* & *Q*))

3.2.4. Simulation of Power Loss Reduction Effects by Multiple DGs Allocation

In this subsection, effects of power loss reduction by the installation of multiple DGs are evaluated using the simple distribution system model as same as the last subsection. In the evaluation, simulations using exact solution method based on the enumerative method described in the last subsection are also implemented. As the procedure of the simulation, firstly combinations of optimal location candidates of DGs are enumerated, and then active power loss for each combination is calculated by power flow calculation. Finally, the combination which minimizes active power loss for the targeted simple distribution system model is selected as the optimal solution.

(1) Simulation Procedure

In the simulation, optimal allocation of DGs is considered for the simple distribution system model used in the last section. Load value of each bus is predefined and DGs are installed at two of five buses in the system model except for Bus1 (Slack bus). For each combination of DG installation buses, active power loss is calculated by changing injecting power of two DGs in incremental steps. The number of combinations for two DGs location is ${}_5C_2$=10. Table 3-8 shows these combinations.

Table 3-8 Combinations of Two DGs location in the Simple Distribution System Model

Case	DG1 (Bus)	DG2 (Bus)
Case1	2	3
Case2	2	4
Case3	2	5
Case4	2	6
Case5	3	4
Case6	3	5
Case7	3	6
Case8	4	5
Case9	4	6
Case10	5	6

In this study B/F method is also used as power flow calculation. With regard to DG type and capacity, *PQ* type DGs are used and active power *P* is set from 0.05 to 0.5 in 0.05 steps. Reactive power is set at 0.5*P* as same as the definition in the last subsection.

(2) Simulation Results and Evaluation

As the result of power flow calculations for all possible combinations of location and sizing of two DGs, the power loss was minimized when DGs were located Bus3 and Bus5 mostly. Figure 3-5 shows the profile of power loss value (*z* axis) by active power capacity of installed two DGs at Bus3 and Bus5. Table 3-9 represents power flow calculation results in case that DGs were installed Bus3 and Bus5. In Figure 3-5, the distribution of power loss values shows convex downward shape, and in all possible combinations of two DGs, distributions of power loss values also show convex downward shape.

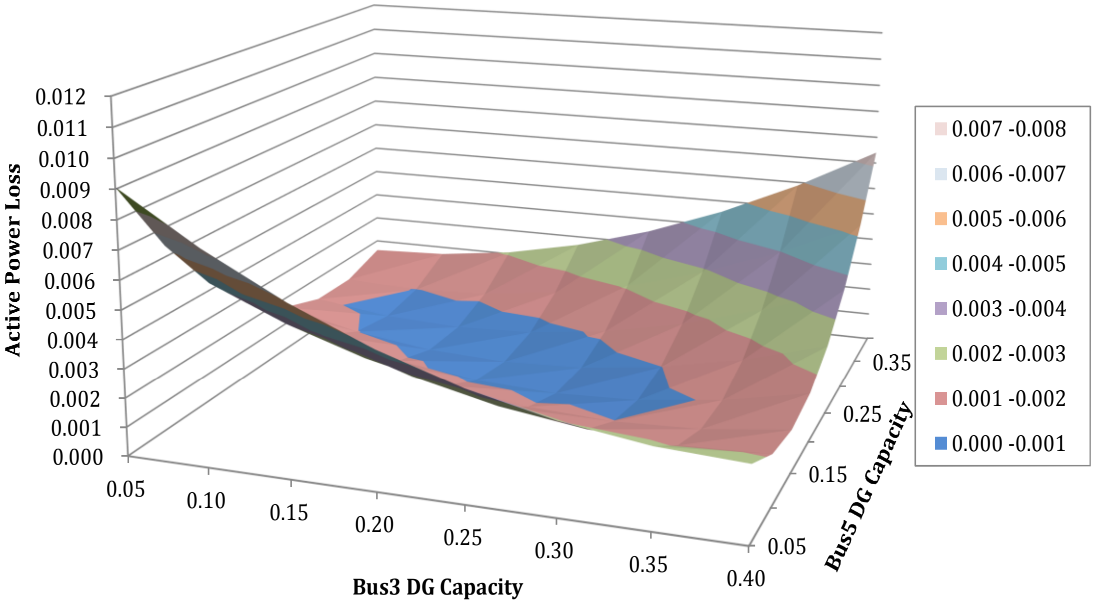


Figure 3-5 Profile of Active Power Loss for Simple Distribution System Model with Two DGs Installation at Bus3 and Bus5

Table 3-9 Power Loss Calculation Result with Two DGs Installation at Bus3 and Bus5 (p.u.×10^{-2})

DG Size		DG Size at Bus3 (p.u.)									
		0.0500	0.1000	0.1500	0.2000	0.2500	0.3000	0.3500	0.4000	0.4500	0.5000
DG Size at Bus5 (p.u.)	0.05	0.9072	0.7340	0.5881	0.4692	0.3768	0.3107	0.2702	0.2552	0.2651	0.2996
	0.10	0.6381	0.4933	0.3753	0.2840	0.2188	0.1793	0.1651	0.1759	0.2114	0.2710
	0.15	0.4260	0.3088	0.2181	0.1535	0.1147	0.1012	0.1127	0.1487	0.2090	0.2932
	0.20	0.2690	0.1787	0.1146	0.0761	0.0630	0.0749	0.1113	0.1720	0.2565	0.3645
	0.25	0.1655	0.1015	0.0632	**0.0502**	0.0622	0.0987	0.1595	0.2441	0.3523	0.4836
	0.30	0.1138	0.0754	0.0623	0.0741	0.1106	0.1712	0.2558	0.3638	0.4950	0.6492
	0.35	0.1124	0.0990	0.1105	0.1465	0.2069	0.2910	0.3988	0.5297	0.6835	0.8598
	0.40	0.1599	0.1708	0.2063	0.2660	0.3496	0.4568	0.5872	0.7404	0.9162	1.1143
	0.45	0.2548	0.2894	0.3484	0.4312	0.5376	0.6672	0.8197	0.9948	1.1922	1.4115
	0.50	0.3957	0.4536	0.5355	0.6409	0.7696	0.9211	1.0953	1.2917	1.5101	1.7502

This means that once combinations of two DG locations are fixed, a combination of optimal capacities for two DGs exist. In case that two DGs are installed at Bus3 and Bus5, active power loss would be minimized when the capacity of active power for Bus3 is 0.2 and Bus5 is 0.25, and the value of active power loss would be 0.000502. Because active power loss for the system without DG is 0.0147, active power loss reduction rate would be dramatically improved to the value of 96.6%. The result shows that active power loss can be reduced dramatically by the optimal location and sizing of DGs and the proposed approach using an exact solution method based on the enumerative method can be utilized for the optimal DGs allocation problem for simple distribution system models.

3.2.5. Solution Method of Optimal Allocation of DG Problem for a Real-size Distribution System

Next, the proposed approach using exact solution based on the enumerative method will be applied to real-size radial distribution system in this subsection. Basically the implementation method is the same as in the previous description, firstly combination of optimal location candidates for DGs is enumerated, and then power flow calculation would be implemented to calculate active power loss. Finally the best solution which minimizes active power loss is selected. However, the distribution system using in this subsection is "real-size" and it should makes combinatorial explosion easily in power flow calculations. Therefore, some practical measures should be considered to reduce the number of candidate combinations for the optimal allocation of DGs.

(1) Definition of the Real-size Distribution System

As a real-size distribution system model, the 126 bus radial system model in [3-14] was used and Figure 3-6 shows the wiring diagram of the distribution system. Bus126 is the slack bus in this distribution system and other all parameters which used for power flow calculations are also same values provided in [3-14][2].

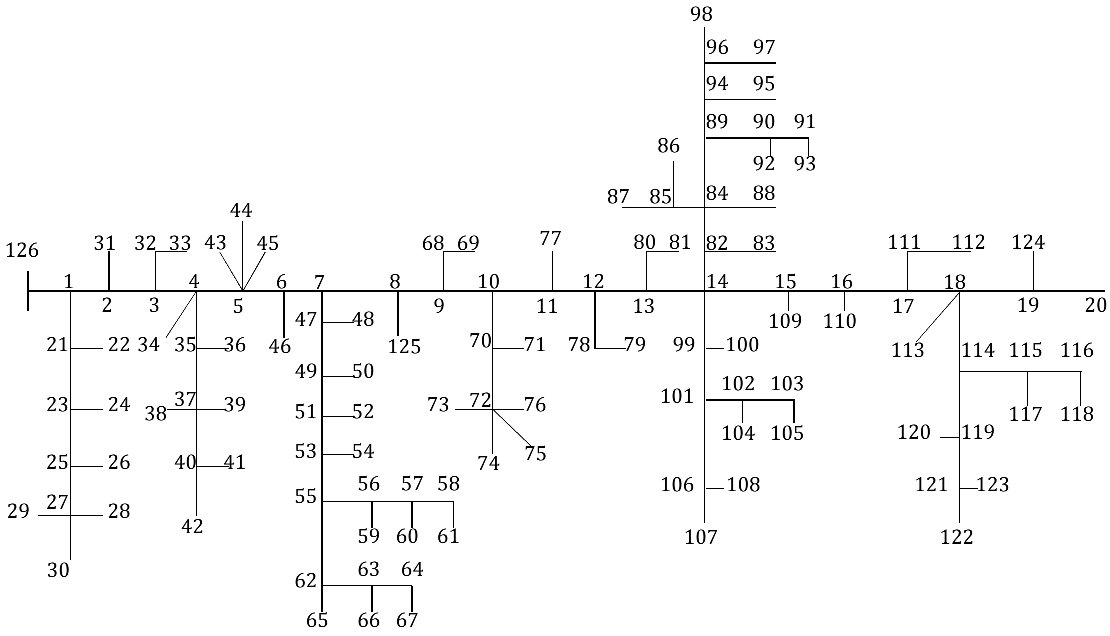


Figure 3-6 Wiring Diagram of Grid. [3-14]

Total load of the system is P=4.2300 Q=2.8870 respectively and from the power flow calculation result, the slack bus provides P =4.4239 and Q =3.1053. Therefore, total active and reactive power loss of the system would be 0.1939, 0.2183 respectively and power loss rate in the system would be 4.383% and 7.030% respectively. The data of amplitude are all per unit (p.u.)

(2) Combinatorial Enumeration for Calculation of Optimal DGs Allocation

Firstly, optimal location candidates for DGs are enumerated. As enumerative method, commonly used "Backtracking method" is utilized in this study. The backtracking method is a typical method for enumeration of all solutions and it has the search policy if current step in a search process had no branch or no feasible solution on the enumeration tree, the search process would be back to the previous step and continue the search process. The

---

[2] Branch and bus parameters provided in [3-14] are attached as Appendix C

depth first search (DFS) for such enumeration tree is the algorithm which realizes this backtracking method. In the proposed method, combinatorial enumeration by the backtracking method is applied to two separated stages; location and capacity of DG, which are two major characteristics for optimal allocation of DG problem. In this research, the method is called "2-Stage Backtracking Method". As the first stage, location candidates for DGs are enumerated, and as the second stage, combinations of DG capacity are enumerated for each combination of location candidate. In this 2-Stage Backtracking Method, the characteristic which was clarified in the last simulation is utilized. That is, the optimal capacity of DG can be decided when optimal location of DG is decided. Let the number of location candidates be K, average number of DG capacity be s, the combination number of the 2-Stage Backtracking Method would be as follows.

$$\sum_k s^k \cdot {}_K C_k \quad (k \mid K_{\min} \sim K_{\max}) \tag{3-14}$$

Although this enumerated combination number does not depend on system size, it shows large values of K, $K_{\min}$, $K_{\max}$ or s might bring combinatorial explosion. (For example, combination number for 10 different capacity values, 20 location candidates and 3 DGs installation would be $10^3{}_{20}C_3$=1,140,000.) Therefore, in the proposed 2-Stage Backtracking Method, location candidates for DGs are grouped and the number of installation DGs is limited to reduce the number of combinations. This constraint is based on the practical condition such that only one DG would be installed for a certain load estimating area. Therefore, the followings parameters are added to shows such constraint for the objective function (3-3).

K_G	:	Set of groups classifying the candidate DG locations
K_g	:	Maximum cardinality for the number of installed DGs in group g ($g \in K_G$)
N_{groupk}	:	Group number to which candidate DG location k belongs ($k \in K$)

Although capacity values in a certain range are enumerated with a constant increment value, the number of combinations is reduced by focusing targeted scope considering the result of 3.2.3 and the well-known "2/3 rule".

(3) Constraints of DG Allocation

In the application of the proposed method to the real-size distribution system, DG location candidates were decided based on the following policies considering practical installation constraints.

- Less than one DG is installed in one of some areas which have a certain amount of power demand
- Considering the simulation result in section 3.2.3 and “2/3 rule”, it is assumed that installation locations of DGs should be on major routes and not be at end buses or branch lines in order to inject power by DG efficiently.

Based on the above policies, Bus126 - 1 - 2 -„,-20 is defined as the main route and active power loss would be evaluated installing some DGs into the main route. Also, the main route is divided by the major branch points (Bus7, Bus14), and DG would be installed each divided group.

Table 3-10 DG Location Candidates Group

Group	Candidate Bus Number
G1	7, 9, 11, 13
G2	14,16, 18, 20
G3	1, 3, 5
G4	55, 72
G5	84, 89
G6	101, 114

Table 3-10 shows group data which are utilized in the simulation, and G1, G2 and G3 are bus groups belonging to main route. G4, G5 and G6 are groups created for complementary considerations. These group categories are used as constraints that DG can be located only at one bus in categorized group. The reason why all buses are not location candidates for DG is to prevent combinatorial explosion.

(4) Consideration cases and input data for simulation

Based on the basic policy that DGs are located at buses in groups on the main route such as G1, G2 and G3, the following three cases are simulated for the evaluation of optimal DG allocation.

Case1: One DG is located in group G1 and G2 respectively.
Case2: One DG is located in group G1, G2 and G3 respectively.
Case3: One DG is located in 4 of these 6 groups (G1, G2, G3, G4, G5 and G6).

In all cases, the type of DG is *PQ* type which is suitable for reducing power loss, and capacity of active and reactive power data are showed in Table 3-11, Table 3-12 and Table 3-13.

Table 3-11 DG Location Candidates and *PQ* Capacity Values for Case 1

Bus	Group	*P* Values* (p.u.)	*Q* Values (p.u.)	n_k
7	G1	0.6~2.2 @0.1	0.5*P*	17
9	G1	0.6~2.2 @0.1	0.5*P*	17
11	G1	0.6~2.2 @0.1	0.5*P*	17
13	G1	0.6~2.2 @0.1	0.5*P*	17
14	G2	0.4~1.4 @0.1	0.5*P*	11
16	G2	0.4~1.4 @0.1	0.5*P*	11
18	G2	0.4~1.4 @0.1	0.5*P*	11
20	G2	0.4~1.4 @0.1	0.5*P*	11

The number followed "@" shows increment value

Table 3-12 DG Location Candidates and *PQ* Capacity Values for Case 2

Bus	Group	*P* Values (p.u.)	*Q* Values (p.u.)	n_k
7	G1	0.6~1.8 @0.1	0.5*P*	13
9	G1	0.6~1.8 @0.1	0.5*P*	13
11	G1	0.6~1.8 @0.1	0.5*P*	13
13	G1	0.6~1.8 @0.1	0.5*P*	13
14	G2	0.5~1.0 @0.1	0.5*P*	6
16	G2	0.5~1.0 @0.1	0.5*P*	6
18	G2	0.5~1.0 @0.1	0.5*P*	6
20	G2	0.5~1.0 @0.1	0.5*P*	6
1	G3	0.6~2.0 @0.1	0.5*P*	15
3	G3	0.6~2.0 @0.1	0.5*P*	15
5	G3	0.6~2.0 @0.1	0.5*P*	15

The number followed "@" shows increment value

Table 3-13 DG Location Candidates and *PQ* Capacity Values for Case 3

Bus	Group	*P* Values (p.u.)	*Q* Values (p.u.)	n_k
7	G1	0.6~1.6 @0.1	0.5*P*	11
9	G1	0.6~1.6 @0.1	0.5*P*	11
11	G1	0.6~1.6 @0.1	0.5*P*	11
13	G1	0.6~1.6 @0.1	0.5*P*	11
14	G2	0.5~1.0 @0.1	0.5*P*	6
16	G2	0.5~1.0 @0.1	0.5*P*	6
18	G2	0.5~1.0 @0.1	0.5*P*	6
20	G2	0.5~1.0 @0.1	0.5*P*	6
1	G3	0.8~2.0 @0.1	0.5*P*	13
3	G3	0.8~2.0 @0.1	0.5*P*	13
5	G3	0.8~2.0 @0.1	0.5*P*	13
55	G4	0.1~0.4 @0.1	0.5*P*	4
72	G4	0.1~0.4 @0.1	0.5*P*	4
84	G5	0.1~0.4 @0.1	0.5*P*	4
89	G6	0.1~0.4 @0.1	0.5*P*	4
101	G6	0.1~0.4 @0.1	0.5*P*	4
114	G6	0.1~0.4 @0.1	0.5*P*	4

The number followed "@" shows increment value

Reactive power data are set as 0.5P considering general power factor values. Also, maximum total capacity of DGs is set as 4.0 from the consideration of total load *P*=4.23, simulation results in 3.2.4 and "2/3 rule".

(5) Simulation Result and Evaluation of Solution

Once DGs location candidates and capacity values are enumerated and selected by the proposed 2-Stage Backtracking Method, power flow calculation for every selected combination is implemented and power loss is decided. In the power flow calculation, the customized program based on the B/F method is utilized and the program adopts various high speed techniques considering actual use with a large number of combinations.

Using branch and bus parameters in [3-14], enumeration of all combinations of DGs locations and capacity values and selection of optimal solutions are implemented for the 126 buses distribution system. The summary of the simulation result is showed in the Table 3-14. PC specification used for the simulation was Intel Core i7 CPU (Central Processing Unit) 2.80GHz with 16GB memory and 64-bit OS is used on the PC.

Table 3-14 Summary of the Simulation Result

Case	Enumeration Number	Power Flow Iteration Number	Optimal Active Power Loss Value	Active Power Loss Reduction Rate r (%) r: 100(b-a)/b	Slack Bus Power		Computation Time (sec.)
					P (p.u.)	*Q* (p.u.)	
Base	—	(5)	(0.1939)(=b)	—	4.4239	3.1053	0.016
1	2,992	3.036	0.0186(=a)	91.6	0.6462	1.1061	0.065
2	50,592	2.655	0.0097(=a)	95.0	0.3397	0.9483	0.889
3	1,590,544	3.004	0.0084(=a)	95.7	0.3384	0.9467	30.935

In every case, optimal solution was obtained in short time. However the number of enumerations for Case3 increased to about 1.6 million while the number of enumerations for Case1 and Case2 are several dozen thousands and computation times were less than 1 second. This means the number might be reaching the limit for using the enumerative method.

Case1, Case2 and Case3 were configured so that their optimal solutions would be better in that order, and active power loss values represented in Table 3-14 shows that. The best value of active power loss is 0.0084 in Case3, and the loss reduction rate compared with the base case (No DG) showed extremely high improvement of 95.7%. The result shows almost zero or very low active power loss distribution systems can be established by adequate allocation of DGs or equivalent voltage compensators, and it shows that an efficient power supply and demand in local communities can be realized utilizing regional DGs and other related devices.

Although the simulation result shows possibilities for nearly zero loss distribution systems with detailed installation of DGs, it is enough results of more than 90% of active power loss reduction. Therefore, even Case1 and Case2 can be very good design for optimal DGs allocation. The simulation result shows the number of candidate combination for optimal allocation of DGs can be reduced drastically by adding practical constraints to location candidates and by narrowing down the scope of capacity values of DGs. In addition, the result that more than 90% active power loss reduction was attained shows the proposed approach can obtain a good enough optimal solution even compared with the optimal solution selected from all enumeration solutions without any constraints.

Table 3-15 DG Locations and Capacity Values in the Optimal Solution in Each Case

		Case 1	Case 2	Case 3
Location 1	Bus	9	13	13
	P(p.u.)	1.90	1.50	1.40
	Q(p.u)	0.95	0.75	0.7
Location 2	Bus	16	18	18
	P(p.u.)	1.10	0.70	0.70
	Q(p.u)	0.55	0.35	0.35
Location 3	Bus	-	5	5
	P(p.u.)	-	1.70	1.40
	Q(p.u)	-	0.85	0.70
Location 4	Bus	-	-	55
	P(p.u.)	-	-	0.40
	Q(p.u)	-	-	0.20
Total Capacity	P(p.u.)	3.00	3.90	3.90
	Q(p.u)	1.50	1.95	1.95

Table 3-15 shows locations and capacity values of optimal solutions which were obtained in Case1, Case2 and Case3. Total capacity of every optimal solution is lower than the defined maximum value 4.0 and that means the value is appropriate.

Figure 3-7 and Figure 3-8 represent profile of voltage and voltages phase angle for Case2 with the optimal DG allocation respectively, and both figures also show those of the base case for comparison. In Figure 3-7, the voltage profile shows a trend of flattening holistically and it means that constraints such as voltage upper and lower limit and apparent current upper limit, which are generally defined in the optimal reactive power distribution problem, would be redundant constraints. In other words, feasible solutions do not exist if solutions would show a trend of flattening and also would not meet these voltage and current constraints. In Figure 3-8, some values of voltage angle show reversed sign. This means that reverse power flow would be occurred in some parts of the system due to voltage rise by DGs installation.

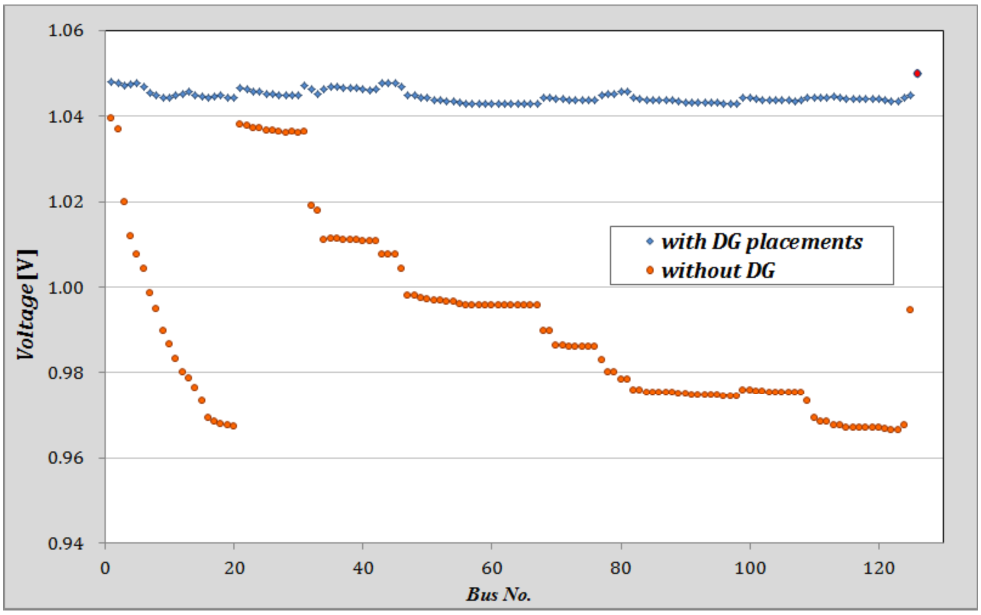


Figure 3-7 Voltage Magnitude Improvement by DG Placements in 126 Bus Distribution System

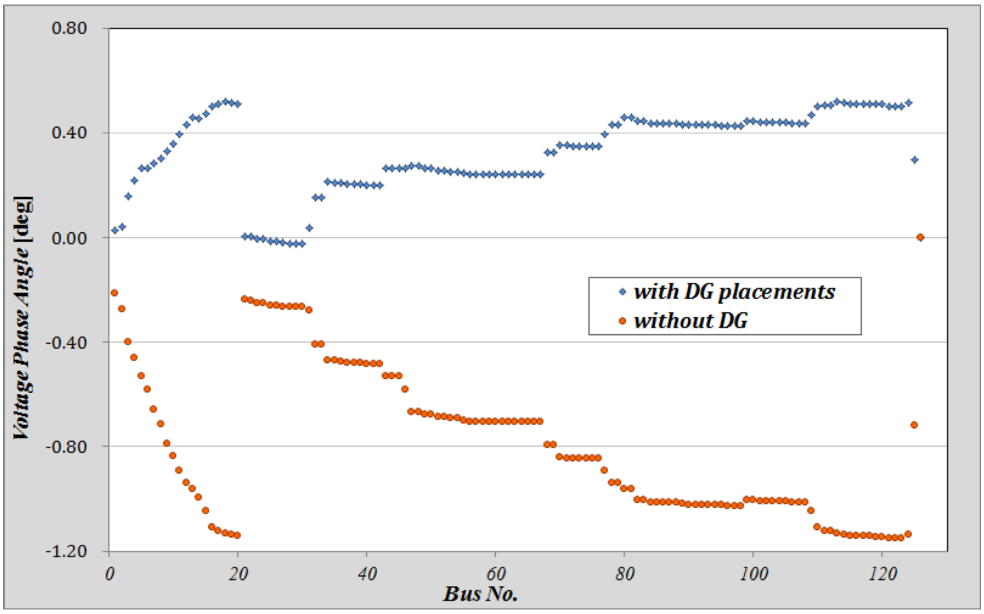


Figure 3-8 Voltage Angle Changes by DG Placements in 126 Bus Distribution System

3.3. Impact Quantification of Renewable Energy Sources Using Stochastic Approach

As the second topics for the optimal power supply in demand-side, this study deals with the expansion of RES. RES expansion is a common challenge in the world to reduce greenhouse gases emissions, and Japan also has a plan to install a large amount of RES for the realization of low carbonate and high efficiency society. The plan says 20% of total electric power would be generated from RES and most of RES expansion would be from photovoltaic (PV) generation systems in low voltage consumers such as residential customers [3-15].

A large number of PV system installations realize low-carbonate power supply and provide some contributions for efficient power supply, such as peak load reduction and power loss reduction etc. On the other hand, various potential challenges have been pointed out. Generally PV systems are installed on customer side and sometime electric power would be injected into distribution systems from the PV systems in the state of excess-power-supply. In such cases, reverse power flow in distribution systems might occur although existing distribution systems assume one way power flow from the upper-side (substation) to the lower-side (consumers). In such reverse power flow occurrences, voltage violations and malfunctions of various distribution devices are concerned. Because the numbers of installed PV systems in Japan is still small at present, it is not clear yet how much impact would actually occur by a large amount of PV installations in the near future.

Therefore, this study proposes a simulation approach to evaluate the status of a distribution system with escalatory installed PV systems, calculating voltage at each bus, injected power at the slack bus, and electric power loss of the system etc. In the simulation approach, PV capacity and power load are treated as stochastic variables because PV capacity is fluctuated corresponding to weather conditions, and power load is also fluctuated by other various reasons such as day of the week, events, area properties such as industrial area or residential area etc. Using these simulation results, impacts by the number of installed PV systems and PV penetration level to the distribution system are evaluated, and also possible maximum and minimum values of total PV capacity, injected power at the slack bus and total power loss are discussed in this section.

3.3.1. Studies and Approaches for Quantifying the Impact of RES

As mentioned in 3.2, various studies have been executed for the benefit evaluation of DG and its impacts on distribution systems [3-9][3-10]. With respect to the application of stochastic approach, a novel algorithm in which the number of on-state DGs, DG location and magnitude of generator power were used as stochastic variables was proposed to evaluate the performance of distribution systems including DG [3-16]. Recently many efforts have been addressed for RES as DG type, because the capacity of major RES generations such as PV and wind power is fluctuated compared with legacy generation systems such as thermal generation. In order to solve RES related challenges, a stochastic analysis approach for power flow simulation in distribution systems with PV systems is proposed [3-17]. In the study, power flow simulation using stochastic variables of power loads and PV generation capacities was executed to evaluate impacts of PV installation, and power loss reduction as the result of the PV installation was calculated using historical distribution status data and weather condition data in a target region. In addition, power loss reduction effect by demand reduction by DG etc., was estimated and a formulation method for the effect of such demand reduction in day-month-year basis was provided in [3-18].

3.3.2. Impact Quantification Using Stochastic Approach

The purpose of this research is to propose a reliable evaluation approach for quantifying the impact of a large number of PV installations into distribution systems. In this subsection, the approach of this research is described.

(1) Definition of Stochastic Variables

Because PV generation capacity depends on weather conditions, generation capacity at each PV installed bus is defined as a stochastic variable. Also, power load at each bus is defined as stochastic variable because it is impossible for power companies to plan each consumer’s power consumption behavior. Using these variables and other parameters, stochastic power flow calculations based on Monte Carlo method are conducted for multiple time-series scenarios, and then PV installation impacts on distribution systems are discussed. The Monte Carlo method is the generic term for numeric calculation methods using random values and it finds solutions approximately from sufficient numbers of simulations. In the stochastic variable for PV capacity, random numbers conforming to a uniform distribution are generated, assuming that high, middle and small solar irradiation amount days such as sunny, cloudy and rainy days would occur uniformly in a target area. On the other hand, random numbers conforming to normal distribution are also generated to the stochastic variable for power load considering general power consumption behaviors in the targeted area.

(2) Distribution System Model

In this study, the 126-buses distribution model in [3-14] was also used. (See Figure 3-6). Same as the last research, the bus126 represents the slack bus, and some other buses have electric load (called Load-Defined-Bus in this research) and others have no load (called Zero-Bus in this research). Branch and bus data defined in this study are based on original values in [3-14]. It is assumed that one PV can be located only at one of these buses except for the slack bus.

(3) Test Data Creation

For simulations, test data were created by reference to various related data.

a. Load Data in Each Bus

Hourly data were needed to be prepared as the minimum data unit for one year. In the data creation, “Past Electricity Demand Data” in Tokyo Electric Power Company supply area in the fiscal year (FY) 2012 [3-19] was used as the reference of power demand fluctuation. For the application of these demand properties to load data, all records were converted into per unit (p.u.) quantities and made scale adjustments based on the original load data in [3-14].

Hourly data set for one day was created for each month considering seasonal data variation. Therefore, 24 (hours) × 12 (months) = 288 sets of power load data created by the above mentioned procedure would be the base data of stochastic variables for power flow calculation.

b. PV Generation Capacity in Each PV Installation Bus

- **Estimation Method of PV Generation Capacity**

Various methods have been proposed with regard to PV generation capacity estimation. Equation (1) defined by Japanese Industrial Standard (JIS) Committees [3-20] was referred in this study.

$$E_{\mathrm{Py}} = \sum\nolimits_{\mathrm{Jan.\text{-}Dec.}} \left\{ K \times P_{\mathrm{AS}} \times H_{\mathrm{Am}} / G_{\mathrm{S}} \right\} \tag{3-14}$$

where,

E_{Py}: Annual PV energy generation (kWh/year)
K: Monthly total design coefficient (performance ratio)
P_{AS}: rating capacity of PV array at standard test condition (kW)
H_{Am}: monthly total solar irradiation on the PV (kWh/m^2·month)
G_{S}: Solar irradiance at standard test conditions (kW/m^2)

Although K is a variable depending on temperature, it is assumed that K is a constant throughout year in this study. Then, estimated PV generation capacity would be proportional to the irradiation value. As the irradiation data in Tokyo, one of measured datasets in Tokyo from "Solar radiation database" provided by New Energy and Industrial Technology Development Organization (NEDO)[3-21] were used.

- **PV Installation Location**

According to PV allocation assumptions, PV installation bus numbers were defined. Table 3-16 shows PV installation bus numbers of 5 different patterns which were used in simulations in this research.

Table 3-16 PV Installation Bus Number

Pattern	Number of PVs	Installation Buses
P1	10	14,30,65,76,97,107,113,122,124,125
P2	20	4,7,10,14,30,42,44,61,65,76,79,86,97,105,107,113,118,122,124,125
P3	30	1,4,7,10,14,20,30,33,42,44,55,61,65,67,69,76,79,81,86,93,97,98,105, 107,112,113,118,122,124,125
P4	40	1,4,7,10,12,14,20,25,30,33,39,42,44,52,55,61,65,67,69,74,76,79,81, 83,86,88,93,97,98,100,105,107,108,112,113,118,122,123,124,125
P5	50	1,4,7,10,12,14,20,22,24,25,28,30,33,39,41,42,44,46,48,52,55,61,65, 67,69,71,74,76,79,81,83,86,88,93,95,97,98,100,105,107,108,110,112, 113,118, 120,122,123,124,125

(4) Power Flow Calculation Method

The Backward and Forward method (B/F method) was used for power flow calculation same as the power flow calculation in 3.2.2.

(5) Simulation Method and Procedure

The conditions of these simulations which were mentioned in above were formulated as follows. For bus i in a target system which L is the set of candidate DG locations, let $\dot{S}_i$ be load, $\dot{G}_{\mathrm{PV}i}$ be PV generation capacity, $\dot{V}_i$ be voltage and $\dot{I}_i$ be injected current, then,

$$\dot{S}_i + \dot{G}_{PVi} = \dot{V}_i \dot{I}_i{}^* \qquad (i \in L \{ L = 1, 2, \ldots, 125\}) \tag{3-15}$$

A dot on the top of the character denotes complex numbers and an asterisk denotes complex conjugate. Current and voltage at each PV installed bus are calculated based on the (3-15) in the B/F method based power flow calculation. Let y_k ($k \in L$) be 0-1 variable which represents status whether PV is installed or not at the targeted bus (1 if candidate PV location k is selected, 0 otherwise), then the number of PV systems N_{PV} would be the following equation and 5 simulation models were prepared in this study.

$$N_{\mathrm{PV}} = \sum_{k=1}^{125} y_k = \{10, 20, 30, 40, 50\} \tag{3-16}$$

In addition, the penetration level was defined as the ratio of annual accumulated PV generation capacity to total demand in a target area, and 5 PV generation capacity penetration levels were prepared in this study. Let PV generation capacity at bus i in a date be $\dot{G}_{\mathrm{PV}i,date}$ ($date$ $\in$ targeted one year) and total load in the target system be $\dot{S}_{\mathrm{total}}$, then, PV penetration level L_{PV} would be as follows.

$$L_{\mathrm{PV}} = \sum_{date} \sum_i \dot{G}_{\mathrm{PV}i} / \dot{S}_{\mathrm{total}} = \{0, 5, 10, 15, 20\%\} \tag{3-17}$$

Therefore, 5 (DG number models) × 5 (DG penetration levels) = 25 patterns of base datasets were prepared for simulations. The number of random value generation for stochastic variable of both PV generation capacity and electric load was 10,000 respectively. In this study, power flow calculation using one hourly data set (24 records) in each month is executed for 12 months (one year) with average power load and PV generation pattern. Therefore, 24×12×10,000 = 2,880,000 calculations were executed for one model pattern, and 72 million calculations for 25 patterns of model data. In each calculation, voltage, current and electric power at each bus, and injected electric power at the slack bus and electric power loss were calculated.

3.3.3. Simulation Results and Discussion

In this subsection, results of the simulation approach and their discussions are described.

(1) Execution of Power Flow Calculation

Table 3-17 and Table 3-18 show the summary of simulation results.

Table 3-17 Summary of Simulation Result (1)

No. of PVs	Penet. Rate Compu. Time		Area Load (*P*) (p.u).	Slack bus inj. Power (*P*) (p.u.)	Rev. P. Flow at Slack	DG Capacity (*P*) (p.u.)	Power Loss (*P*) (p.u.)	Voltage Range (p.u.)
10	0 (83.083sec)	Min.	954.59	983.51	0	0.00	28.66	0.96
		Max.	1,088.65	1,126.56		0.00	38.22	1.05
		Ave.	1,021.64	1,054.92		0.00	33.27	-
	5 (83.198sec)	Min.	954.67	928.49	0	44.34	25.65	0.96
		Max.	1,088.22	1,072.61		57.73	34.76	1.05
		Ave.	1,021.67	1,000.64		51.08	30.05	0.00
	10 (83.093sec)	Min.	954.53	872.54	0	88.78	23.25	0.96
		Max.	1,089.44	1,022.43		115.47	32.06	1.05
		Ave.	1,021.66	946.92		102.17	27.43	-
	15 (82.972sec)	Min.	954.68	816.14	0	133.27	21.45	0.96
		Max.	1,088.87	972.11		173.38	29.81	1.05
		Ave.	1,021.63	893.79		153.24	25.41	-
	20 (83.553sec)	Min.	954.42	759.23	11 (May)	177.55	20.19	0.96
		Max	1,089.13	923.53		230.99	28.09	1.05
		Ave.	1,021.64	841.25		204.33	23.94	-
20	0 (83.979sec)	Min.	954.38	983.35	0	0.00	28.68	0.96
		Max.	1,088.89	1,126.79		0.00	38.23	1.05
		Ave.	1,021.66	1,054.93		0.00	33.27	-
	5 (83.093sec)	Min.	954.98	929.47	0	46.13	25.83	0.96
		Max.	1,088.58	1,072.49		55.99	34.92	1.05
		Ave.	1,021.64	1,000.75		51.08	30.19	-
	10 (84.450sec)	Min.	954.24	873.90	0	92.40	23.45	0.96
		Max.	1,088.89	1,020.24		112.06	32.16	1.05
		Ave.	1,021.64	947.11		102.16	27.64	-
	15 (84.515sec)	Min.	954.53	819.46	0	138.52	21.64	0.96
		Max.	1,089.03	969.22		168.01	29.93	1.05
		Ave.	1,021.66	894.00		153.25	25.59	-
	20 (84.423sec)	Min.	954.43	764.06	1 (May)	184.65	20.33	0.96
		Max.	1,089.37	919.63		223.85	28.18	1.05
		Ave.	1,021.65	841.36		204.33	24.04	-
30	0 (85.838sec)	Min.	954.29	983.23	0	0.00	28.64	0.96
		Max.	1,089.52	1,127.53		0.00	38.30	1.05
		Ave.	1,021.64	1,054.91		0.00	33.27	-
	5 (85.238sec)	Min.	954.17	928.74	0	47.03	25.85	0.96
		Max.	1,088.72	1,072.40		55.14	34.94	1.05
		Ave.	1,021.65	1,000.80		51.08	30.23	-
	10 (85.128sec)	Min.	954.78	875.28	0	93.97	23.58	0.96
		Max.	1,089.32	1,020.25		110.27	32.22	1.05
		Ave.	1,021.64	947.18		102.16	27.71	-
	15 (85.079sec)	Min.	954.48	820.81	0	141.06	21.79	0.96
		Max.	1,088.66	967.65		165.40	29.98	1.05
		Ave.	1,021.65	894.09		153.24	25.67	-
	20 (85.170sec)	Min.	954.97	766.91	0	188.06	20.44	0.96
		Max.	1,088.49	916.89		220.44	28.21	1.05
		Ave.	1,021.65	841.44		204.33	24.12	-

Table 3-18 Summary of Simulation Result (2)

No. of PVs	Penet. Rate Compu. Time		Area Load (P) (p.u).	Slack bus inj. Power (P) (p.u.)	Rev. P. Flow at Slack	DG Capacity (P) (p.u.)	Power Loss (P) (p.u.)	Voltage Range (p.u.)
40	0 (85.838sec)	Min.	954.29	983.23	0	0.00	28.64	0.96
		Max.	1,089.52	1,127.53		0.00	38.30	1.05
		Ave.	1,021.64	1,054.91		0.00	33.27	-
	5 (85.238sec)	Min.	954.17	928.74	0	47.03	25.85	0.96
		Max.	1,088.72	1,072.40		55.14	34.94	1.05
		Ave.	1,021.65	1,000.80		51.08	30.23	-
	10 (85.128sec)	Min.	954.78	875.28	0	93.97	23.58	0.96
		Max.	1,089.32	1,020.25		110.27	32.22	1.05
		Ave.	1,021.64	947.18		102.16	27.71	-
	15 (85.079sec)	Min.	954.48	820.81	0	141.06	21.79	0.96
		Max.	1,088.66	967.65		165.40	29.98	1.05
		Ave.	1,021.65	894.09		153.24	25.67	-
	20 (85.170sec)	Min.	954.97	766.91	0	188.06	20.38	0.96
		Max.	1,088.49	916.89		220.44	28.13	1.05
		Ave.	1,021.65	841.44		204.33	24.10	-
50	0 (87.290sec)	Min.	953.40	982.31	0	0.00	28.64	0.96
		Max.	1,088.98	1,126.91		0.00	38.27	1.05
		Ave.	1,021.63	1,054.90		0.00	33.27	-
	5 (87.151sec)	Min.	955.02	929.96	0	47.86	26.02	0.96
		Max.	1,088.79	1,072.72		54.24	35.06	1.05
		Ave.	1,021.66	1,000.93		51.08	30.36	-
	10 (87.037sec)	Min.	953.74	874.76	0	95.86	23.72	0.96
		Max.	1,088.92	1,019.54		108.56	32.43	1.05
		Ave.	1,021.65	947.39		102.17	27.91	-
	15 (86.906sec)	Min.	954.40	821.77	0	143.71	21.99	0.96
		Max.	1,089.14	967.44		162.75	30.20	1.05
		Ave.	1,021.64	894.29		153.25	25.90	-
	20 (86.842sec)	Min.	954.57	768.01	0	191.74	20.62	0.96
		Max.	1,088.31	915.04		216.97	28.41	1.05
		Ave.	1,021.65	841.66		204.33	24.34	-

Starting from left, item names are “the number of PV generations”, “PV penetration level and computation time”, “ lectric load (active power)”, “Slack bus injected power (active power)”, “The number of reverse power flow occurrence in the slack bus”, “PV generation capacity”, “Power loss (active power)”, and “scope of voltages in the system”. For some items, minimum, maximum and average data are provided.

In order to conduct such a large number of power flow calculations, an original simulation program was developed and utilized for all simulations in this research. PC specification used for these simulations was Intel Core i7 Processor 3.20GHz with 8GB memory and 64-bit OS and computation time for all model patterns were about 85 seconds (83 ~ 88 seconds).

In this simulation, average one-day power load data set and average one-day PV generation capacity record set for each month were used to reduce computation time. However, the result shows that it should take under 1 hour even if power flow calculation would use daily electric load data.

$$85\ (\text{sec.}) \times 30\ (\text{days}) = 2{,}250\ (\text{sec.}) = 42\ \text{min.}\ 30\ \text{sec.} \tag{3-18}$$

Values for "Slack bus injected power" shows injected power at the slack bus for the distribution system. The amount of injected power would be changed depending on PV penetration level and be maximum value at 0% of PV penetration level. When injected power from PV systems would be very large, reverse power flow at the slack bus might occur. In this simulation, 11 times of reverse power flow occurred at the slack bus with 10 PV systems and 20% of PV penetration level and 1 time with 20 PV systems and 20% PV penetration level in May. Although the voltage constraint 1.0 ± 0.05 (p.u.) were defined, voltage violation did not occur in the simulations.

(2) Discussion for the Results of Simulations

As mentioned in above, reverse power flow at the slack bus occurred with 10 or 20 PV systems and 20% of PV penetration level. All 12 reverse power flow at the slack bus occurred from 0 pm to 2 pm in May, and the result reflects that May is the month with highest solar irradiation in Tokyo. The reason why reverse power flow occurred only with the small number of PV systems such as 10 or 20 installed environments should be due to concentrated power injection because the smaller the number of PV systems, the larger injected power amount per one PV in the same penetration level. If such situation would occur near the slack bus, reverse power flow might occur easily. In this time of the simulation, maximum penetration level was 20%, so reverse power flow at the slack bus would occur easily if penetration level would be larger.

Figure 3-9 and Figure 3-10 show injected active power at the slack bus with 20% of PV penetration level, and the number of installed PV systems is 10 and 50 respectively. There are no big difference between these two charts and also no big difference among other charts with same PV penetration level and different number of installed PV systems. These shows that there should be no big difference in slack bus injected power even if the number of PV systems installation would increase in the same penetration level. Figure 3-11 and Figure 3-12 show active power at the slack bus with 50 PV systems installed environment and PV penetration level is 0% and 10% respectively. Figure 3-12 (penetration level 10%) shows the load in daytime is offset by PV generation and injected power at the slack bus is reduced. Figure 3-10 (penetration level 20%) also shows the load in daytime is offset by PV generation, but injected power at the slack bus decreases too much and this is not effective as the aspect of load levelling.

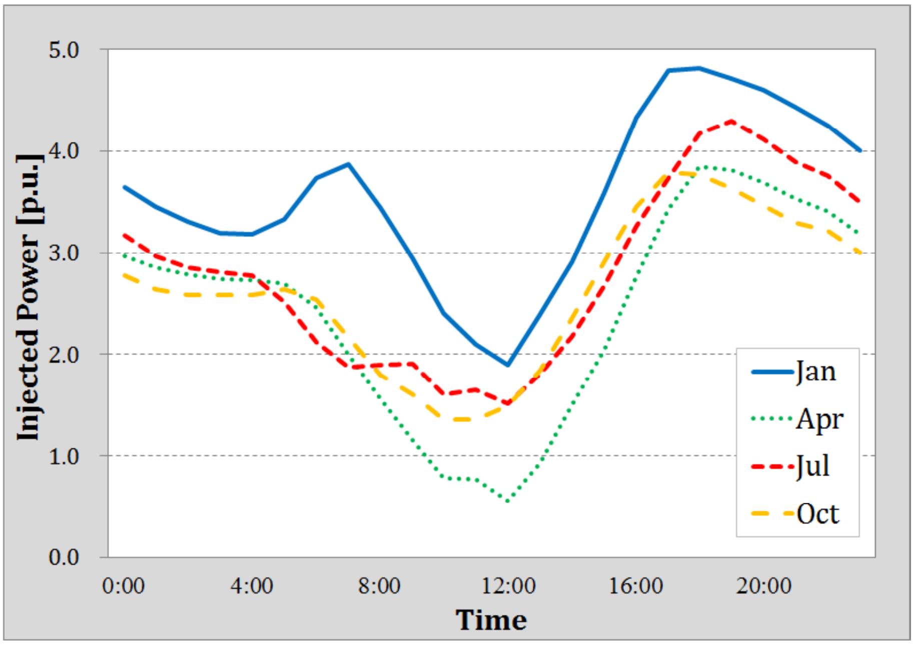


Figure 3-9 Slack Bus Power Injection, 10 PVs and 20% Penetration Level

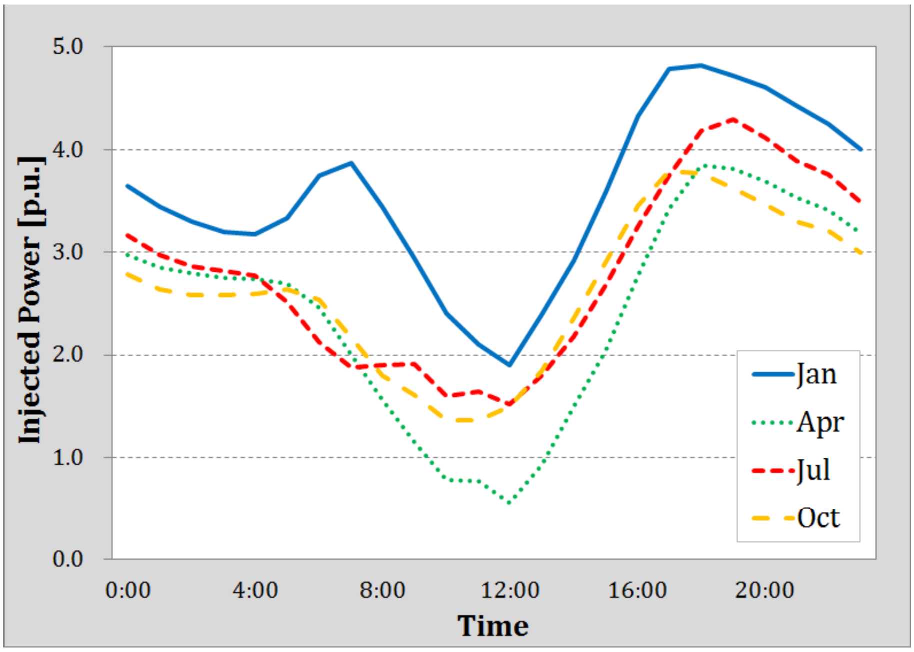


Figure 3-10 Slack Bus Power Injection, 50 PVs and 20% Penetration Level

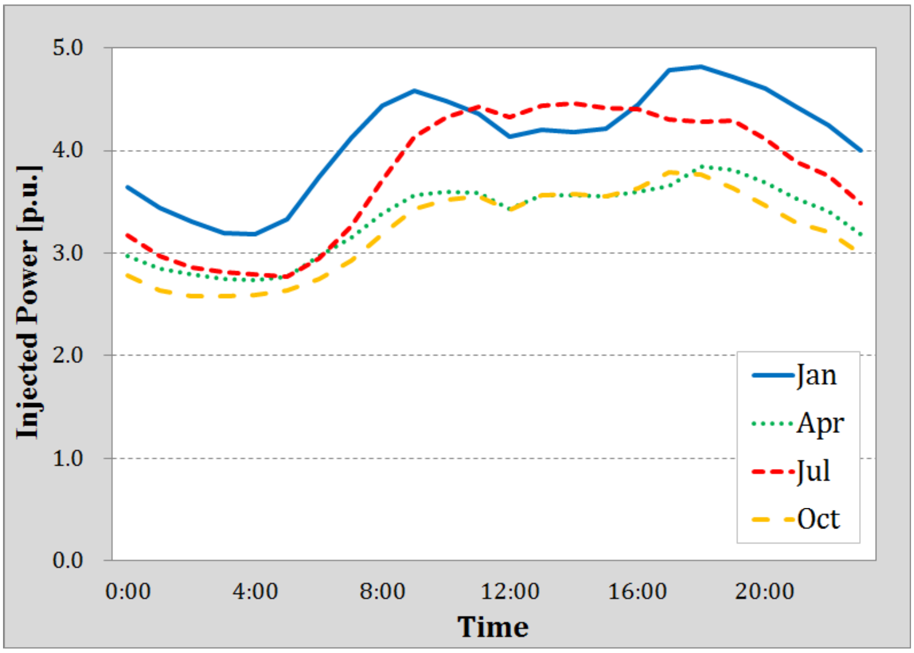


Figure 3-11 Slack Bus Power Injection, 50 PVs and 0% Penetration Level

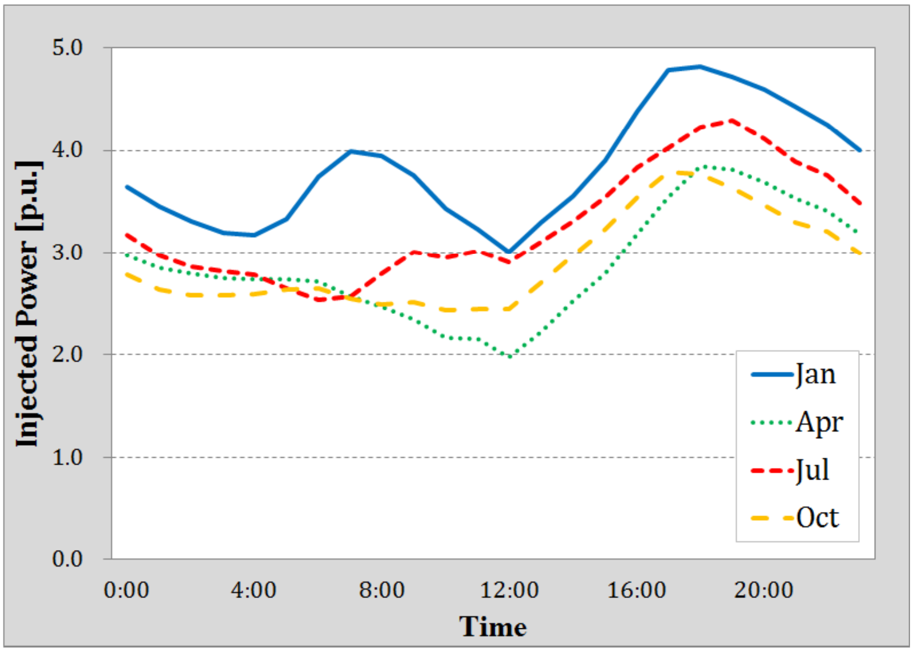


Figure 3-12 Slack Bus Power Injection, 50 PVs and 10% Penetration Level

Large scale electric power injection from PV systems is not always good and thus it is necessary to consider adequate power injection amount and PV penetration level.

In addition, Figure 3-10 and Figure 3-12 show that PV generation does not contribute to the reduction of power load peak in the evening. This shows that PV generation cannot be used for evening and night time load directly and the larger the PV penetration level increases, the more prominent evening and night time peak load amount would be appeared. Considering the penetration of electric vehicles (EVs) in the near future, it is expected that electric load for battery charge would increase from evening to midnight and the tendency should be growing. However, the result shows PV generation cannot be used for the growing demand directly.

Also, it is found that there is one load peak around noon in summer season and other season has two load peaks in morning and evening from Figure 3-11 which shows demand curve without PV systems. Therefore, PV generation property would be effective for load reduction in summer season because daytime load would be canceled by the PV generation properly. However, daytime load in other seasons, especially in winter, would be canceled mostly (too much) and PV generation cannot use for evening and night power load directly. Therefore, collaborative operation between PV systems and power storages such as batteries should be necessary considering effective and efficient power systems in the near future.

Figure 3-13 represents power loss by PV penetration level and this chart shows power loss decreases corresponding to the increase of PV penetration level. Therefore, the increase of PV generation amount reduces power injection at slack bus and thus it contributes to power loss reduction.

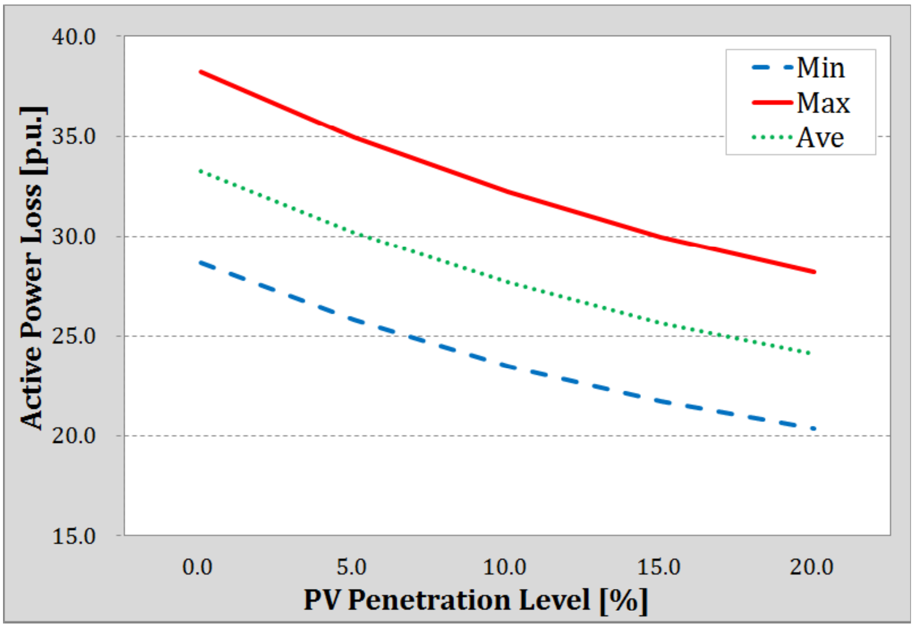


Figure 3-13 Power Loss Reduction by PV Penetration Level

Figure 3-14 shows power loss reduction at PV penetration level 20% by the number of PV systems. Although there is little difference among the calculation results of power loss due to the number of installed PV systems, in the same penetration level, the chart shows power loss was larger corresponding to the number of PV systems. Therefore, in case that total PV generation amount in a distribution system would be constant, small number of large capacity generators would be effective compared with a large number of small capacity generators in the aspect of power loss reduction.

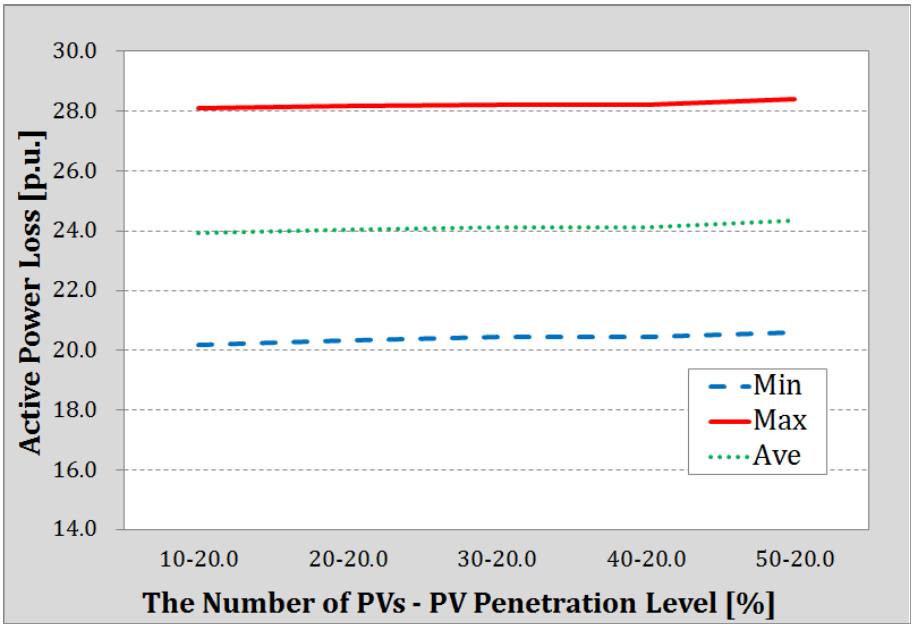


Figure 3-14 Power Loss Reduction at PV Penetration Level 20% by the Number of PVs

3.4. Summary

In this chapter, researches for effective installation of DGs were described as optimal power supply in demand-side.

Firstly, optimal installation of DG was considered. The application of the proposed enumeration method to the simple distribution system model showed that single DG installation can dramatically contribute to the reduction of power loss. Qualitatively, the amount of loss reduction is influenced by DG location and size and is maximal in case of both active and reactive power injection compared with either only active or reactive power injection. Then, this approach was applied to optimal installation of multi DG installation problem. After the consideration of 2 DG installation problem, the proposed approach was applied to the 126 bus distribution system model and the reduction of active power loss was evaluated. The simulation result shows optimal location and size of DGs which reduced active power loss more than 90% could be found in a short time. From these results, we think the effectiveness of the approach as a practical active power loss reduction method could be verified for the migration to future low carbonate power system from the existing systems. The proposed approach using exact solution based on the enumerate method is a different approach from approximate methods such as metaheuristic or analytical methods which are generally used for this kind of problems. While the enumerative method is simple and versatile and has many advantages in its application, it has a critical challenge which combinatorial explosion tends to occur. In order to solve the challenge, new approach which reduce the number of enumerated combinations drastically was considered.

Secondly, impact of PV systems on distribution systems considering variable load and PV generation amount was considered and various simulations based on stochastic approach were conducted. Because the amount of PV generation depends on season, time, and weather conditions, it is very difficult to estimate expected power generation in the future and thus it is also difficult to estimate impact of PV installation to power loss reduction. Therefore, the Monte Carlo method was used to power flow calculation for distribution system with a large number of PVs. The result showed the increase of PV installation would contribute to daytime load reduction and this would lead to power loss reduction. However, some capacity control methods should be necessary in the aspect of load leveling and peak cut for evening and night time power demand. Also the simulation result showed that the number of PV systems provided little impact if PV penetration level would be the same. This might be that PV allocations were uniformly over the distribution system model in all scenarios at this time. The impact of the number of PV systems with non-uniform PV allocation scenarios should be considered because power companies cannot decide the installation location of PV systems.

Using the Monte Carlo method, effects or impacts estimation using unknown variables can be simulated and that could be useful tools which calculate profit or benefit in the future with unknown variables.

Chapter References

[3-1] K. Kuroda, T. Ichimura, H. Magori and R. Y , “A New Approach for Optimal Location and Sizing of Distributed Generation using an Exact Solution Method,” International Journal of Smart Grid and Clean Energy (ISSN: 2315-4462), vol.1, no.1, pp.109–115, September 2012

[3-2] K. Kuroda, Y. Matsufuji, T. Ichimura, H. Magori and R. Y location of Dispersed Generations in Distribution Networks to Realize Low-Carbonate Power System,” Journal of Power System Technology (ISSN 1000-3673), vol.36 (12), pp.1-10, December 2012

[3-3] K. Kuroda, H. Magori and R. Yokoyama, “Basic Consideration for Optimal Allocation of Shared Dispersed Generation in Many Small Dispersed Generations Installed Environment（小規模分散電源大量導入環境における共用分散電源の最適配置に関する基礎検討）,” The 2013 IEEJ Annual Meeting Record, 6-149, March 2013 (in Japanese)

[3-4] M. E. Baran and F. F. Wu, “Network reconfiguration in distribution systems for loss reduction and load balancing,” IEEE Transaction on Power Delivery, vol.4, no.2, pp.1401–1407, April, 1989

[3-5] K. Nara, A. Shiose, M. Kitagawa, and T. Ishihara, “Implementation of genetic algorithm for distribution system loss minimum re-configuration,” IEEE Transaction on Power Systems, vol.7, no.3, pp.1044–1051, August 1992

[3-6] Y. J. Jeon, J. C. Kim, J. O. Kim, J. R. Shin, and K. Y. Lee, “An efficient simulated annealing algorithm for network reconfiguration in large-scale distribution systems,” IEEE Transaction on Power Delivery, vol.17, no.4, pp.1070–1078, October 2002

[3-7] D. Zhang, Z. Fu, and L. Zhang, “An improved TS algorithm for loss- minimum reconfiguration in large-scale distribution systems,” Electric Power System Research, vol.77, no.5–6, pp.685–694, April 2007

[3-8] J. V. Schmill, “Optimum size and location of shunt capacitors on distribution feeders,” IEEE Transaction on Power Apparatus and Systems, vol.84, no.9, pp.825–832, September 1965

[3-9] H. L. Willis, “Analytical methods and rules of thumb for modeling DG- distribution interaction,” IEEE Power Engineering Society Summer Meeting 2000, vol.3, pp.1643–1644, July 2000

[3-10] N. Acharya, P. Mahat and N. Mithulananthan, "An analytical approach for DG allocation in primary distribution network," International Journal of Electrical Power and Energy Systems, vol.28, no.10, pp. 669–678, December 2006

[3-11] D. Q. Hung, N. Mithulananthan, and R. C. Bansal, "Analy l Expressions for DG Allocation in Primary Distribution Networks," IEEE Transaction on Energy Conversion, vol.25, no.3 pp.814–820, September 2010

[3-12] O. I. Elgerd, "Electric energy system theory: an introduction," McGraw-Hill, 1971

[3-13] H. Kikuchi, T. Takebayashi, T. Nobumoto, H. Magouri, R. Yokoyama, "Development of Power Flow Simulator for CEMS - Development and Verification of Prototype Power Flow Simulator – (配電系統向け潮流シミュレータの開発ー不平衡負荷を考慮した単相 3 線式変圧器モデルの検証ー)," The 2012 IEEJ Annual Meeting Record, 6-103, March 2012 (in Japanese)

[3-14] H. Yang, F. Wen, L. Wang and S. N. Singh: "Newton-Downhill Algorithm for Distribution Power Flow Analysis," Proceeding of the 2nd IEEE International. Conference on Power and Energy (PECon2008), pp.1628-1632, December 2008

[3-15] "Establishing a Low Carbon Power Supply System," Report by the Study Group on Low Carbon Power Supply System, July 2009 (in Japanese) [Online]. Available at Ministry of Economy, Trade and Industry web site:
http://www.meti.go.jp/report/data/g90727ej.html

[3-16] W. El-Khattam, Y. G. Hegazy, and M. M. A. Salama, "Investigating Distributed Generation Systems Performance Using Monte Carlo Simulation," IEEE Transaction on Power Systems, vol.21, no.2, May 2006

[3-17] A. G. Marinopoulos, M. C. Alexiadisb and P. S. Dokopoulos, "Energy losses in a distribution line with distributed generation based on stochastic power flow," Electric Power System Research, vol81, no.10, pp1986-1994, October 2011

[3-18] K. Kuroda, H. Magori, T. Ichimura, and R. Y International Smart Grid Conference and Exhibition (ISGC&E) 2013, July 2013

[3-19] "Past Electricity Demand Data," [Online]. Available Tokyo Electric Power Cooperation web site:
http://www.tepco.co.jp/en/forecast/html/download-e.html

[3-20] Japanese Industrial Standards Committee, "Estimation method of generating electric energy by PV power system," JISC8907, October 2005 (in Japanese)

[3-21] “Solar radiation database,” (in Japanese) [Online]. Available at New Energy and Industrial Technology Development Organization (NEDO) web site: http://www.nedo.go.jp/library/shiryou_database.html

Chapter 4 Demand-side Optimal Power Utilization

In this chapter, technologies and measures for demand-side optimal power utilization selected as one of critical components of Smart Grid in chapter two are considered with profitable business models.

4.1. Expectations for Demand-side Optimal Power Utilization Technologies

In chapter two, "Optimal Power Utilization" was selected as one of critical categories to realize Smart Grid and some key technical research topics were also defined. Here, expectations of these topics are confirmed and detailed research subjects to be considered in this chapter are decided.

According to the result of the consideration in chapter two, "Optimal Power Utilization" consists of the following components.

- Demand-side efficient energy management (visualization, device control, demand forecast by energy management systems (EMS) such as building, home and Factory EMS (called BEMS, HEMS and FEMS respectively)
- Various electricity price programs including demand response (DR)
- Smart equipment and Smart appliance (autonomous control)

In this study, demand-side efficient energy management and various electricity programs including DR are focused because both components require effective information utilization to provide new values.

Although consumer's benefit from various types of demand-side EMSs and price programs implemented for the purpose of optimal power consumption should be mostly electricity cost reduction, there is the major difference between the purpose of EMS and price program. EMS is provided for energy utilization efficiency in demand-side and thus it is used to optimize consumers' power consumption and their total electricity costs are reduced as the result of the optimization. On the other hand, price programs by power companies are provided to lead their customers' power consumption behaviors for the operation optimization in power companies, and a certain part of the benefit from the optimization is passed on their customers.

Therefore, the following discussions should be necessary in order to find effective methods for the demand-side optimal power utilization.

(1) Benefit and Cost Evaluation of Demand-side EMS

Because power consumers' interest in this area is mostly on the possibility of electricity cost reduction, expansion of demand-side EMS would be promoted if consumers' benefit would be apparent by the combination of high accuracy benefit simulations and autonomous consumers' equipment control. Although major source for this benefit should be the efficiency improvement in consumers' power usage, it is necessary to understand that waste reduction has limitation. In the first year, a consumer might reduce their energy consumption cost dramatically by the installation of EMS. However, additional cost reduction in following years should be difficult because apparent wastes should have been removed by the last year. In addition, cost reduction size depends on customer's power consumption size generally, so it is difficult for small and medium enterprise (SME) and residential consumers to cover their EMS installation and operation cost by only energy cost reduction. Therefore, actual benefit for energy consumers to install EMS should be clarified firstly and effective functions of EMS utilizing information communication technology (ICT) should be proposed. ICT contribution in EMS should be to provide various cost simulation and optimization, and autonomous control methods based on the consumers' optimal operation schedule. Therefore, optimization should be the key factor in this area and it should be effective for decision makers if the relation between power consumption and business profitability would be clarified because optimal power consumption to maximize its profitability could be calculated.

(2) Benefit and Cost Evaluation of Power Company's Price Programs Including DR

Various electricity price programs are provided for the purpose of efficient power supply by peak cut and shift using electricity price elasticity. However careful discussion should be required whether benefit from these price programs is reasonable for their preparation cost and consumers' inconvenience caused by power consumption behavior changes. Especially in SME and residential consumers, the price elasticity should be relatively small because of their small total power consumption and thus more incentives or additional benefit might be necessary. Although DR is one of expected methods to provide additional benefit for power consumers, it is necessary to understand that business models in DR programs require power companies to generate revenue from the reduction of electricity sales amount, while they generally make revenue from power sales. Therefore, a special power market environment and management rules are required in order to generate benefit for both DR program providers and consumers. In addition, service infrastructure preparation cost should be taken into account because the electricity price change considering actual supply and demand would require real-time data collection and these data processing systems, and two way communication systems between power companies and their customers. Because these price programs should be provided as one of power company's services, the cost for advance metering infrastructure (AMI) components (smart meters, communication networks, data collection systems and customer-side devices such as in-home display (IHD)) need to be prepared by power companies generally.

Therefore, ICT contribution for the price program area should include clarification of electricity elasticity, cost simulation for various electricity price programs and autonomous control methods based on both power company's optimal operation and consumer's incentives. Also it should be necessary to consider the benefit passed on customers from power companies should be increased, as well as demand-side EMSs.

Based on above discussions, detailed discussions about demand-side EMS and DR are conducted in this chapter to clarify effectiveness of these measures and conditions to expand considering Japanese near future environment.

4.2. Demand-side Energy Management Systems

In order to realize effective energy consumption, various kinds of EMSs have been proposed. In this section, demand-side EMS, which is focused in this research, is defined and effectiveness of this kind of EMS is considered. In addition, studies for providing effective energy management are discussed.

4.2.1. Overview of Energy Management Systems and Studies for Energy Saving

The term "EMS" is used for a wide range of meanings and major purposes and functions are sometimes different. Therefore, EMS categorization and major functions for each EMS in this study are defined firstly.

(1) EMS Categorization

In general, EMS is defined as the information system which supports optimization of energy consumption in buildings, factories and households etc., utilizing ICT. On the other hand, regional and wide-area power supply and demand balancing system for stable power supply is also called EMS and it is described as Community EMS (CEMS) in chapter two and some are called wide area EMS or supply-side EMS.

These EMSs have been considered to be applied for various purposes such as energy saving, CO_2 emission reduction and disaster resilient energy infrastructure. Because there are various types of EMS, this research defines major EMS types for the purpose of clarifying the characteristics of them.

Firstly, EMSs can be categorized by supply-side EMS and demand-side EMS. Supply-side EMS is for the stable power supply and managed by power companies and regional system operators. Demand-side EMS is for the consumers' benefit increase such as electricity cost reduction etc., and BEMS, FEMS and HEMS are categorized in this type. Referring to the energy consumption status data in Japan [4-1], 2009 energy consumption in the consumer category, which is composed of commercial and household use, increased 1.38 and 1.23 times respectively compared with 1990, while energy consumptions in transportation and industry categories were 1.06 and 0.88 times respectively. Therefore, energy reduction in consumer area is one of big challenges in Japanese energy policy and effective EMS application is one of expected measures.

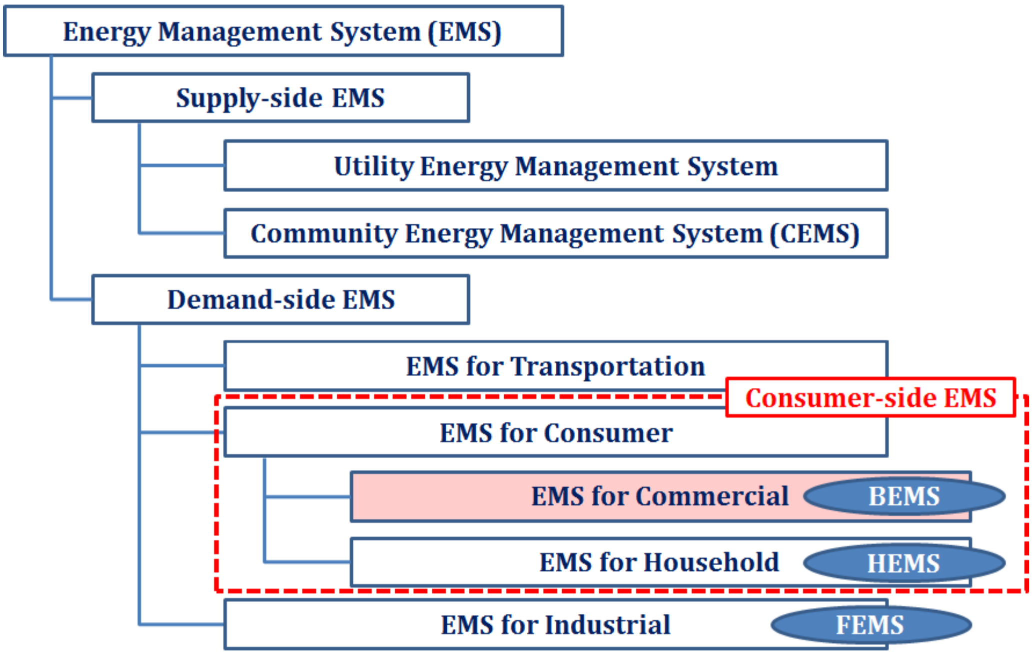


Figure 4-1 Categorization of Energy Management Systems

Figure 4-1 shows EMS categorization defined in this study, and this paper focuses on the consumer-side EMS and especially focused on the EMS for commercial sector, because clarification of EMS installation benefit in the area should be the most effective to promote EMS and to optimize energy consumption.

(2) Functions and System Structure of Consumer-side EMS

In general, EMS collects energy-related data and makes visualization using these data firstly, then energy consumption status is analyzed and optimization would be conducted. In addition, sometimes demand monitoring and controls of energy consumption devices are also conducted as necessary.

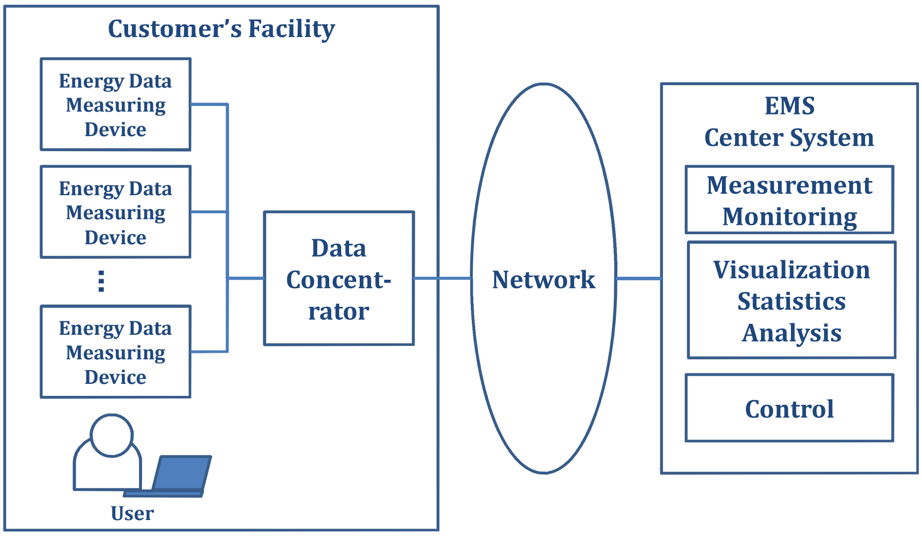


Figure 4-2 Overview of Consumer-side EMS Structure

In order to realize these functions, EMS requires many components such as energy data measurement devices, data transfer network and information systems which totalize and analyse collected data. Also, optimized operation schedules and their transfer to control devices should be required to realize optimal operation using analyses data. Figure 4-2 shows an overview of general required system structure in Consumer-side EMS.

4.2.2. Studies of Energy Saving Using EMS

EMS related studies have been executed and building energy management is one of especially active research areas recently. A building energy management solution using ZigBee[3] and power line communication (PLC) was proposed in [4-2] and it describes that

---

[3] ZigBee is a trademark of the ZigBee Alliance.

the proposed solution was able to save 34% of total energy consumption for the building. In [4-3], multiple gateway system for wireless sensor network was proposed focusing on huge data transfer and processing, and an efficient data transmission method decreasing power consumption and data delay for sensor data collection was provided. In [4-4], an energy management methodology using multi-agent systems for BEMS with combined heat and power system optimization was described and a case study was presented for a typical food center to demonstrate the proposed method. As an actual demonstration project case study, [4-5] describes a BEMS solution including energy usage, cost and carbon emissions reduction, and the solution was installed on smart grid test bed in Jeju Island, South Korea. Although many researches related to advanced technologies such as RES and energy saving measures have been conducted like these, studies for the impact of energy reduction for business profitability by EMS have not been discussed sufficiently.

4.2.3. Current Status of Consumer-side EMS

Here, in order to understand the current status of BEMS, both BEMS installation status in the world and Japan were confirmed and their characteristics and challenges are described.

(1) Global BEMS Market

In many researches and studies, BEMS is regarded as the one of Smart Grid elemental technologies expected to expand.

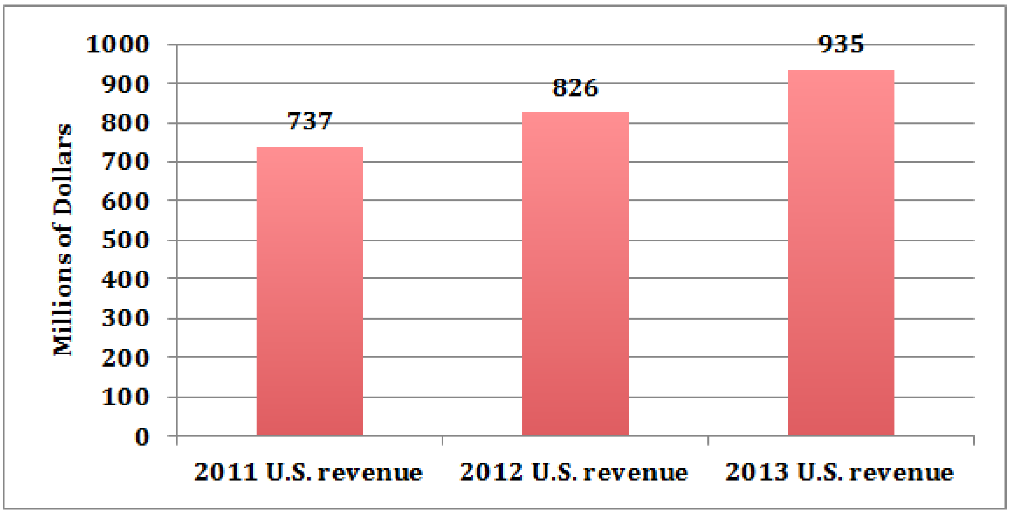


Figure 4-3 Revenue of BEMS in the world [4-6]

According to “Advanced Energy Now 2014 Market Report” [4-6] which is the research report of the recent BEMS installation status, the world BEMS market was expanded to 2.4 billion United States dollars (USD) in 2013 from 1.9 billion USD in 2011 and the United States (U.S.) market which is the largest BEMS market in the world, was expanded to 940 million USD in 2014 from 740 million USD in 2011 (Figure 4-3). This report pointed out the largest change in recent years is the installation of the "cloud technology" and this enables building energy managers to compare energy consumption data among buildings easily. Also BEMS would be the capability of real-time optimal energy operation through the collaborative operation with building automation systems for energy management. On the other hand, this report pointed out it took pretty long time to realize effective operation in customer-side and thus most BEMS vendors focus on marketing and sales promotion compared with new functional developments.

(2) Japan Market

The Great East Japan Earthquake on the 11th, March 2011 made the reliability for the stability and safety of power systems in Japan collapsed completely, which was highly trusted by most of Japanese people before the disaster. It became impossible to use nuclear power generation which was occupied more than 30% of total power generation in Japan before the disaster, and thus energy saving in commercial and industrial (C&I) area became imperative. In the situation, electric power companies in Japan had been able to keep a sort of generation reserve margin by the interruptible power service contracts with large C&I enterprises and then one of next challenges would be the power saving in SMEs because energy saving measures have not been promoted in them. Therefore the Ministry of Economy, Trade and Industry (METI) had conducted a support measure which subsidized a part of the EMS installation expense for SMEs with 50kW – 500kW electricity contract since April 2011 [4-7] and from the viewpoint of the world-wide BEMS expansion as mentioned in above, this BEMS support measure was expected to prime EMSs installation. In order to use the measure, business power consumers needed to use specified BEMSs provided by previously certificated 22 "BEMS aggregators" and a subsidy application was needed to be conducted by these BEMS aggregators. In addition, BEMS aggregators were needed to show the estimation for the number of BEMS installations previously and the total number of estimated BEMS installation before the business commencement was more than 40,000. Roughly speaking, about 2,000 new BEMS contracts would be estimated every month and most of BEMS aggregators expected more than 1,000 BEMS contract for two years although the number of target BEMS contracts was different by each BEMS aggregator. It means that BEMS aggregators assumed that BEMS installation would spread rapidly.

Figure 4-4 shows the BEMS installation target and the result in the subsidy measure based on [4-8]. As the result, the number of actual BEMS installations was 6,268 although total target BEMS installation was 63,684 and it was only 9.8% toward the target. Although it is necessary to analyse why the result was completely different with the target, it is true that the most of SMEs in Japan have not installed BEMS and do not conduct detailed energy management based on the energy consumption data.

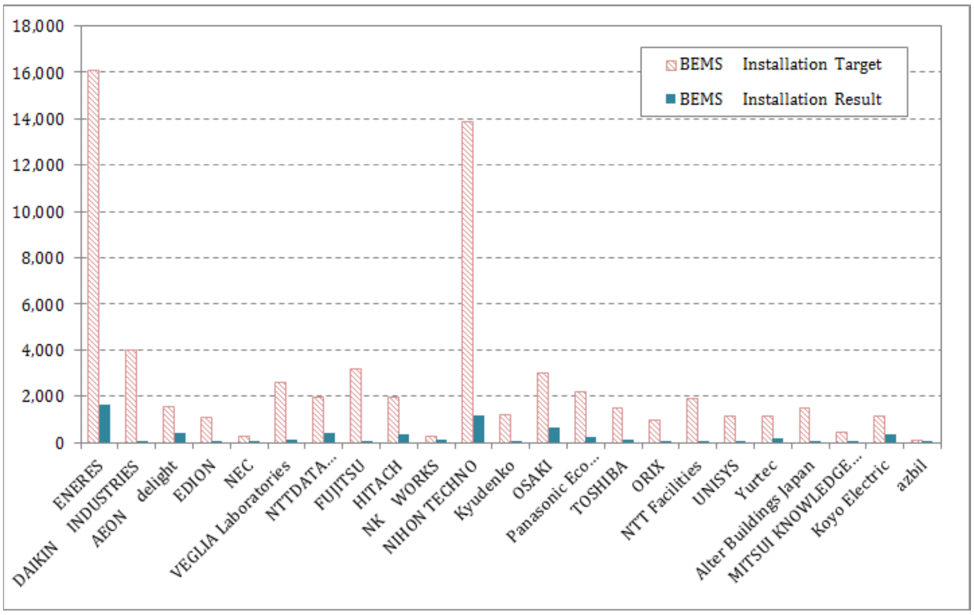


Figure 4-4 BEMS Installation Target and Result

As mentioned in the chapter two, it is essential to recognize energy data in detail for the realization of advanced energy management applications in Smart Grid, and measures such as BEMS would be necessary for advanced energy management. Based on the aspect, the promotion of BEMS, consumer-side EMS, installation will be discussed in the following subsections.

4.2.4. Approach for Benefit Quantification of Consumer-side EMS Installation

In this subsection, purposes and challenges of consumer-side EMS are discussed and procedures for the establishment for quantification of the EMS installation benefit are considered.

(1) Benefit Realization Concept of Consumer-side EMS

Major objectives for consumer-side EMS should be optimization of both power consumption and cost reduction. Electricity cost reduction by EMS should be realized by the following three elements mainly.

a. Basic Charge Reduction by Peak Cut

Generally, electricity price consists of basic charge and metered charge. By the reduction of the peak time power usage by EMS, basic charge, which is decided by the peak time power usage, can be reduced and then total electricity price should be reduced. Let current basic charge be C_F current unit price of electricity be p_U, and amount of power consumption in the target month be V_m, then monthly electricity price P_m would be as follows.

$$P_m = C_F + p_U \cdot V_m \tag{4-1}$$

If basic charge would be reduced to $C_{F'}$ by the peak reduction, benefit for basic charge reduction B_F would be as follows.

$$B_F = C_F - C_{F'} \tag{4-2}$$

b. Total Power Consumption Reduction by the Elimination of Wasted Energy Consumption

There must be wasteful power usage which is not necessary to consume such as standby electricity, and it would be clarified by power consumption visualization. By the reduction of such wasteful power consumption, total power consumption should be reduced. In the equation (4-1), V_m would be reduced to $V_{m'}$. Then benefit B_V would be as follows.

$$B_V = p_U \cdot (V_m - V_{m'}) \tag{4-3}$$

c. Energy Cost Optimization by Peak Shift

This type of cost reduction is achieved by electricity price programs such as “Time of Use (TOU)” etc., in which electricity unit price in each time slot is different. By the control of power consumption behavior corresponding to the electricity price for each time slot, optimal power consumption would be addressed. In the equation (4-1), P_U should be changed to P_{AVE}, which is the average electricity unit price. Then the benefit B_P would be as follows.

$$B_P = (p_U - p_{AVE}) \cdot V_m \tag{4-4}$$

where, $p_{AVE} = \frac{1}{n} \cdot \sum_{i=1}^{n} p_{Ui}$, $V_m = \sum_{i=1}^{n} V_i$, n: the number of time slots for the target month, p_{Ui}: unit price for time slot i, V_i: power consumption for the time slot i.

DR in which incentives from power companies and system operators, getting benefits from the demand reduction by consumers, should be provided to the consumers and it is included in this category.

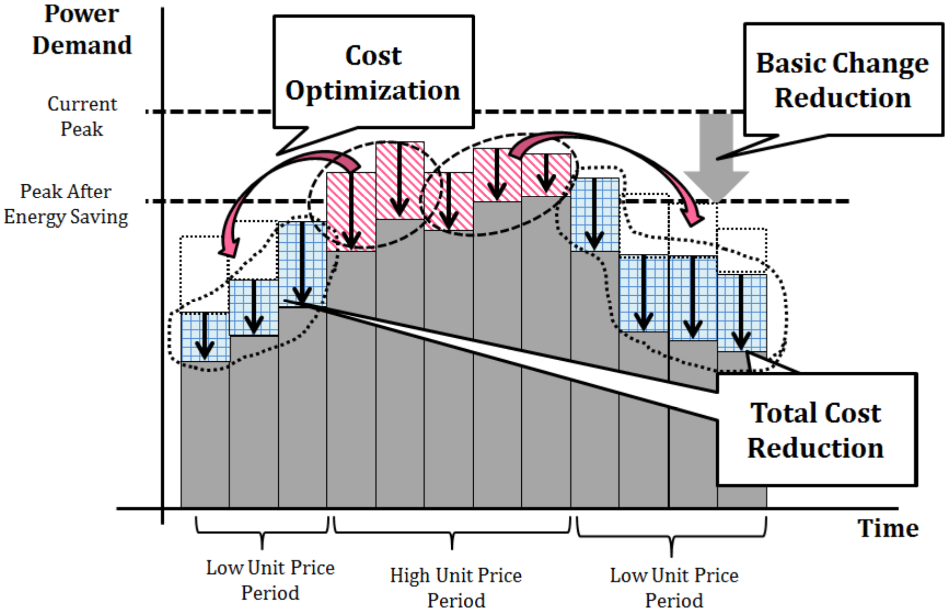


Figure 4-5 Benefit Realization Concept of Consumer-side EMS

Figure 4-5 shows an overview of benefit realization concept of consumer-side EMS. Total benefit of the installation of the EMS B_{Total} would be as follows.

$$B_{Total} = B_F + B_V + B_P \tag{4-5}$$

$$B_{Total} = C_F - C_{F'} + 2(p_U \cdot V_m - p_{AVE} \cdot V_{m'}) \tag{4-6}$$

(2) Establishment of a Benefit Quantification Method by EMS Focusing on Profitability

Next, the profitability of consumer-side EMS is formulated considering the EMS concept described in above.

a. General EMS Installation Benefit Calculation

Installation effect (benefit) of the EMS can be calculated as “energy cost reduction provided by the EMS” minus “initial and accumulated operation cost of the EMS”. Let initial cost be C_I, monthly operation cost be $C_{m,O}$ average monthly electricity reduction cost be $\varDelta P_{m,AVE}$, and payout period be T (month), then the following equation should be satisfied.

$$C_I + C_{m,O} \times T = \varDelta P_{m,AVE} \times T \tag{4-7}$$

where, $\varDelta P_{m,AVE} = B_{Total}$ in (4-6).

Figure 4-6 represents the cost function of the EMS installation and operation. If the break-even point would exist and sales revenue would not decrease, business administrators should make the decision to install the EMS. Therefore, if consumer-side EMS would not be used widely, it means that business administrators would not convince the break-even point existence in the near future and feel high risk for the initial investment recovery.

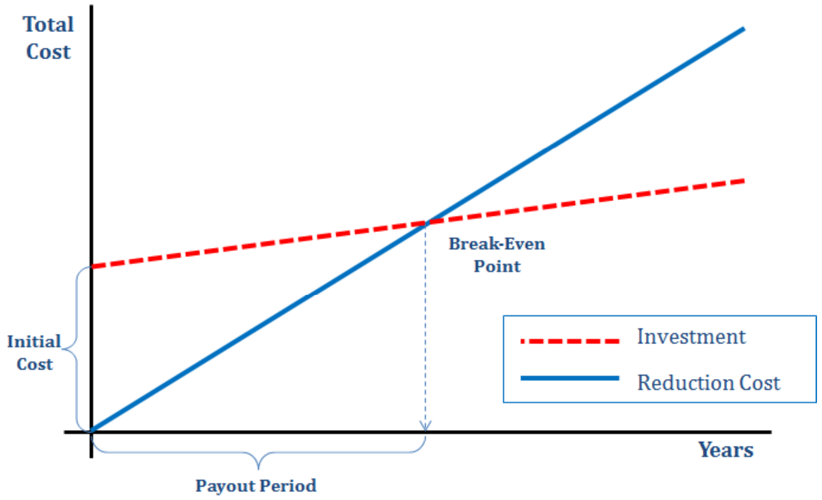


Figure 4-6 Cost Function of Consumer-side EMS Installation and Operation

b. Guarantee of Energy Cost Reduction and Maintaining Profitability

In the installation of EMS, both the break-even point existence and the business profitability maintaining or improvement should be crucial. Therefore, the aspect of business profitability is considered in addition to the simple cost function showed in (4-7) in this research.

Let the average difference of monthly sales revenue except for the energy cost difference be $\varDelta R_{m,AVE}$, then the (4-7) would be changed as follows.

$$C_I + C_{m,O} \times T = (\Delta P_{m,AVE} + \Delta R_{m,AVE}) \times T \tag{4-8}$$

Because it is necessary to achieve both electricity cost reduction and business profitability maintaining, the fluctuation of business profitability would be considered by changing settings of power consumption equipment in this research. For example, when total profitability in case that temperature setting would be turn up 1 ˚C in summer season would be discussed, it is necessary to consider performance or productivity changes while electricity cost would be down.

4.2.5. Challenges for the Expansion of Consumer-side EMS

If consumer-side EMS installation benefit would be clarified in commercial sector, this should be important for business administrators of enterprises and many of them should be proactive for the installation of EMS. However, the number of EMS installation in consumer sector has not become large as most EMS providers expected in spite of power shortage due to the Great East Japan disaster. Here, challenges for the expansion of consumer-side EMS are discussed.

(1) Consideration of Reasons for Slow Penetration of Consumer-side EMS

According to "2010 White Paper on Small and Medium Enterprises in Japan" [4-9], energy efficiency actions in SMEs have not been improved compared with major enterprises.

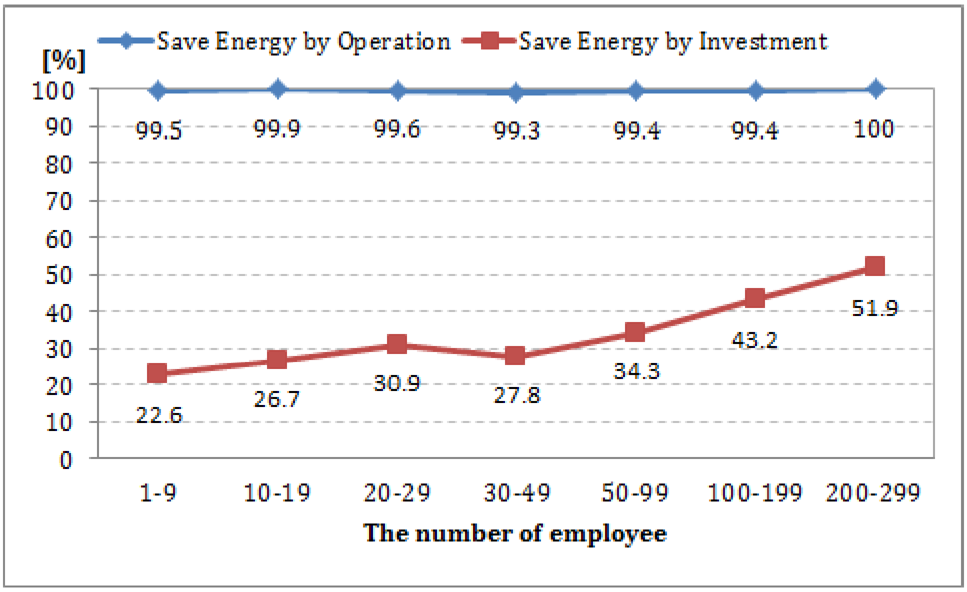


Figure 4-7 State of Action on Energy Conservation by Size of Workforce [4-10]

“Energy Conservation through Investment” such as installation of high-efficiency equipment and control devices has not been promoted, whereas “Energy Conservation through Practice” such as appropriate management of temperature settings, and lighting switch On/Off have already been executed in many enterprises. Figure 4-7 shows “state of action on energy conservation by size of workforce” researched in [4-10].

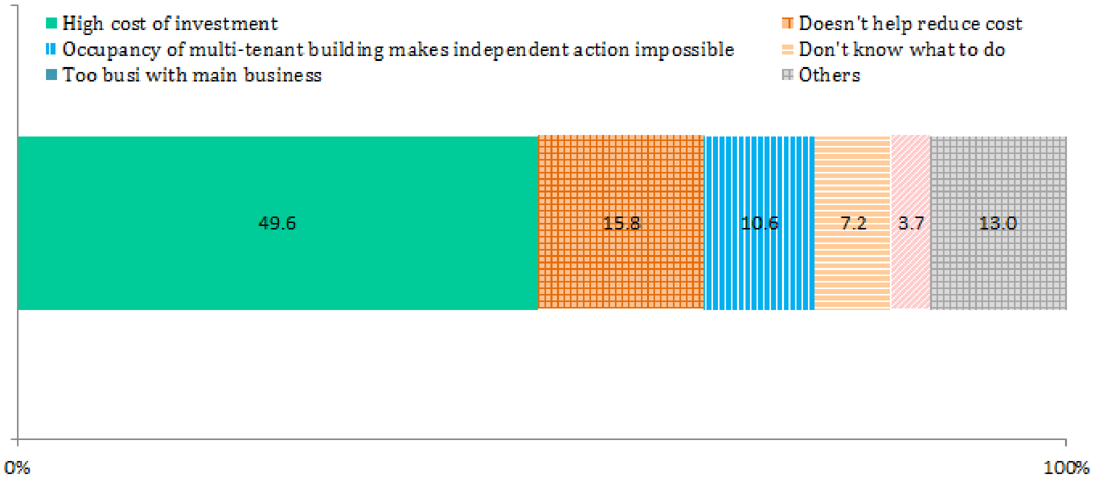


Figure 4-8 Reason for not Engaging in Energy Conservation Through Investment [4-10]

As the main reason, about the half of SMEs answered “High Cost of Investment” and the next major reason was “Doesn’t Help Reduce Cost”. From these reasons, it is found that SMEs have been promoted “Energy Conservation through Practice”, however the effect of these non-investment activities are limited and most of SMEs in Japan should be skeptical for the return on investment (ROI) of the energy saving activities. Or as 7.2% of the population said “Doesn’t know what to do”, the existence of learning curve for customer-side EMS might be a reason as mentioned in 4.2.3(1). In addition, electricity related cost is not large especially in small enterprises and thus cost reduction benefit would be small and the benefit might not cover the installation and operation cost. Even if the benefit would cover the installation and operation cost, the investment recovery period would be long due to its large scale investment and small cost reduction. From these reasons, it is difficult for household customers to get enough benefit by electricity saving by EMS, thus home energy management system (HEMS) should be used not only for energy cost reduction method but also for various service base infrastructure.

Moreover, “the investment” in the research is mainly for energy saving equipment such as LED (light emitting diode) lightings, air-conditioners and other efficient electric appliances. Because the installation of consumer-side EMS does not reduce electricity cost itself but just supports to find rooms for optimal electricity utilization, it should be more difficult for SME administrators to decide such EMS installation without clarified benefit or guarantee of investment recovery such as subsidies.

(2) Approach toward Existing Challenges

While there are many challenges to install consumer-side EMS, detailed energy metering and information exchange mechanisms are essential for optimal energy utilization. Therefore, it is necessary that consumer-side EMS installed enterprises should be able to get additional and clarified benefit by the installation of the EMS, and as an important purpose, this research should provide beneficial tools to evaluate EMS installation benefit, especially for business power consumers who manage offices, shops and buildings etc., by the clarification of EMS installation cost, and cost reduction effects and impact for business profitability for some characteristic business types. The followings are basic concepts and their approaches.

- **Optimized Power Consumption**

Optimized power consumption should be defined as the power consumption which maximizes the power consumer's profitability and the amount of saving energy. This means that enterprises should be achieved saving energy without decreased productivity.

- **Profitability Change by Temperature**

Evaluation of the relation between energy saving and work performance should be one of good models to understand profitability change by temperature. For example, an enterprise whose main business depends on the work performance of employees is necessary to consider different property of each employee if profitability of the enterprise would be estimated. For retail businesses such as restaurant, supermarket etc., indoor temperatures might impact to their sales and retailors should evaluate the relation of energy saving and customers' behavior.

- **Utilization of Stochastic Variables for Unknown Values**

Unknown values such as work performance for work room temperature or sales amount for shop temperature can be defined as stochastic variables. By the execution of the Monte Carlo method using these stochastic variables, the relation between energy management and enterprise profitability should be calculated, and such EMS installation benefit should be more accurate using statistical data for the definition of stochastic variables generation rules.

- **Optimal Setting**

Optimal settings for parameters such as temperature and distribution models used for the Monte Carlo method are also needed to be considered through this approach. Utilization of historical data should be useful for accurate results.

4.2.6. Consideration of Evaluation Method for Effective Consumer-side EMS Installation

In this subsection, an evaluation method for effective consumer-side EMS installation is considered using some assumed business models.

(1) Formulation of Earning Structure

The profit of a month can be calculated as the accumulated profit in business days in the month. Here, profitability change would be considered with 1 unit reduction of power consumption. It means measures such as 1 ˚C air-conditioner temperature turn up or 10% light turn off etc. As the first example, let the change of work performance be L, which is defined as the rate of variability for the average production amount P_{AVE}, then total production amount P_{ALL} would be as follows.

$$P_{ALL} = P_{AVE} \times (1 + L) \tag{4-9}$$

Let work performance variability of employee i in temperature t ˚C environment be $L_i(t)$, then total production amount P_{ALL} in temperature t ˚C environment would be as follows.

$$P_{ALL} = P_{AVE} \sum_{i=1}^{n} (1 + L_i(t)) \tag{4-10}$$

where n is the number of employees in the enterprise.

Here, three aspects of power saving by consumer-side EMS are considered. The first is the basic charge reduction by peak cut or shift. In this case, power demand for peak time (e.g. from 11 am to 2 pm) need to be reduced. Therefore, (4-10) would be modified into the following equation using one day production loss $P_{d,LOSS}$, and average production from 11 am to 2 pm, $P_{11am\text{-}2pm,AVE}$.

$$P_{d,LOSS} = P_{11am-2pm,AVE} \cdot \sum_{i=1}^{n} L_i(t) \tag{4-11}$$

For example, annual productivity reduction $P_{y,LOSS}$ is calculated by the accumulation of the volume of peak cut electricity and showed as follows.

$$P_{y,LOSS} = pcdate \cdot P_{11am-2pm,AVE} \cdot \sum_{i=1}^{n} L_i(t) \tag{4-12}$$

where $pcdate$ is the number of peak cut dates for a target year.

Here, work room temperature should be controlled so that $P_{y,LOSS}$ should be smaller than basic charge reduction benefit B_F in (4-2).

Secondly, in retail and catering businesses which customers come into their business facilities such as shopping stores, restaurants etc., their indoor temperature might influence customers' purchase behaviors. Then the rate of variability for purchased amount of customer j in indoor temperature t ˚C environment be $B_j(t)$, the average sales revenue be R_{AVE}, then total sales revenue R_{ALL} in the shop temperature t ˚C environment would be as follows.

$$R_{ALL} = R_{AVE} \sum_{j=1}^{m} (1 + B_j(t)) \tag{4-13}$$

where m is the number of customers in the facility.

In above these two examples, optimal temperature for employee i or customer j can be defined as random variable. Therefore, these kinds of variables can be treated as stochastic variables and profitability by consumer-side EMS installation would be analyzed by the Monte Carlo method.

(2) Formulation for Productivity Change Simulation

The formulation of benefit quantification of EMS for the simulation model case is considered. Let average monthly revenue be $R_{AVE,\ month}$, work performance change rate for employee i in temperature t be $L_i(t)$, then revenue from June to September $R_{6\text{-}9}$ would be as follows.

$$R_{6-9} = \sum\nolimits_{month} R_{AVE,month} \sum_{i=1}^{n} (1 + L_i(t)) \tag{4-14}$$

where n is the number of employees, *month*: June, July, August, September.

Same as the revenue from June to September, revenue from December to March $R_{12\text{-}3}$ would be as follows.

$$R_{12-3} = \sum\nolimits_{month} R_{AVE,month} \sum_{i=1}^{n} (1 + L_i(t)) \tag{4-15}$$

where *month*: December, January, February, March.

For April, May, October and November, it is assumed that fluctuation of electricity cost would be small and energy cost in each month would be the same as average monthly electricity price. As the result, the annual revenue R_{year} would be as follows.

$$R_{year}=R_{6\text{-}9}+R_{12\text{-}3}+\sum\nolimits_{month}R_{AVE,month} \tag{4-16}$$

where *month*: April, May, October and November.

On the other hand, let average monthly electricity cost be $C_{AVE,month}$, power consumption reduction rate for each month be e_{month}, then annual electricity cost reduction $C_{reduction,year}$ would be as follows.

$$C_{reductionyear}=\sum_{month=1}^{12}C_{AVE,month}\cdot e_{month} \tag{4-17}$$

Therefore, annual revenue R_{ALL} in this case would be as follows.

$$R_{ALL}=R_{year}+C_{reductionyear} \tag{4-18}$$

In order to clarify EMS installation effect, it is necessary to consider EMS installation and operation cost and payout period in (4-7), where $\triangle R_{ma}$ in (4-7) is the difference between R_{ALL} and the revenue in the previous year.

4.2.7. Information Communication to Promote Consumer-side EMS

It should be necessary to focus on the EMS installation impact to profitability in addition to electricity cost reduction and thus the evaluation approach was proposed to promote consumer-side EMS. In order to use this evaluation approach, non-energy related additional data and their collection measures would be required. For example, detailed weather and temperature data, performance data of facilities and statistic data related to human behaviors are typical. In addition, more detailed status data should be need to collected in order to recognize accurate conditions for human activities or facilities performance. Although these data and their collection infrastructure should contribute to consumer-side EMS promotion, statistic and detailed data collection requires a lot of data collection infrastructures including sensors, communication network and data processing information systems, and it lead to high installation cost of EMS. Therefore, the important challenge of consumer-side EMS installation is to achieve detailed and various status data collection and low cost at the same time. Because low cost infrastructure requires implementation cost reduction in addition to equipment cost reduction, wireless and auto configuration technologies which can reduce implementation cost should be expand. Table 4-2 shows information and its infrastructure to promote consumer-side EMS.

Table 4-1 Information and its Infrastructure to Promote Consumer-side EMS

Required infrastructure	
Energy data collection infrastructure	Sensor (Current transformer (CT), Voltage transformer (VT), Digital, Analog), Smart Meter, Cubicle type high voltage receiving equipment, Communication network in the facility and between service provider and consumer Data collection systems and interfaces to other back office systems
Additional data collection infrastructure	Sensor (CT, Digital, Analog), Communication network in the facility Data collection system and interfaces to other back office systems and external systems such as weather information system, market information system.
Required Information	
Electricity related information	・Power consumption amount (Total, Equipment, Area etc.) ・Electricity quality (Voltage, Current, Power factor etc.)
Profitability related information	・Revenue related information (Revenue, Sales amount, Cost etc.) ・External information (Weather, temperature, irradiation) ・Environmental information (Indoor temperature, CO_2, illuminance etc.

4.3. Demand Response (DR)

Generally, DR means “response of power demand for its pricing” and it is a kind of mechanism which promotes power demand reduction in case of power supply shortages by paying considerations from power companies to their customers on a contract basis. Unlike the existing one-way power supply from power companies to their customers, collaboration control between power supply and demand sides is a major characteristic point of Smart Grid and DR is one of demand adjustment functions in demand-side. In some power markets, DR programs have been already provided and contributed to demand adjustments (e.g. peak cut, peak shift) and electricity reserve. Therefore, in this section, DR programs applied to some power markets are systematically organized firstly, and then effectiveness of these DR programs is considered. In addition, the applicability of DR programs for Japanese power market is discussed and effective DR penetration models in Japan are considered.

4.3.1. Previous Studies and Systematical Reorganization of DR Programs

In this subsection, current major DR programs are listed up and reorganized by their characteristics.

(1) Previous Studies of DR

In various studies, the definition of DR and provided programs in some power markets were introduced. In [4-11], various DR programs were categorized as incentive based program (IBP) or price based program (PBP), and IBP were divided into “Classic Program” and “Market Based Program”. PBP is based on a dynamic pricing which reflects wholesale electricity price and thus it is not a flat rate. The final target of these programs is to level power demand curve providing high-price in peak time slots and low-price in non-peak time slots. In [4-12], DR programs in major U.S. markets, such as NYISO (the New York Independent system operator (ISO)), PJM (Pennsylvania, New Jergey and Maryland) interconnection and ISONE (ISO New England), were classified into two big program types; “Emergency Program” and “Economic Program”, and execution results of these programs such as demand reduction results and registered capacities were introduced. Also the research explained power retailer’s price menus which were equivalent to PBP in [4-11] as a method to shift price volatility risks to their customers or to take the risks themselves. Reference [4-13] and [4-14] studied DR programs for business and residential customers respectively and pay back programs which customers got rebate corresponding to their demand reduction were introduced in addition to price reduction based DR programs.

(2) Classification of DR Programs

In order to consider effective DR programs which promote demand reduction in peak time slots, this research reorganizes existing DR programs by the viewpoints of benefit for service providers such as power companies and consumers. To generate the benefit, it is important to understand who provides incentives of DR programs, that is who will get benefits by the demand reduction in consumer-side.

Considering consumers' participation styles, most of DR programs can be classified into either market participation style or price menu style (which is provided by power companies including DR aggregators). That means incentive providers of DR programs can be markets and/or power companies. Therefore, various DR programs are categorized into market base and price menu base firstly and then detailed consideration to promote DR programs are discussed.

a. Market Based DR program

In this program type, the incentive providers are markets (i.e. power exchange (PX), ISO, regional transmission organization (RTO) or network operator etc.) and the benefits include power supply reliability improvement, market stability and operation efficiency etc. Although autonomy initiative models providing subsidies for regional environmental issues might be considerable, this is out of scope in this research.

Next, incentive amount in the market base DR programs is considered. The U.S. market based DR programs are categorized into "Emergency Program" and "Economic Program" in [4-12]. These program types in the market based programs are important to consider incentive estimation. Emergency Program is for the purpose of power supply reliability, therefore the urgencies of this type of DR programs are very high and some programs require penalties such as charges or suspension of trading in case that contracted demand reduction would not be achieved. Economic Program is for the purpose of market price reduction, price stabilization, power procurement from various generation sources, sufficient reserved capacity and load leveling etc. Basically, possible demand reduction amounts in these programs are registered before trading, and rebates would be paid from the market corresponding to demand reductions, or penalties would be paid by consumers for the non-attainment demand reduction time slots.

As same as normal power exchange, bulk trading is efficient in DR programs and thus DR aggregators who aggregate many consumers' demand reduction volumes have appeared in the U.S. and other markets. In addition, some U.S. markets provide DR programs for ancillary service [4-15]. In this kind of programs, DR is used for a power supply reserve method for voltage and frequency management in power systems. Therefore, it is classified as Emergency Program in this research.

b. Price Menu Based DR Program

Incentive providers in price menu based program are power companies and/or intermediate agents such as aggregators who take economic benefits by consumers' demand reduction. Here some price menus which promote demand cut and shift are introduced.

- Time Of Use (TOU)

One day is divided into some time slots and set a different electricity unit price for each time slot. By setting higher electricity unit prices on peak time slots and lower electricity prices on non-peak time slots, demand shifts are promoted.

- Critical Peak Pricing (CPP)

For specific dates or time slots in which power supply would not meet demand, additional cost for power use to TOU price would be required to consumers targeting for larger amount of demand shifts.

- Real Time Pricing (RTP)

Electricity price for each time slot fluctuates reflecting wholesale electricity price. It is sometime called dynamic pricing.

- Peak Time Rebate (PTR)

In this program, consumers would be paid rebates corresponding to their demand reduction amount, while incentives of TOU, CPP and RTP for consumers are possible cheaper electricity price.

(3) Reorganization of Major DR Programs

Figure 4-9 represents major DR program types which are reorganized based on the incentive provision viewpoint.

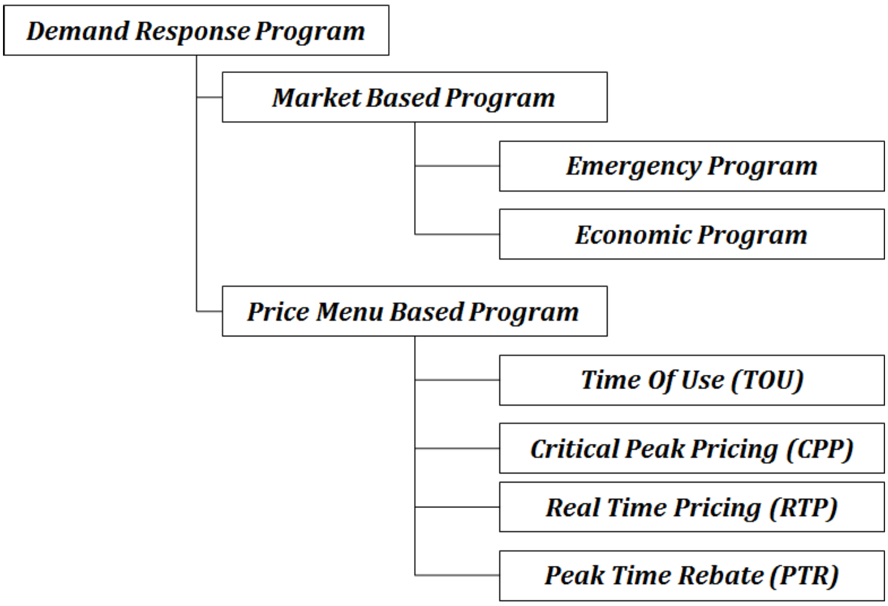


Figure 4-9 DR Program Types Based on the Viewpoints of Incentive Provision

4.3.2. Current Status of DR Penetration

Here, current status of DR programs in the U.S. and Japan is described respectively.

(1) The United States

In the U.S., various DR programs have been provided commercially and related rules are also defined. The Federal Energy Regulatory Commission (FERC) publishes the status of the U.S. DR programs regularly.

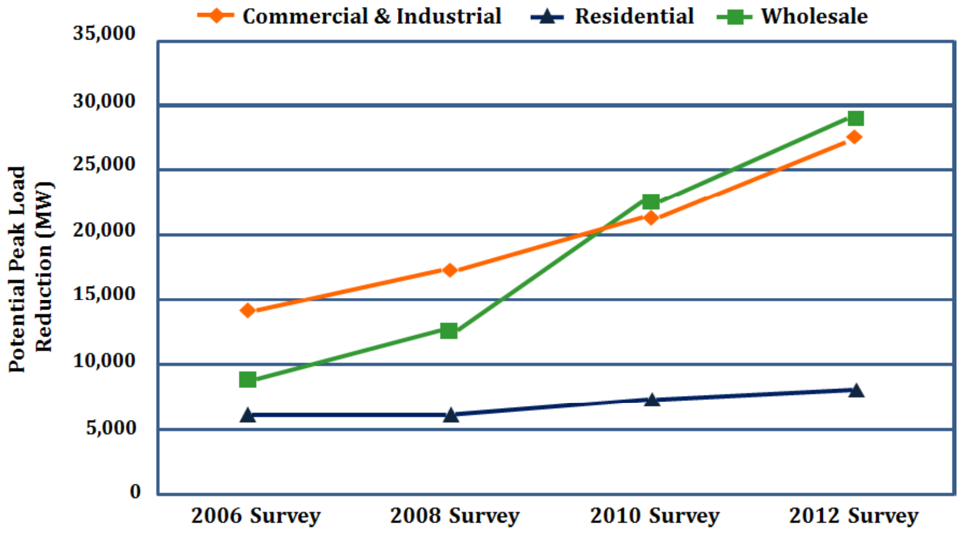


Figure 4-10 Reported Potential Peak Load Reduction by Customer Class in 2006, 2008, 2010 and 2012 FERC Surveys [4-17]

2010 FERC surveys [4-16] shows that 53,063 MW in peak load was reduced by DR programs in 2010 and it was increased about 42% compared with the 2008 survey. Moreover, 2012 FERC surveys [4-17] shows potential peak load reduction by C&I customers increase by 31% and wholesale entities increase by 26% respectively. Also, as showed in Figure 4-10, 80% of potential peak load reduction was achieved by wholesale electricity companies and C&I customers. However, potential peak power reduction capacity of residential sector is still small and low increase rate. Therefore, major target of DR market should be wholesale electricity companies and C&I customers. Figure 4-11 shows the reported potential peak load reduction by program type and by customer class. In the chart, "Incentive Based Programs" is the same meaning of "Market Based Program" in this research and "Time-Based Programs" is the same meaning of "Price menu Based Program" in this research. From the chart, most of effective DR programs are in "Market Based Program" and DR programs in "Price Menu Based Program" have not got good result except for TOU.

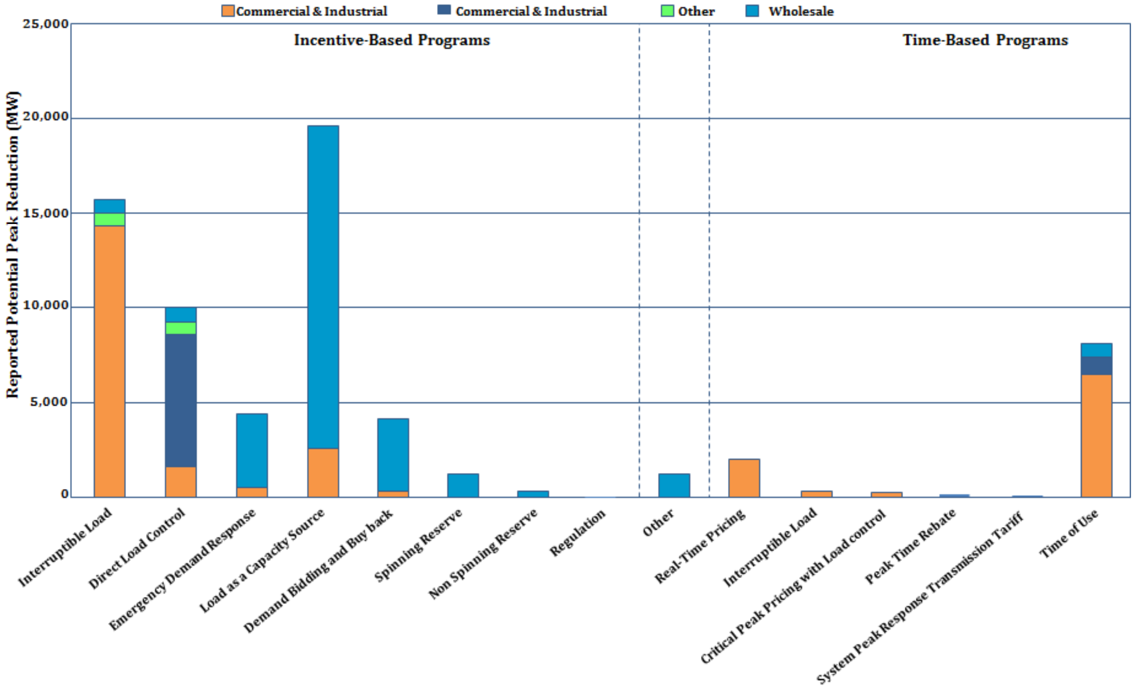


Figure 4-11 Reported Potential Peak Load Reduction by Program Type and by Customer Class FERC surveys [4-17]

(2) Japan

In Japan, field trial DR programs have been provided in some traditional electric power companies, and some new entrants called power producer and suppliers (PPSs) provide commercial DR programs. Because DR service in Japan is on the initiation stage, it takes a good amount of time to evaluate the effectiveness of DR service in Japan. The following three points should be major features of Japanese DR programs.

a. Contract for Control of Demand and Supply in Large C&I Customers

From electric power shortage due to the Great East Japan Disaster, power companies promoted the electric power contract for control of demand and supply with large electric power consumers. Consumers who have the contract with power companies, have to reduce their demand in power shortage situation. These consumers can get incentives for such inconvenient power usages and this can be a kind of DR program.

b. DR Targeted Segment; SME and Residential

Because most of large power consumers have contracts for control of demand and supply, major target segments of DR in Japan are SMEs and residential consumers. Roughly speaking, total amount of used power of SME and residential is as large as the large power consumer segment respectively.

c. Price Menu Based DR Programs

Because wholesale power exchange in Japan have not been activated so far, there are not market based DR programs and current trial and commercial DR programs in Japan are price menu based.

4.3.3. Effects of DR Programs

In this subsection, benefits and their generating mechanisms for each DR program are considered. Also, some conditions of success for expansion of these DR programs are considered.

(1) Reliability Benefit

"Emergency Program" is provided as a prevention method for serious damages of power systems such as power outage in case that power supply amount would not meet the demand in a certain time slot. Therefore, markets (or system operators) can pay equivalent to the expected loss in serious power system damage as the incentive, if such serious damage would be avoided. To estimate the expected loss, risk values might be used. Generally risk value is calculated by the following formula.

$$\text{Risk} = \text{Probability} \times \text{Consequence} \quad (4\text{-}19)$$

To calculate an outage risk, "Outage Probability" and "Outage Consequence" are necessary. With respect to the "Outage Probability", statistical data can be used and the accuracy of the probability should be improved if outage related data such as power reserved capacity, weather information in a targeted area etc., could be used. With respect to "Outage Consequence", estimated financial damage of the outage in the targeted area such as opportunity loss and penalties to be paid can be used.

Using these estimation methods, reasonable incentive should be able to be decided. Generally incentives for DR programs in "Emergency Program" type are large amount compared with "Economic Program" because generally outage damage would be large amount, therefore "Emergency Program" is very important not only for the market reliability improvement but also for the expansion of DR effectiveness.

(2) Economic Benefit

In this study, economic benefits from a long-term perspective such as reduction of capital investment for new additional power plants construction by DR programs are out of scope, because this study consider if the optimal power system would be achieved with DR programs, new additional power plants were not necessary originally.

The purpose of both "Economic Program" and "Price Menu Based Program" is to obtain economic benefit. Although incentive providers for consumers are different in these two types of programs, it is necessary to provide benefits to both power companies and consumers to expand effectiveness of DR programs. Therefore, effective supplier's benefit models of both programs are considered here by formulation of them.

In DR programs, consumers' demand reduction means sales revenue reduction for power companies. Therefore it is necessary for them to obtain benefits more than the sales revenue reduction by the programs.

Here, let benefit of a power company be $B(V)$, power sales amount be V and maximum value of V be v_{max}, then the following conditions should be satisfied if economic related DR programs would be provided.

$$\{V : 0 < V < v_{max}\} \tag{4-20}$$

$$B(V) \leq B(m) \quad \{V : 0 < V \leq m\} \tag{4-21}$$

$$\max B(V) = B(m) \tag{4-22}$$

$$B(m) < B(V) \quad \{V : m < V\} \tag{4-23}$$

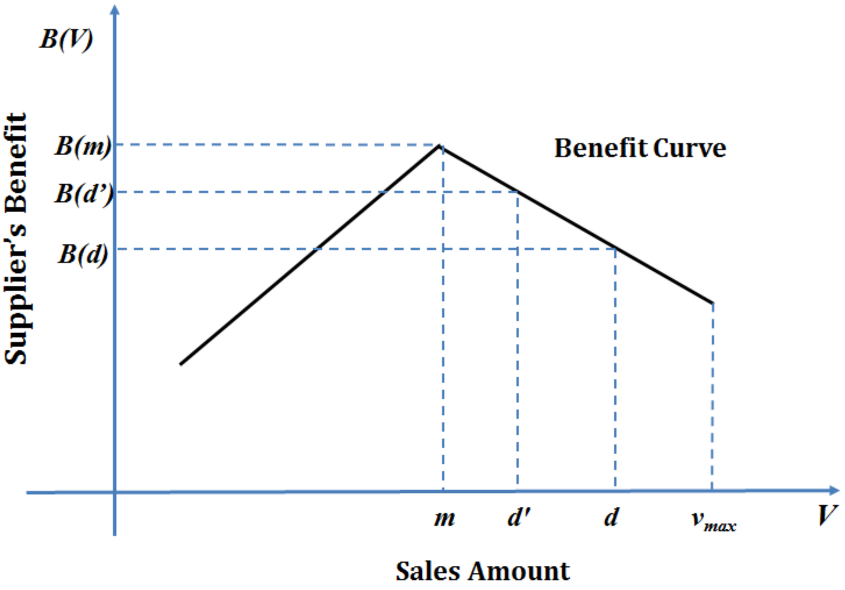


Figure 4-12 Benefit Curve for DR Programs Categorized in Economic Program and Price Menu Based Program.

As showed in Figure 4-12, this model would be achieved under the environment that benefits would be decreased if electricity sales amount would be more than m. In case that the power company would need to supply d amount of power ($d > m$, $\{d, m \in V\}$), if consumers would reduce their demand from d to d' ($d' > m$, $\{d' \in V\}$), benefits of the power company would increase b.

$$b = B(d') - B(d) \tag{4-24}$$

From the viewpoints of the power company, the benefit could be larger with sales amount reduction until m even if some cost would be paid, and the cost would be the source for incentive. Therefore, maximum incentive I_{max} would be as follows.

$$I_{max} = B(m) - B(d) \tag{4-25}$$

In order to satisfy above these conditions, multiple different price electricity commodities exist in the participated market and it is necessary for the power company to procure high price electricity commodities more than its profitable price. For example, in case that a power retail company which has procured m electricity from a generation company needs to buy additional high price power from markets if the company need to provide electricity more than m to their customers, required conditions are satisfied. Only in such case, benefits for both power companies and consumers can be provided.

From the consideration of benefit models of economic related DR programs, major market conditions to generate benefits for both power companies and consumers by these programs are possibilities of power companies' (suppliers') power supply capacity shortages for the consumers' demand, and availability for such shortened capacity from markets. It means that the model would be difficult if the capacity of the generator's supply is enough for the consumer's demand or power companies cannot procure additional power from markets. On the other hand, this model would be practical in case that a small new entrant aggregates more customers than their power supply capability and can procure power from other power companies or markets. However, it looks very difficult for these power companies to obtain large benefit by only price menu based program.

(3) Conditions Required for DR Penetration

Assuming that the origination of DR program would be the incentive provided by the entities which obtain benefit, conditions of DR program success would be clarified by above various considerations of DR programs and their mechanisms.

a. Emergency Program Provision by System Operators

Because a power outage makes great damage, reasonable cost for preventing outages should be used. This program should be necessary to maintain power system reliability and to provide incentives both DR program providers and consumers for the expansion of DR market.

b. Various Trading Commodities in a Power Exchange

From the viewpoint of DR program providers, it is necessary to prepare countermeasures in case customers would not reduce their demand as required. Considering the necessity of multiple power commodities with different price and the efficiency of power trading, the revitalization of PX is the critical factor for the success of DR programs.

c. Adequate Power Supply and Demand Size

DR programs can provide benefits only in the market which power supply capacity is not enough for the peak demand and electric power can be procured in the market with higher price if necessary. The U.S. DR markets which have gotten successful results meet these conditions. In addition, it is necessary to consider the regulation design and subsidies for the market efficiency, price stability and environmentally enhancing because regulations and subsidies influence the result of DR programs, although it is not discussed in this study.

4.3.4. Approach for Effective DR Programs in Japan

In this subsection, challenges of DR programs for small size consumers such as SMEs and residential customers, which are main targeted segments in Japan, are clarified and countermeasures to solve them are considered. It is assumed that these consumers can join only to "Price Menu Based Program".

(1) Reasons of Limited Penetration of DR programs for Small Size Consumers

While DR programs in the U.S. for wholesale market and industry and commercial customers have been progressed, DR programs for residential customers are still small scale as mentioned in 4.3.2(1). As the one of the reasons, it is pointed that access methods for DR programs has not been implemented widely, thus it is difficult for consumers to join these programs even if they want to join [4-14]. These access methods include various price menus, and smart meter and related devices installation for realizing these menus. Recently deployments of smart meters have increased and field trials and commercial DR programs have been conducted all over the world. On the other hand, DR programs for small size consumers such as SMEs and residential customers have some difficulties to generate benefits in essentials. Customer's benefits by reducing power consumption are small because each customer's power demand is small and it is difficult to provide enough incentives to customers from such small benefits. In addition, it is possible for large size business power consumers to manage their electric power by dedicated group if benefits would be larger than the cost and lost by inconvenience of demand cut or shift, but it would be almost impossible for small size consumers to manage their electric power all day.

(2) Conditions for Penetration Increase of DR programs for Small Size Consumers

In this research, an approach for the expansion of DR programs for small size consumers is proposed by considering an enlargement method of incentives of those programs. In the consideration, the following assumptions are defined.

- Electricity meters which can measure consumption data by defined time slots have been installed.
- Measures for joining the program (such as Consumer-side EMS or In-Home Display) which provides information of electricity price and incentive of DR programs have been installed in each customer.

- Methods for replying customer's intension to join the program have been prepared in each customer.

Considering DR expansion preventive matters showed in 4.3.4(1), the followings can be set as the conditions for the expansion of DR programs for small size consumers.

- Existence of an organization which aggregates each customer's reduced demand and negotiate with market and/or power companies. (DR aggregator)
- Customer configurable automatic control of electric appliances in building or home, or remote control of these appliances in emergency based on a contract. (for efficient building and home appliance management)

In addition to them, the adoption of conditions described in 4.3.3(3) should be necessary for the success of DR programs for small consumers by power companies.

(3) Approach for DR program Effectiveness Improvement

Finally, a new approach is considered for the enlargement of benefit for both consumers and program providers.

In 4.3.3(3), it is described that DR programs can provide benefits in the market which supply capacity is not too much for the required demand, and electric power can be procured from the market with higher price if necessary. Although it depends on markets whether such conditions would be satisfied, it is true that supply capacity of renewable energy is shortened compared with demand in most countries, regions or markets. It means the condition would be satisfied for surplus demand for renewable energy. In this case, someone who wants to use renewable energy for a certain time slot might buy the renewable energy even if the price of that was expensive compared with lower price electric power commodities. Therefore, the following conditions should be satisfied for electric power commodities E_0, E_1,..., E_n if the DR program would be provided.

$$PE_0 < PE_1,\ PE_2, \ldots,\ PE_n \quad (n \in N\,(n \geq 1)) \tag{4-26}$$

$$C_0 < D < C_0 + \sum_{i=1}^{n} C_i \quad (n \in N\,(n \geq 1)) \tag{4-27}$$

where,

PE_0 : Retail price for the lowest renewable energy E_0

PE_n : Retail Price for renewable energy E_n

P_0E_0 : Procurement Price for the lowest renewable energy E_0

P_0E_n : Procurement Price for renewable energy E_n

C_0 : Amount of E_0

C_n : Amount of E_n ($n \in N\ (n \geq 1)$)

D: Customer demand for renewable energy

Therefore, maximum incentive I_{max} would be,

$$I_{max} = B(C_0) - B(\sum_{i=0}^{n} C_i) \tag{4-28}$$

where, $B(C)$: Benefit of program provider

$$B(C_0) = C_0(PE_0 - P_0E_0) \tag{4-29}$$

$$B(\sum_{i=0}^{n} C_i) = \sum_{i=0}^{n} C_i(PE_i - P_0E_i)) \tag{4-30}$$

By the recent raising of environmental awareness, residential power consumers might select power commodities by not only financial benefit aspect but also their preferences such as environment-friendliness etc. In addition, environmental regulations and taxes might make business power consumers use higher price renewable energy for their business profitability. Therefore, they might select not lower priced oil or carbon originated power but higher price renewable energy and DR would be applied to renewable energy demand reduction.

Also, this kind of DR profitable case might be applicable for PPSs which are new entrants of new electric power market in Japan. Currently, total power generation capacity of PPSs compared with that of historical electric power companies is very small and thus sometimes they cannot sell their electric power even if their potential customers want to contract with them. In this case, required conditions of profitable DR programs can be satisfied. Combination of RES and DR might be one of effective electricity service menus to realize both customers' and service provider's benefits.

4.3.5. Information Communication to Promote DR Programs for Small Size Consumers

Generally "Emergency Program" would be provided with a high necessity for demand reduction in case of power supply shortage, and incentives of these programs would tend to be large. Therefore, this kind of programs should be also provided for small size consumers for incentive enlargement. In order to provide these programs to small size consumers, it is necessary to exchange data between customers and the market, and thus data exchange infrastructure would be necessary. In addition, because market emergency programs require quick response for demand reduction requirement by the market compared with "Economic Program", data exchange frequency would be high such as every 15 minutes etc., considering the U.S. market cases.

Considering exchanging data through the infrastructure, major incentives which promote DR for small size consumers should include price reduction and environment-friendliness. Therefore, it is necessary to provide related information of these two major aspects. Generally the diversification of electricity price menus would be complex and it would be difficult for customers to evaluate the optimal price menu. Customer's interests are in whether they can obtain their expected values and it would be essential to provide obtained value information.

Table 4-2 shows information and its infrastructure which promote DR programs for small size consumers.

Table 4-2 Information and its Infrastructure Promoting DR Programs for Small Size Consumers

Required infrastructure	
AMI: Advanced Metering Infrastructure	・ Smart Meter, Communication network between service provider and consumer. ・ For participating to Emergency Program, frequent information exchange such as every 15 minutes is required.
Display Terminal	・ PC, Smart Phone, In-Home Display etc., for information provision from service provider and for consumer's response to service provider's offers.
Required Information	
Price Related Information	・ Accumulated incentive amount ・ Forecast information of future obtaining incentive amount etc.
Environment related information	・ Accumulated contribution amount by CO_2 emission reduction ・ Accumulated contribution to forestation ・ Forecast information of future contribution amount etc.

4.4. Summary

In this chapter, EMS and DR which are two typical measures for optimal power consumption were considered to explore future effective power utilization in consumers.

With respect to EMS, this study proposed an approach to evaluate the impact of energy reduction on the enterprise productivity, which has not been considered enough, in order to clarify the real effect of consumer-side EMS, whereas many researches for energy reduction effect by EMS have been studied. As the result, it was clarified that EMS should be used for waste energy reduction mainly and energy management activities should not impact on enterprise productivity and profitability. In addition it is important for electric power consumers to understand that excess energy saving results in revenue or productivity reduction. Generally the impact on energy cost by energy reduction is much smaller than that of profit of the enterprise, so balanced energy utilization considering both environmental and business sustainability issues is essential. Also, this research showed that it was important to find optimal environment, and consumer-side EMS and the proposed method can be contribute to decide optimal settings for electricity utilizing equipment. As the future work, RES should be added to this evaluation approach. Although optimal power consumption from the aspect of enterprises' productivity might require larger electric power compared with optimal energy amount from the aspect of CO_2 emission, RES, which is environmental friendly but expensive, can be a solution for such the trade-off problem.

Also, DR was considered as a solution for the optimal power utilization method in this study. DR is also one of expected technologies for the future efficient energy utilization and the effectiveness expansion of DR programs is one of the big challenges in the world. In order to expand DR implementation effects, it is necessary to obtain benefits continuously for program participants. Therefore, this research focused on the benefit of DR programs. Through the reorganization of DR programs and clarification of incentive generating mechanisms, this paper described that it was difficult to obtain enough effects in Japan only applying existing DR programs in the world and various arrangements for the targeted market and combination of adequate DR programs were required. In the consideration, some DR promotion points, especially for small size consumers were considered showing incentive provision models and it showed that renewable energy had possibilities to promote DR programs for these consumers. Moreover, because most of renewable energy generations such as PV and wind power have problem of fluctuating output, new DR programs might be required for power supply reliability and stability.

Although this paper focuses on benefits for suppliers in major DR program types and does not prescribe influences of regulation, subsidies and customer behavior related information, regulation and subsidies affect incentive definition mechanisms and consideration of customer behaviors for DR programs should help program providers to ensure their profitability. Through these researches, we would like to contribute to realize future advanced EMS which can control consumers' demand and promote installation of renewable energy generations.

Chapter References

[4-1] "Energy Conservation Policies of Japan," Agency of Natural Resources and Energy Conservation and Renewable Energy Department, November 2011

[4-2] H. C. Tung, K. F. Tsang, L. L. Lai, K. L. Lam, and H. Y. Tung, "Hybrid energy management solution for smart building," IEEE International Conference on Consumer Electronics (ICCE) 2011, pp.509-510, January 2011

[4-3] H. Xuan, M. Y . Mizutani, "Efficient Multiple Gateway System for WSN Management in BEMS," Ninth International Conference on Networked Sensing Systems (INSS) 2012, pp.1-2, 2012.

[4-4] Z. Peng, S. Suryanarayanan and M.G. Simoes, "An Energy Management System for Building Structures Using a Multi-Agent Decision-Making Control Methodology" IEEE Transactions on Industry Applications, vol49, no.1, pp.322-330, February 2013

[4-5] K. Park, Y. Kim, S. Kim, K. Kim, W. Lee and H. Park, "Building Energy Management System based on Smart Grid," IEEE 33rd International Telecommunications Energy Conference (INTELEC) 2011, pp.1-4, October 2011

[4-6] "ADVANCED ENERGY NOW 2014 MARKET REPORT - Global and U.S. Markets by Revenue 2011-2013 and Key Trends in Advanced Energy Growth," Navigant Research, February 2014 [Online] Available at http://puc.hawaii.gov/wp-content/uploads/2014/02/AEN-2014-Market-Report.pdf

[4-7] "Guideline for the application of Fiscal Year 2011 Energy Management System Installation Promotion Subsidy (平成23年度エネルギー管理システム導入促進事業費補助金（BEMS）交付申請の手引き)," Sustainable open Innovation and Initiative, September 2013 (in Japanese)

[4-8] "Energy Management System Installation Promotion Subsidy (BEMS) Appeal points, BEMS Installation Application Status, Installation Target and Estimation (エネルギー管理システム導入促進補助金 (BEMS) 事業者からのアピール・BEMS導入申請状況、目標値、見込み値)," Sustainable open Innovation and Initiative, February 2014 (in Japanese)

[4-9] “2010 White Paper on Small and Medium Enterprises in Japan, Ministry of Economy,” Trade and Industry and Japan Small Business Research Institute, September 2010

[4-10] “Survey of Action on Energy and Environmental Issues (平成 21 年度エネルギー環境問題への中小企業の対応に関する調査),” Mitsubisi Research Institute, commissioned by SME Agency, November 2009 (in Japanese)

[4-11] M. H. Aladi, E. F. El-Saadany, “Demand Response in Electricity Markets: An Overview,” IEEE Power Engineering Society General Meeting, pp.1-5, June 2007

[4-12] N. Yamaguchi, T. Imanaka and H. Asano, “Current Status and Issues of Demand Response Program in US (米国における需要反応プログラムの実態と課題),” Y05028, CRIEPI Report, May 2006 (in Japanese)

[4-13] M. Takahashi, H. Asano and N. Yamaguchi, “An Analysis of Potential Demand Shaving in Japanese Commercial Building Sector by Demand Responsive Strategies and Technologies (業務部門のデマンドレスポンスによる需要調整の技術的ポテンシャルの評価) ,” Y08034, CRIEPI Report, May 2009 (in Japanese)

[4-14] T. Hattori and N. Toda, “Demand Response Programs for Residential Customers in the United States – Evaluation of the Pilot Programs and the Issues in Practice (米国における家庭用デマンドレスポンス・プログラムの現状と展望 ー パイロットプログラムの評価と本格導入における課題 ー),” Y10005, CRIEPI Report, March 2011 (in Japanese)

[4-15] K. Schisler. T. Sick and K. Brief, “The Role of Demand Response in Ancillary Services Markets,” Transmission and Distribution Conference and Exposition 2008, pp.1-3, April 2008

[4-16] “FERC: ‘Assessment of Demand Response and Advanced Metering’,” Staff Report 2011, February 2011

[4-17] “FERC: ‘Assessment of Demand Response and Advanced Metering’,” Staff Report 2012, December 2012

Chapter 5 Optimal Supply and Demand Collaboration for Power Service Provision

In this chapter, technologies and measures for optimal power supply and demand which were discussed in chapter two are considered as one of critical components of Smart Grid with profitable business models. Although it might look that technologies and measures discussed in this chapter are benefits for network operators, power system networks in Smart Grid are common infrastructure and benefits in the infrastructure should be pay-back to network user, such as competitive power companies (Generation and Retail), electricity service providers including power producer and supplier (PPS), and power consumers.

5.1. Expectations for Collaborative Operation between Supply and Demand sides

In chapter two, “optimal power supply and demand” is one of critical categories which realize Smart Grid and some key technical research topics were also defined. As mentioned in chapter three and chapter four, it is expected that various demand-side new technologies should be implemented for the realization of future effective power systems. In Smart Grid realization, solutions by collaborative operation between supply and demand sides would be expected in addition to solutions by individual technologies improvement.

(1) Information Fully Utilized Distribution Systems Stabilization Support

It is expected that large number of renewable energy source (RES) generations such as photovoltaic (PV) systems would be connected into distribution systems and this might cause some problems such as voltage sag and rise, which influence distribution system stability. Although existing distribution automation systems and bulk installation of batteries are discussed for these problems generally, such measures require large scale investment. Therefore the utilization of Information communication technology (ICT) should increase for distribution system stabilization and reduce the investment for expensive hardware installation. Assuming advanced metering infrastructure (AMI) would be completely installed in the near future, it should be possible to recognize real-time distribution system status such as voltage and current etc. These distribution system status data can be used for the detection of asset failure symptoms and real-time fault detection etc. In addition, it would be possible to forecast power supply amount including dispersed generation (DG) capacity and demand in the target area accurately, and optimal schedule for distribution assets based on the forecast can be developed.

(2) Development of Optimal Operation Schedule and Autonomous Update Utilizing Real-time Measured Data

Optimal operation would be possible if real-time collection data from AMI etc., can be utilized for real-time schedule updating for each asset. Although it is necessary to develop more advanced technologies in various ICT areas such as sensors, networks, data collection and storage systems, and data processing systems, ultimate goal of Smart Grid should realize such optimal and autonomous power systems.

5.2. Collaborative Operation for Low Carbon Society in Japan

As mentioned in chapter three, the installation of a large number of RES is a big challenge in Japan and recent Smart Grid and Smart City demonstration projects promote such RES expansion activities. The core effort of RES expansion in Japan is mainly residential PV system installation and total expected amount of PV capacity would be 28MW in 2020 which is 20 times of the capacity in 2005 [5-1]. Therefore, many PV systems would be installed into low-voltage distribution systems and it is concerned that such many PV systems installed environment causes unreliability of power supply systems.

While such PV system installation has been promoted, Japanese power companies have facilitated the installation of AMI for remote metering penetration and some leading power companies have plans that all their smart meters installation will have been completed around 10 years [5-2].

From these two movements in Japan, this research proposes a new distribution system stabilization measure by utilization of smart meter information considering many PV systems installed environment. The measure consists of two major functions. The first is voltage monitoring function for distribution systems which would become more difficult to manage, and the second is a simulation function for confirming the status change of distribution systems by different values of substation bus voltage and disconnection of some PV systems when it is expected that voltages of some demand points would be deviate from appropriate value scope.

5.2.1. Characteristics of Japanese Distribution Systems and Their Challenges

Firstly, characteristics of distribution systems in Japan and its expected challenges in the near future are described.

a. Outline of Distribution Systems in Japan

Typical Japanese distribution systems operate with radial topological structure, and are composed of 6.6(kV) high-voltage (HV) line and 200/100(V) low-voltage (LV) line. Figure 5-1 shows outline of a typical distribution system in Japan.

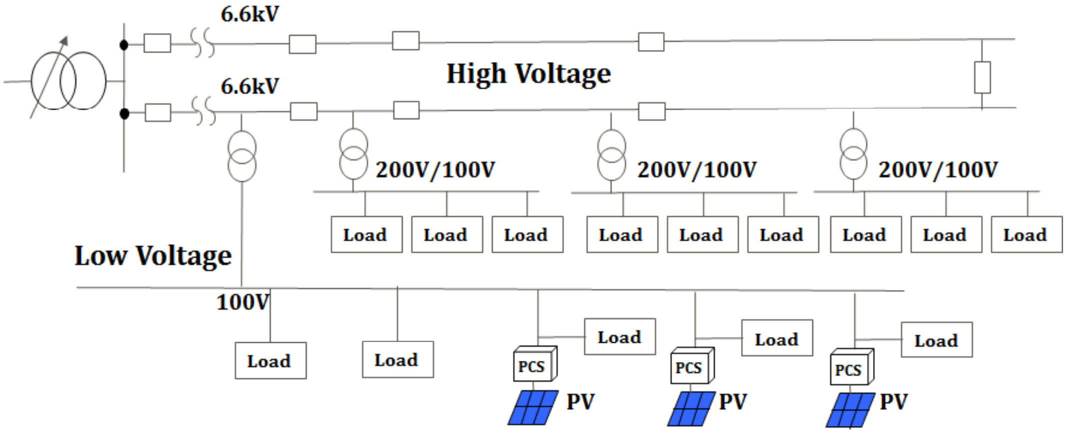


Figure 5-1 Typical Distribution System in Japan

b. Challenges in Japanese Distribution Systems

The electric voltage used in Japanese distribution system is defined as 101 ± 6(V) for the standard voltage 100(V) and as 202 ± 20(V) for the standard voltage 200(V) in the Electricity Business Act in Japan. Power companies control the voltage of their supplying power within the defined scope by considering voltage drop width from the power supply start point. At present, the voltage drop width calculation assumes one way power flow from a distribution substation to supply areas and is executed for high and low voltage distribution systems respectively.

However, more than a certain amounts of power injection into a distribution system from PVs cause reverse power flow and voltage rise, and sometime these lead to voltage violations in some parts of the system. Although some voltage regulators have been implemented in distribution systems, it is raised that the possibility of their malfunction in many PV systems installed areas because they assume one-way power flow. Therefore it is necessary to manage and control this voltage change problem in the near future distribution systems, however it looks there is no effective support tools at present.

5.2.2. Voltage Issues in Distribution Systems and Their Previous Studies

A great deal of effort has been made on the study for PV system installations and their impact on distribution systems. Reference [5-3] used a large PV to evaluate some impact issues of distribution systems, focus on loading scenarios and voltages with a PV plant model. Reference [5-4] studied a method that determines the maximum amount of PV generation capacity that could be connected in a distribution feeder. For the optimal allocation problem, a loss sensitivity factor method was used for DG and PV systems in [5-5]. Since the dynamic phenomenon is becoming an important issue in distribution systems, dynamic impacts of plug-in electric vehicles (PEVs) and PV systems with energy storage device was studied in [5-6]. In addition, various voltage issues in distribution systems by the installation of distribution resources were introduced in [5-7]. Distribution assets which mitigate the voltage issues were described in [5-8], and [5-9] utilized demand response (DR) as the measure which mitigated such voltage issues.

While many studies related to technologies solving individual issues of PV systems installed environment have been reported, it is necessary to study holistic voltage status recognition measures and support tools to find optimal setting for the target distribution system under the many PV systems installed environment and it should come to the front as for the future considering actual distribution systems operation. Therefore, real-time monitoring and simulation for voltage and current status in distribution systems should be essential in order to realize future optimal distribution system operation. In addition, a new user interface which supports rapid understanding of complex and large information in one view should be necessary.

5.2.3. Approach to Solve the Challenges in Future Distribution Systems

In this subsection, requirements to solve voltage issues mentioned in above are described and a new distribution system management method which realizes these requirements is considered.

(1) Consideration of New Management Method for the Stability of Distribution Systems

In order to control the voltage distribution of an area within a defined scope, reinforcement of distribution system assets and the sending end voltage control in substations (substation bus voltage control) have been implemented. However, voltage fluctuation due to many PV installations should be large in short term compared with general voltage rise or sag issues, and thus some different regulating measures should be required. Therefore this study considers a new voltage management method for future distribution systems to solve such issues, and three major characteristic functions of the method are described below.

a. Data Collection by Smart Meters

As mentioned in above, many electrical meters are expected to replace with smart meters in Japan. Therefore, this study considers utilization of smart meter data. By the collections (and calculations) of smart meter data in a target area, all voltage values for power demand points in the area can be recognized. It means that operators can find voltage issues occurrence by checking collected data in the target area.

b. Execution of Power Flow Calculation

By the power flow calculation using power voltage and current data collected by smart meters and other attribute data, it is possible to calculate power voltage and current for upper nodes of smart meters in distribution systems. In addition, reverse power flow occurrence status becomes apparent because power flow direction can be recognized by the power flow calculation.

c. Execution of Voltage Distribution Simulation

The purpose of this study is to provide a support tool for stable and sustainable power supply in many PV systems installed areas. Therefore if some issues were caused or expected to occur in such areas, countermeasures should be provided. The first possible measure for regulating voltage should be a substation bus voltage control. This should be effective if the impact of substation bus voltage change on a distribution line voltage status could be understood preliminary. Another possible measure might be disconnection of PV systems which are operated in the voltage issues occurrence part to prevent a large scale outage occurrence. These two simulation functions should be effective support tools which mitigate voltage issues in many PV systems installed areas.

(2) Major Required Support Functions for the Stability of Distribution Systems

From detailed considerations, three major functions are described below as essential functions to support distribution system stability in the near future many PV installed environment.

a. Base Function

By the utilization of the latest status data in a target distribution system which are collected by smart meters frequently, power voltage and current status in the area can be managed, and also power voltage and current status data for any nodes in the distribution system can be calculated using power flow calculation. Therefore, data collection and power flow calculation functions should be the base functions.

b. Voltage Status Visualization Function

By plotting voltage status data from power flow calculation on the map, it is possible to understand the voltage distribution in the distribution system rapidly. Also, by the evaluation of power flow direction, it is easy to recognize the occurrence of reverse power flow. Therefore, power status visualization function, which is collected and calculated data integration with geographic information system (GIS) should be provided.

c. Voltage Status Simulation Function

In order to forecast the status of a distribution system in the near future, the impact of parameters' change on the voltage status need to be simulated. For example, power supply amount and substation bus voltage control simulations should be executed considering the near future generation amount by many PV systems in a target area.

(3) Distribution System Management Method to Realize Required Functions

As for the future, dynamic power flow calculation for distribution systems should be becoming increasingly important as an effective measure for real-time distribution system voltage management. However, it was found that there are various challenges in order to realize the real-time voltage management due to huge and frequent measured data generation, and changed distribution assets settings. Therefore, the necessity of power supply route management and the proposed countermeasure are described below.

a. Necessity of Power Supply Route Management for Distribution Systems

Generally distribution systems in Japan adopt multiple lines and connections structure. Therefore, there might be multiple routes from substation to a certain demand point, but actually power supply route would be unique by switch on/off settings in a system. So, electrical structure of the distribution system in Japan would be radial structure. Because these power supply routes are changed as needed by some switch settings, an actual power supply route recognition mechanism is necessary to conduct power flow calculation. However it is difficult to recognize real-time electrical connections among these assets generally. Therefore this study proposes a new distribution system management approach which manages both asset connections as material objects and their electrical connections in an integrated fashion.

b. Basic Concept of the New Distribution Systems Management Approach

As the new approach of the distribution systems management, three management concepts composed of “Equipment Management”, “Location Management” and “Power System (Grid) Management” and their integration are proposed and features of these concepts are described below.

- Equipment management: manages individual asset as material objects. In the concept, distribution assets are categorized into “individual asset” such as electrical poles etc., and “span asset” such as power line cable etc., and they are managed with attribute data.
- Location Management: manages location of each asset in rectangular coordinates without consideration of physical and electrical connections.
- Power System Management: manages electrical connection of managed assets using connection point (Node) and branched asset (Branch). In the concept, power line cables and switches are managed as “Branch” and their connection points are managed as “Nodes”. Although each management concept and its related management systems already have been introduced into many power companies, generally each management system is used for its specified purpose and not related each other efficiently. In the proposed approach, these three concepts have relations each other by linkage data showed in Table 5-1.

Table 5-1 Linkage Data between Three Concepts in the Proposed Approach

	Equipment Management	Location Management	Power System Management
Equipment Management	-	Asset Location	Electrified Asset
Location Management	Asset Location	-	Location of Electrical Connection
Power System Management	Electrified Asset	Location of Electrical Connection	-

By the integration of data for these three concepts, actual power supply routes can be calculated considering both distribution systems' topology and each distribution asset settings. Figure 5-2 illustrates the creation method of actual distribution system model using the proposed approach.

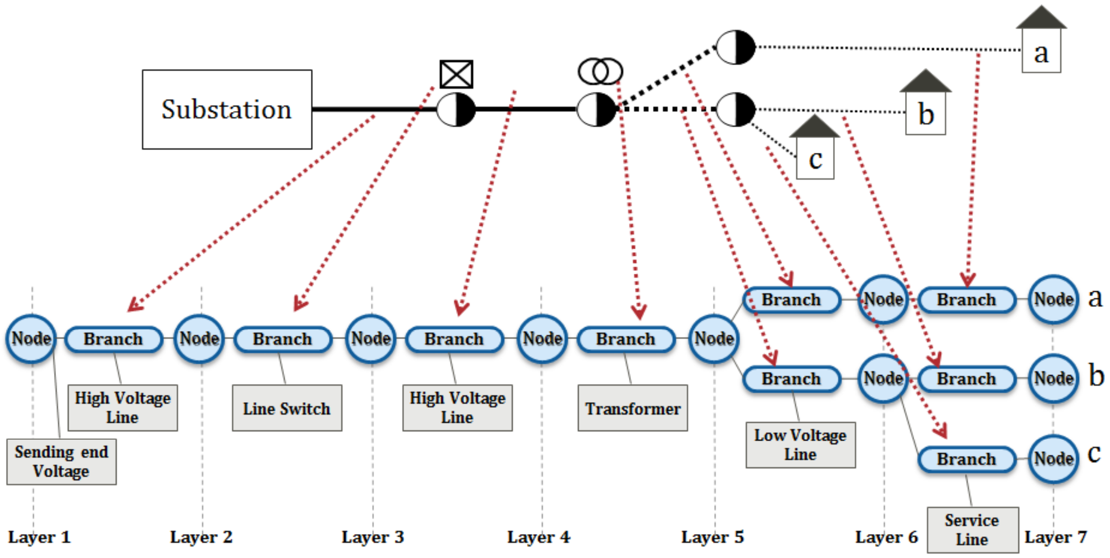


Figure 5-2 Distribution System Model Using the Proposed Approach

c. Active System Structure Creation Procedure

It should be necessary to create real-time power supply route for advanced distribution system management. Figure 5-3 shows the procedure to decide real-time power supply route, and the route will be called as "active route" and the distributions system composed with "active routes" is called "active system" in this study.

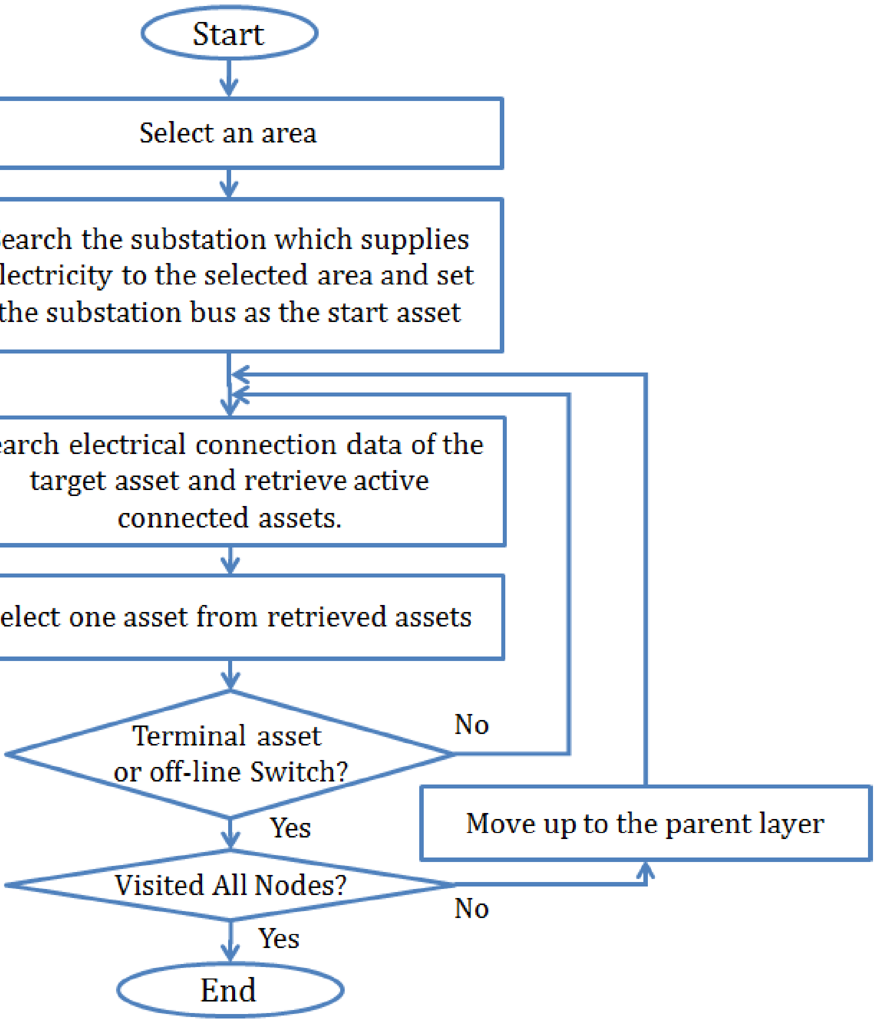


Figure 5-3 Active Route Structure Search Procedure

5.2.4. Consideration of Implementing Functions for Distribution Systems Voltage Management through Prototype System Development

For the evaluation of the proposed voltage management and distribution systems management approach, a prototype system has been developed considering actual implementation for power companies or system operators. Figure 5-4 shows the functional structure of the prototype system and details of each function is described below.

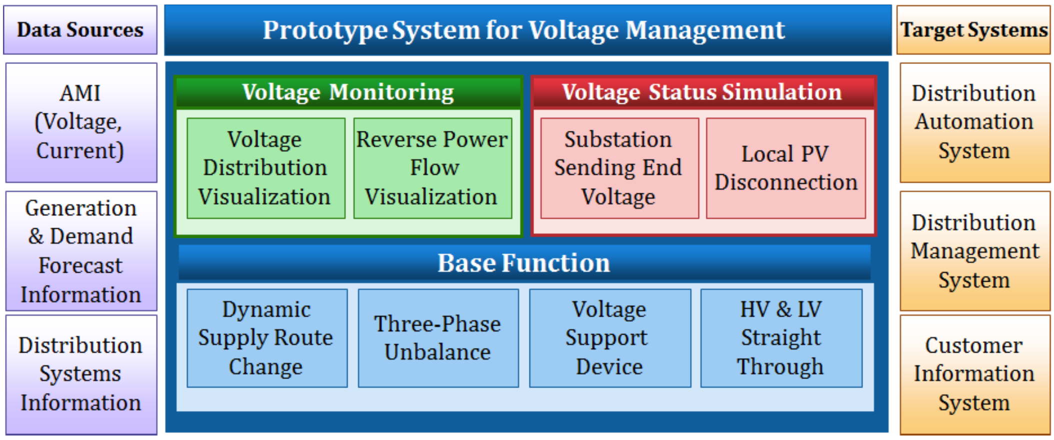


Figure 5-4 Functional Structure of the Prototype System

(1) Base Function

In order to make operators recognize voltage status of the target distribution area using smart meter data, meter data management and power flow calculation are two core key elements of this function. The followings are major requirements and their countermeasures as the base function considering actual implementation.

a. Dynamic Changing Power Supply Route

By the adoption of the new distribution systems management approach described in 5.2.3(3), it is possible to create “active system” which has active power supply routes, and thus almost real-time distribution system status can be recognized by power flow calculation using the latest data from smart meters with “active system”.

b. Three-Phase Unbalance

In actual high voltage distribution systems, three-phase distribution systems are adopted. In case that many PV systems are installed into a low voltage distribution system, it is pointed that many installations of single phase devices such as PV into low-voltage distribution line increase three-phase unbalance in high voltage distribution line and that makes the distribution voltage management difficult [5-10]. Therefore, the prototype system needs to be able to analyze three-phase unbalanced distribution systems.

c. Various Voltage Regulation Devices

Real-time voltage controls for distribution systems should be collaborative operation of information utilized control mechanisms and voltage support devices. Therefore, the power flow calculation in the prototype can be used for the distribution system model with major voltage regulation hardware devices such as various types of transformers, step voltage regulators (SVRs) and DGs.

d. Straight through Power Flow Calculation from High Voltage Distribution system to Low Voltage Distribution System

In order to regulate voltages in complex future low voltage distribution systems, a straight through power flow calculation from a substation to demand points should be required. Using the new distribution system management approach and support of many distribution assets and devices in the active routes and system calculation, power supply routes from substation to power supply points can be created, and then the straight through power flow calculation should be possible by the consideration of transformers connecting high voltage line and low voltage line.

e. High Speed Power Flow Calculation

In addition to above mentioned requirements, high speed data processing is required for the dynamic power flow calculation to manage huge and frequent data from a large number of smart meters.

Table 5-2 Summary of Power Flow Calculation Speed Test

Node Number	File Load Time (msec)	Initial Parameter Setting(msec)	Power Flow Calculation Time(msec)	Data Output Time(msec)	Total Processing Time(msec)
669	16	0	15	16	47
6,532	203	15	16	31	265

In the prototype, the backward and forward (B/F) method was adopted for the power flow calculation as same as chapter three and data are efficiently stored using the proposed distribution system management method. The summary of the power flow calculation speed test results are showed in the Table 5-2. Computer specifications used for the simulation were Intel Core™2 Duo CPU (Central Processing Unit) E7400 2.80(GHz) with 2.96(GB) memory and 32-bit operating system. Although computation time for the power flow calculation was focused in the test and the results are reasonable for actual distribution systems, the result shows sum of file load and data output (I/O) time is larger than the power flow calculation time. Therefore, it was found that parameter setting and I/O time reduction were also necessary considering actual implementation. Also, the "active system" calculation time should be considered although the calculation might execute in parallel with power flow calculation.

(2) Voltage Monitoring Function

In order to solve various issues due to many PV system installations, a method to recognize voltage status in distribution systems rapidly would be essential. However voltage distribution in future distribution systems should be complex and it is not enough for the rapid voltage status recognition to provide only voltage and current information.

In the prototype system, voltage and current value at each node was calculated by the power flow calculation using the latest data from smart meters, and the result would be plotted on distribution assets in the map. With respect to data display, not only displaying calculated values on the map but also using various indication methods such as color variations and visual icons etc., were implemented to realize rapid recognition of complex voltage distribution and power flow direction. For example, voltage values calculated by the power flow calculation were plotted with icons representing poles and customers on the map, and colors of these icons would be different based on voltage levels.

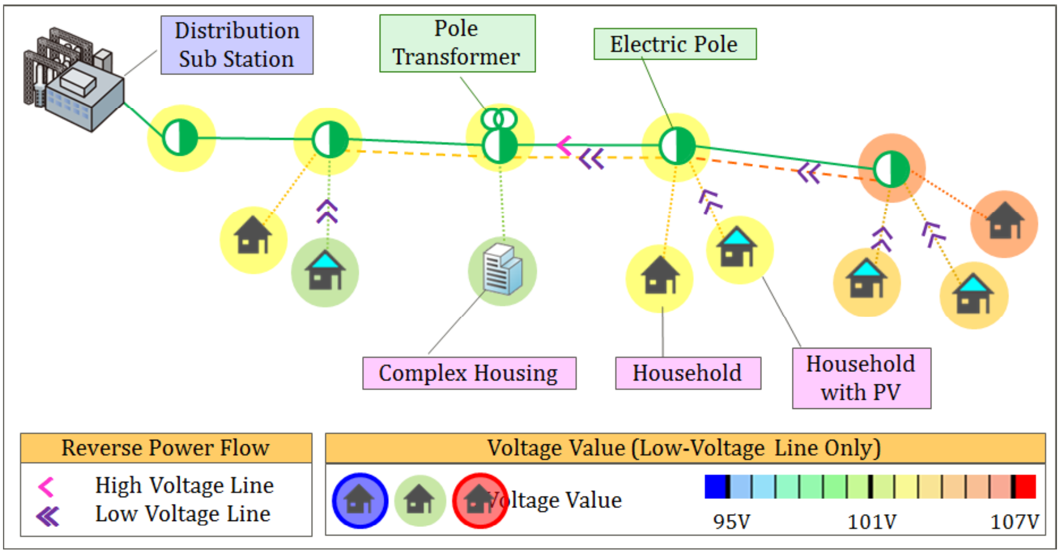


Figure 5-5 Visualized Comprehension Method of Voltages in Distribution Systems.

Figure 5-5 shows an example of voltage deviation status in a distribution system and it is easy to find that supplied power voltage in right hand side customers in the figure approaches to limit value.

Figure 5-6 shows a sample voltage distribution in a distribution line which is another visualization method of the function. With this visualization method, operators can recognize real-time voltage distribution status in a certain distribution line rapidly and status transition over time.

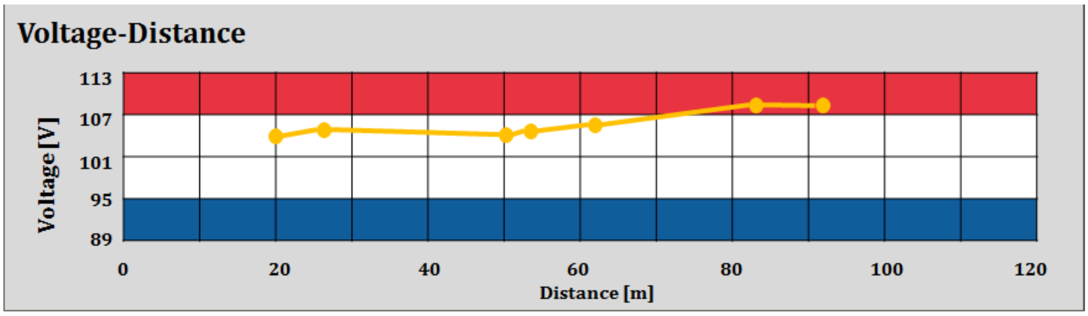


Figure 5-6 Voltage Distribution in a Distribution Line

(3) Voltage Status Simulation Function

In the future complex voltage management in distribution systems, adjustment works would be necessary if voltage values in some areas would approach to the limit of the defined scope in order to prevent voltage violations. However it is very difficult to decide voltage adjusting level because amount of electricity generation and demand in areas vary from second to second.

In the prototype system, some simulation functions were implemented to support above mentioned voltage issues. Total demand and generation amounts for each time slot in a distribution area can be calculated using demand and generation forecast functions, which are provided by other systems, and then voltage scope of substation bus for the area would be simulated so that all nodes' voltages in the lower systems of the substation would be satisfied with the regulated voltage scope for each time slot. In addition, the simulation function for PV disconnection was implemented in order to prevent a large area outage due to voltage violations as the ultimate measure in the prototype system.

Figure 5-7 shows an image of substation bus voltage transition in the prototype system. Red colored time band shows voltage violation occurrence in the simulation, and operator can simulate substation bus voltage so as not to occur any voltage violation.

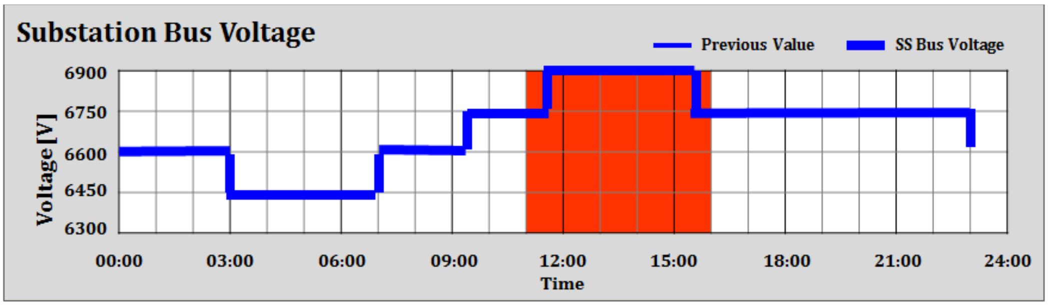


Figure 5-7 Comprehension of the Voltages Violation Time Slots and Substation Bus Voltage Control Simulation

5.2.5. Assumed Business Cases Using the Proposed Distribution Systems Voltage Management

At the end of this section, assumed business cases using the prototype system are described. Figure 5-8 shows simulation execution images of the prototype system and includes 3 stages of simulation for voltage management in a distribution system.

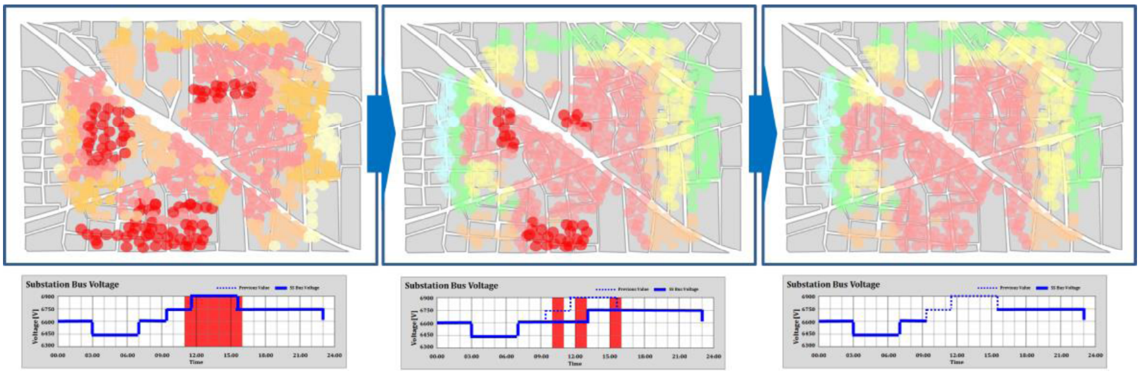


Figure 5-8 Simulation Images of the Prototype System

(1) Forecasting Expected Voltage Violation Area

The left hand side diagrams of Figure 5-8 show a screenshot for expected voltage distribution in a high density PV installed area one day and the bus voltage transition of the substation which supply power for the area. Larger amount of PV generations compared with PV owner's power demand would be generated and excess amount of power would be injected into the distribution network. In such case, power voltage of many load points in the distribution system should increase. Therefore, simulation results of the prototype system should show voltage violation areas and time slots, and monitoring operators can find and recognize that some part of the network shows higher voltage than limit value (106(V)).

(2) Control of the Distribution System by Adjusting the Substation Bus Voltage

Because supplied power voltage for each node would be higher as a whole, the substation bus voltage would be adjusted in order to reduce power voltage totally. The center diagrams of Figure 5-8 show the screenshot and the substation bus voltage transition of the prototype system after the substation bus voltage adjustment. In most areas, power voltage would become within the regulated scope. However, there are still a few areas which have “RED” colored icons.

(3) Disconnection of PV systems

As the final measure, the PV disconnection function was provided in this prototype system. PV disconnection means not only PV system disconnection physically from the distribution system, but also power injection suspension temporally. Because the least number of PV systems should be disconnected, the PV disconnection function need to disconnect PV systems individually. The right hand side diagrams of Figure 5-8 show the screenshot and the substation bus voltage transition of the prototype system after some PV systems disconnection. In all areas, power voltage would become within regulated scope.

5.3. Outage Management System and Metering Data Utilization

As the second measure for optimal supply and demand, outage management which is one of expected area to improve by Smart Grid realization is discussed in this section.

Power companies use various control and information systems such as supervisory control and data acquisition (SCADA) and distribution automation (DA) for distribution systems control and distribution management system (DMS) and outage management systems (OMS) for effective information provision for efficient distribution systems management including prevention of power outage and rapid power restoration in case of outages etc. In this research, the utilization of metering data for OMS is focused as the consideration of information utilization for outage management and an approach of outage location prediction utilizing smart metering data is proposed and its practicability is discussed.

5.3.1. Definition of Outage Management and Procedures

OMS is specified for rapid outage prediction and restoration and [5-11] defines outage management as follows.

> "*A system of computer-based tools and utility procedures to efficiently & effectively -*
>
> - *become aware of,*
> - *diagnose & locate, a*
> - *provide feedback to affected customers*
> - *dispatch trouble/repair crews,*
> - *restore*
> - *maintain historical records of*
> - *compute statistical indices on*
>
> *electrical outages*"

Figure 5-9 shows procedures of outage management using OMS with AMI data introduced in 0 and it illustrates major tasks from an outage occurrence to its restoration.

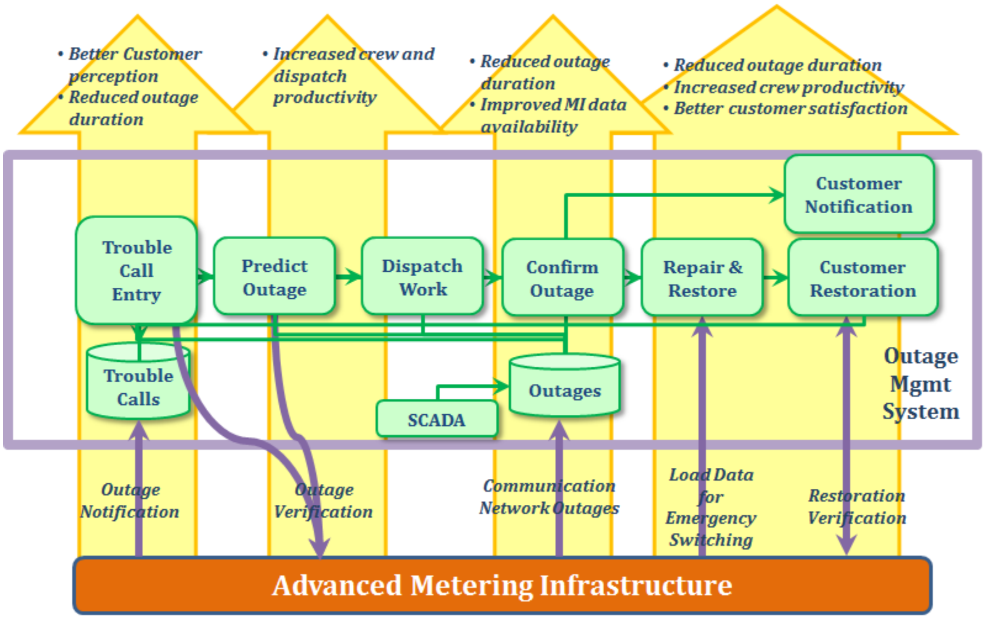


Figure 5-9 Procedures for Outage Management 0

5.3.2. Utilization of Metering Data for Outage Management

With the recent smart meter installation, the movement using meter data has appeared.

(1) Previous Studies for Outage Management Utilizing Metering Data

Some studies which utilize data from automated meter reading (AMR) and AMI for outage management have been conducted in addition to existing SCADA data utilization. In [5-13], outage location was predicted by no responses for the polling operation with the communication network using power line communication (PLC). In [5-14], data filters based on probabilistic and fuzzy theory were developed because of low data quality in AMR, and OMS with high quality data was provided. In addition, 0 describes the effectiveness of “Last Gasp” message which includes outage occurrence information and is sent from smart meters in case of outage, and the paper said that it was possible for power companies to predict outage location by the utilization of last gasp messages without enough outage notification from customers. Also, many studies proposed “alive monitoring” function, which confirmed devices’ on-off status by pinging operations, and most of studies utilizing meter data were related to outage detection or outage location prediction. This research also considers rapid outage location prediction by the utilization of metering data.

(2) Outage Prediction Approach Using Metering Data

There are major two approaches to predict outage occurrence utilizing meter data. The first approach is last gasp messages utilization 0, [5-15]. Generally, the last gasp messages would be sent from smart meters using electricity stored in smart meters. While this approach can send outage occurrence information rapidly and accurately, it requires a last gasp message generating mechanism in each meter. Because it means cost up for smart meters, it is necessary to compare the cost for the outage occurrence consequence with the last gasp messages generation mechanism for all meters.

As the second approach, data collection fault information might be used to predict outage occurrence because metering data collection (transfer) cannot be executed if electric power would not be supplied to smart meters due to an outage. However, data collection fault is not directly linked to outage occurrences because data transfer faults would also occur in failures of network devices and communication errors etc. Therefore, other additional information such as data collection status of neighbor meters and status information of shared communication devices such as data concentrators or gateways should be required to predict outage occurrences using metering data.

This research discusses the possibility of the second approach as one of additional metering data utilization methods considering cost effectiveness of AMI and Smart Grid.

5.3.3. Consideration of New Approaches for Outage Management Utilizing Metering Data

In this subsection, basic ideas and approaches for supporting outage management tasks for power companies are described.

(1) Basic Idea of Utilization of Metering Data for Outage Management

When a smart meter could not transfer its metering data due to a communication error or single service outage, its neighbor meters should be able to transfer their metering data. However, all these meters cannot transfer their metering data in case that an outage would occur in these meters located area. Because metering data collection would be conducted frequently, data collection status monitoring for smart meters in a target area might support to judge whether a single meter disconnection or an area outage occurrence.

(2) Major Challenges of Metering Data Utilization

The followings are major challenges and their solutions of metering data utilization for outage management.

a. Judgment on Whether Outage Occurs or Not

When a data collection fault would be detected, it should be necessary to judge whether it is due to an outage or other reasons such as communication errors etc. The followings are confirmation measures.

- **Neighbor Meters**

In case that a data collection fault was due to an outage, data collection from meters located on downstream of the failure point should be all failed. Therefore, neighbor meters which use common devices with the faulted meter should be checked for recent data collection status.

- **Communication Devices**

Generally, metering data would be transferred to center systems via data collection devices such as concentrators or gateways in AMI. For the reliable communication in AMI, major communication devices and networks should be monitored regularly by some management systems and errors would be logged. By using such information, only high priority fault information can be selected.

- **Other Communication Information**

For one data collection, many data exchanges between communication devices are conducted frequently in communication network, and major records are logged including errors. Therefore, some error detections in communication level might be faster than the data collection fault of power consumption and these might be used for outage occurrence judgment. In addition, network routing information can be used for outage prediction. For example, wireless communication such as radio-frequency mesh or 3G, 4G (the third and fourth generation) mobile phone network are major communication technologies for AMI, and network status are changed and sometimes network route would be changed in case that some network devices would be failed.

b. Rapid Outage Location Prediction:

At present, the standard metering interval using smart meters in Japan is 30 minutes. Therefore, metering data collection fault would be detected 30 minutes later from an outage occurrence at the latest, and 30 minutes should be too long as outage detection time. However, each metering data collection (transfer) does not need to meet its metering timing but should be distributed in the aspect of data traffic leveling. For example, in the area where 30 smart meters are located and all these meters are connected to the same distribution system, one minute interval metering data collection would be optimal considering data traffic leveling in the system. If an outage would occur in this area, one data collection fault meter would increase every one minute. Therefore, it is necessary to consider how to collect metering data and how to display collection fault meters in order to support rapid detection and prediction of the outage occurrence.

(3) Required Functions

From the above discussion, major required functions to utilize metering data for outage management are described as follows.

a. Metering Data Collection Status Monitoring

Firstly, it should be necessary to monitor the status of regularly collected (transferred) metering data. Using several collection fault data, outage occurrence and location might be predicted.

b. Alive Monitoring Mechanism

When a smart meter could not transfer its metering data, it should be necessary to check whether neighbor meters could transfer their metering data or not. Therefore, it is necessary to conduct communication tests for the data collection fault meter and its neighbor meters, and thus “alive monitoring” function such as “pinging” which is used for the network connection test would be required.

c. Communication Error Monitoring:

To understand the reason of a data collection fault, it should be effective to use communication error information for smart meters and other communication devices such as concentrators or gateways etc.

5.3.4. Simulations for Effective Outage Management Utilizing Metering Data

In this subsection, required information for simulations including distribution system model, presumptions, outage scenarios and visualization approach are discussed for effective outage management utilizing metering data.

(1) Distribution System Model Creation

Figure 5-10 shows the radial distribution system model created to conduct simulations.

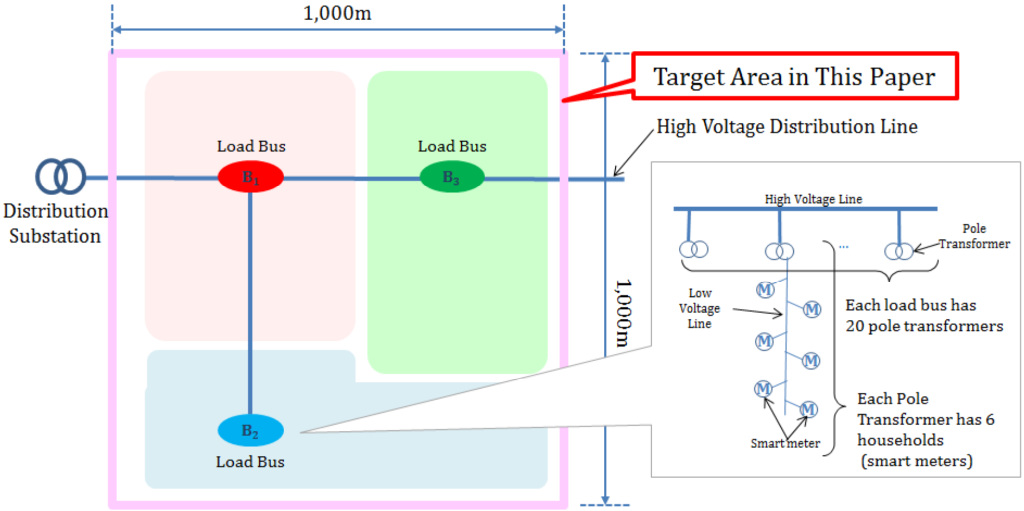


Figure 5-10 Distribution System Model

The double circles icon in the left hand side means a distribution substation and HV distribution line starts from the substation to customer areas. The HV line has three load buses and each load bus has pole transformers which supply electric power for households. The number of connected pole transformers to each load bus and households to each pole transformers were defined referring to the distribution system model for residence in [5-16]. Topologies for cabling from a pole transformer to each household are not defined in this research because more frequent metering data collection should be required in order to recognize this level of failures. Parameters for the model are showed in Table 5-3.

Table 5-3 Parameters for the Distribution System Model

Item	Value	Description
Area	1 km^2	1km × 1km
Population	900	Population Density: 900/km^2
Households	360	Average people per household: 2.5/household
Pole Transformers	60	Households per Transformer: 6

(2) Overview of Simulations and Data Preparation

Assuming that smart meters were fully installed in the area, how data collection fault information would be recognized was simulated. In the simulation, a center system conducts metering operations regularly for virtual smart meters defined in the system model, and data collection faults would be detected if meters had fault flag in their data. Each meter has its location and connected pole transformer information, and each pole transformer has its connected load bus information. In addition, the following assumptions were defined for the metering simulations.

- Metering interval in each meter: 30 minutes
- Data collection (transfer) method from each meter:

  Data collections (transfers) from meters are distributed with multiple metering groups in consideration of data traffic leveling.
    - The number of metering group: 60 (Data collection interval: 30 seconds)
    - Metering group for each meter defined randomly
- All data collection (transfer) faults in the simulation are due to outage occurrences. (Faults due to communication errors do not consider in this simulation.)

Table 5-4 shows the part of meter property data.[4]

Table 5-4 Partial Meter Property Data

Meter Number	Metering Group	Location		Connected Pole Trans.	Connected Load Bus
		x coord.	*y* coord.		
1	12	10	10	1	B_1
2	20	10	15	1	B_1
3	25	10	20	5	B_1
4	10	10	25	5	B_1
5	38	10	30	9	B_1
6	6	10	35	9	B_1
7	13	10	40	13	B_1
8	42	10	45	13	B_1
9	31	10	50	17	B_1
10	11	10	55	17	B_1
11	60	10	60	41	B_3
12	29	10	65	41	B_3
13	1	10	70	45	B_3
14	26	10	75	45	B_3
15	18	10	80	49	B_3
16	46	10	85	49	B_3
17	54	10	90	53	B_3
18	50	10	95	53	B_3
19	11	10	100	57	B_3
20	7	10	105	57	B_3

---

[4] Complete data are provided in Appendices D

(3) Outage Patterns

The followings are outage occurrence patterns discussed in this research in consideration of failure locations.

a. Failures in Low Voltage Distribution Line, Service Line and Consumer-side

Because network structures from pole transformers to consumers are not considered in this system model, detailed failure location predictions using topology information for these areas are not conducted. However, about 70 – 75(%) of trouble calls are single service outages, and over a third of them are customer problems 0, therefore the cause confirmation method for single service outage need to be considered.

b. Failures from Load Buses to Pole Transformers

In this pattern, data collection fault would occur only for smart meters connected to a certain pole transformer. Through simulations, it should be discussed how this type of outage would be recognized by metering fault information.

c. Failures in HV Distribution Line

In failures at HV distribution line, data collection from all smart meters which are located on downstream of the failure point would be failed.

(4) Proposed Visualization Approach

In order to support the prediction of outage occurrence locations, some visualization approaches are proposed.

a. Visualized Icons for Smart Meters, Pole Transformers and Load Buses

Figure 5-11 shows icons for distribution assets and devices used to visualize the status of them on the distribution system model.

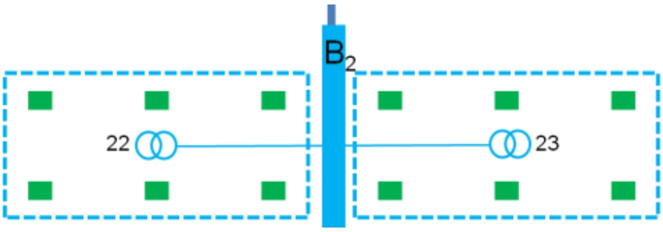
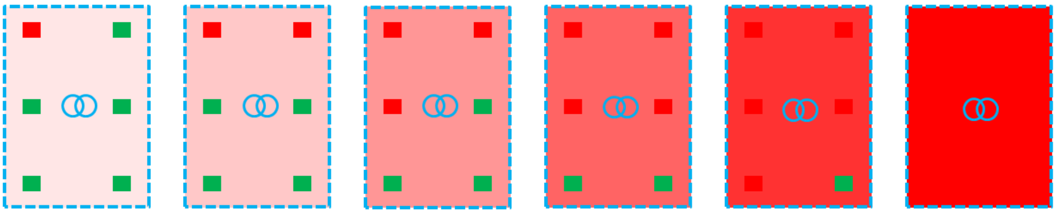


Figure 5-11 Smart Meters, Pole Transformers and Load Buses

Small green boxes show smart meters and double circles show pole transformers. Smart meters in a same color and line type box are connected to the same pole transformer located in the center of the box. In order to identify data collection fault meters, the color for the smart meter icons would be changed from green to red. Wide lines on HV distribution line mean load buses and each line has the bus name and the same color as connected pole transformers.

b. Visualization of Data Collection Status

If data collections for multiple meters connected to a same pole transformer would be failed, the probability of outage occurrence in the area under the transformer would increase corresponding to the number of data collection fault meters. Therefore, if the number of data collection fault meters connected to the same transformer could be showed on the area map visually, high probability areas of outage occurrence should be apparent and the service level for customer's outage call should be improved.



Collection Fault = 1 Collection Fault = 2 Collection Fault = 3 Collection Fault = 4 Collection Fault = 5 Collection Fault = 6

Figure 5-12 Visualization Method of Data Collection Status for Smart Meters Connected to the Same Transformer

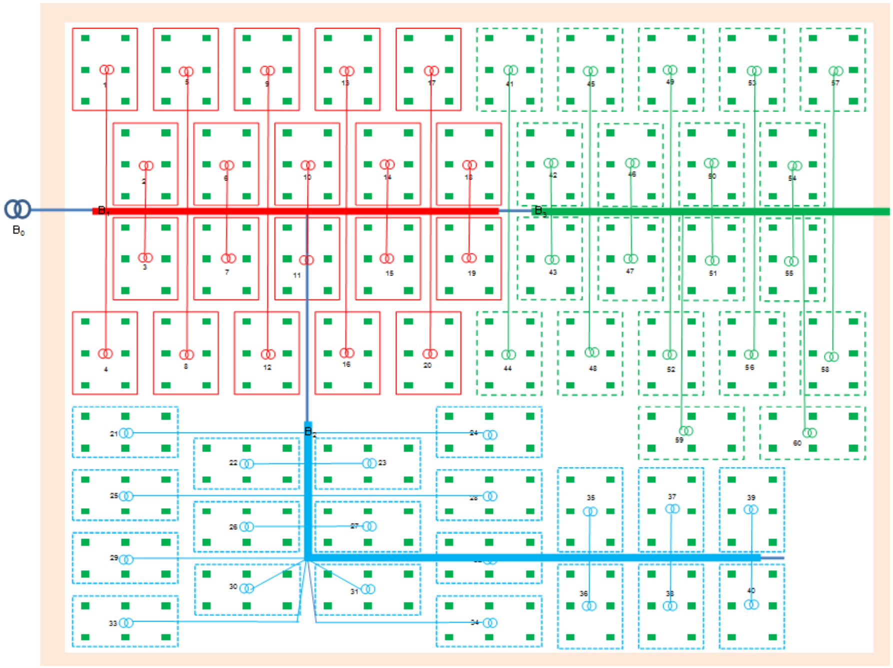


Figure 5-13 Visualized Distribution System Model

Figure 5-12 shows a visualization image of data collection status for smart meters grouping by each same connected transformer. The color of the box also would be changed from white to red corresponding to the number of data collection fault meters. With this visualization approach, an outage under a pole transformer should be recognized easily and the accuracy of outage prediction might increase. The distribution system model using these icons is showed in Figure 5-13.

5.3.5. Simulation of Visualization Support Approaches and Discussions

In this subsection, some basic and detailed simulations would be conducted for defined outage occurrence patterns and proposed visualization approaches are evaluated to support outage occurrence predictions.

(1) Outage Location Prediction Using Metering Data Collection Fault Information

Here, visualization images of using the proposed approach are described for outage patterns defined in 5.3.4(3).

a. Failures in Service Line and Consumer-side

If single service outage would occur, data collections after the outage would be failed and the icon of the data collection fault smart meter changed to red as showed in Figure 5-12. In case of customer problems, data collection should be successful and the "alive monitoring" function might be used for the judgment on whether outage occurs or not in the actual operation.

b. Failures from Load Buses to Pole Transformers

Outage occurrences due to failures from load buses to pole transformers are considered. In order to confirm how metering data collection faults are recognized in case that pole transformers would be in failure, the number of data collections detecting data collection faults would be counted through metering simulations. Because each pole transformer has 6 smart meters in the distribution system model, 6 data collection faults for smart meters connected to the failure pole transformer should be detected if all metering data collections would be conducted.

Table 5-5 shows the number of data collections for 1 to 6 data collection fault smart meters. From the simulation result, the 1st metering data collection fault would be detected with the 9 data collections (4.5 minutes later from the outage occurrence) on average.

Table 5-5 Basic Simulation Data

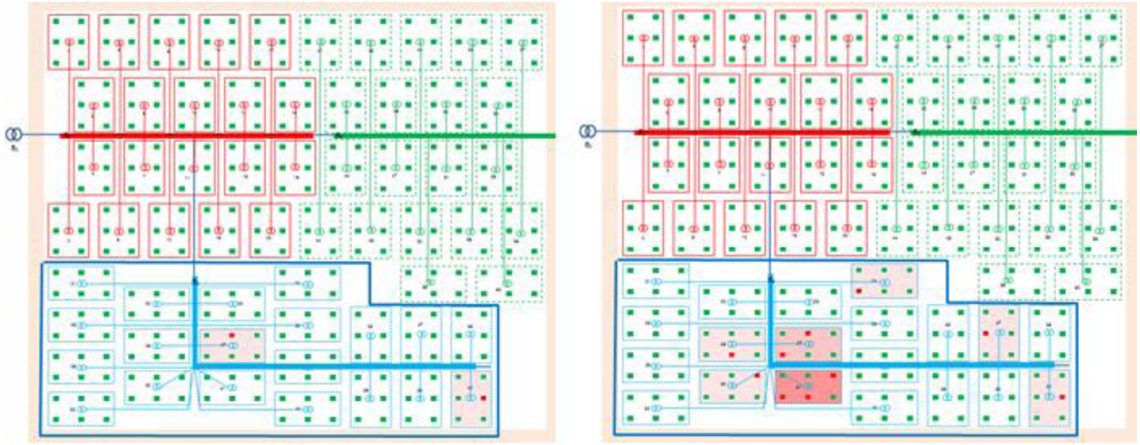
No. of data collection fault meters	No. of Min. data collection	No. of Max. data collection	No. of Ave. data collection
1	1	35	9.0
2	3	40	18.5
3	6	48	25.7
4	13	53	32.7
5	20	58	42.2
6	24	60	50.2

The probability of outage occurrence would increase, if several data collections would be failed, and the number of minimum, maximum and average data collection for the detection of several data collection faults are 3, 40 and 18.5 respectively. This means that an outage should be detected 1.5 ~ 20 (average 10) minutes later from the outage occurrence and it should be an issue that it might take 20 minutes to detect the outage. Therefore, this approach should not be a method for the first outage detection however it should be an effective method for the status confirmation when a customer would notify an outage occurrence, because data collection for meters which connected to the same pole transformer for the customer's meter should be failed if a failure in transformer level or higher would occur. In addition, because the color of the box in which smart meters are connected to the failed pole transformer would be changed to red corresponding to the number of data collection fault meters, operators can easily find the high probability of outage occurrence area by the monitoring of the box color transition.

c. Failure on HV Distribution Line

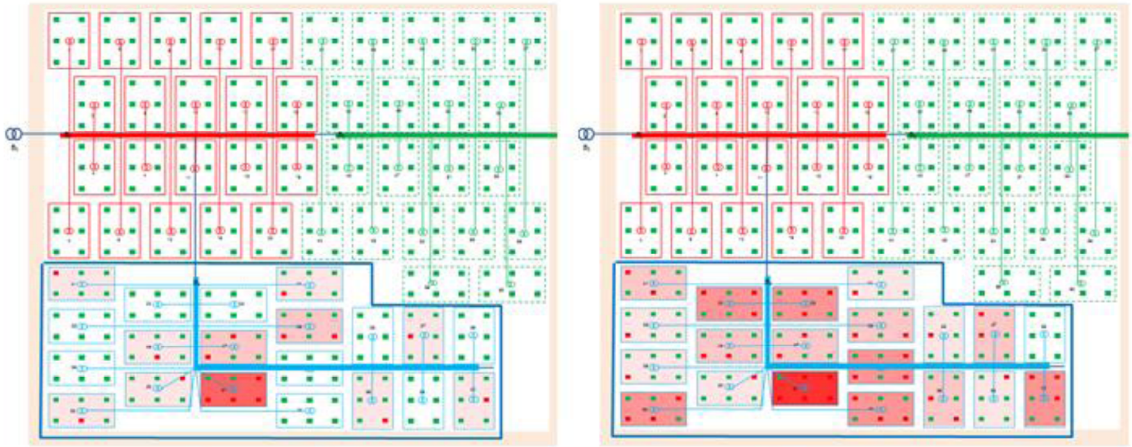
The failures on HV distribution line would be simulated and how outage would be recognized over time would be discussed. Figure 5-14 shows data collection status transition in an outage for the distribution system model at 1, 3, 5 and 10 minutes later from the outage occurrence and the area covered by the blue colored line shows outage occurrence. 1 minute later from the outage occurrence, data collections for 2 smart meters were failed. In this stage, a power company's operator can recognize the possibility of outage occurrence in the area for load bus B_2. 3 minutes later, the operator can recognize that data collections for all smart meters in the area for load bus B_2 were failed and for other smart meters were completed normally. If there is no communication error in this area, the operator can judge that outage in the area for load bus B_2 must occur.

Using metering data, area outages can be predicted in a few minutes later from the outage occurrence only with every 30 minutes metering data, if data collection (transfer) interval would be reduced considering data traffic leveling. The approach was established only with data visualization ideas. All data should be collected with normal metering works and no additional data such as "last gasp" would be required.



1 minute later

3 minutes later



5 minutes later

10 minutes later

Figure 5-14 Data Collection Status Transition in an Outage

(2) Utilization of Data Collection Success Information

In addition to metering data collection fault information, utilization of data collection success data is discussed.

a. Outline of This Method

In an area outage, data collection for all meters located in the area should be all failed. Therefore, if data collection for one meter in an outage assumed area would be successful, assumed outage would not occur. Using this information, it is possible to focus outage range with "alive monitoring" to other smart meters in case that data collection for a certain smart meter would be failed. In the system model, data collection failure for one meter has several possibilities of failure events and these events have conditions in metering data collection described in Table 5-6.

Table 5-6 Possibilities of Outage Range for One Metering Data Collection Fault

Failure Point	Conditions in Data Collection		Example for the Measuring in the system model*
	Collection Fault (Outage)	Collection Success (No Outage)	
Smart Meter, Service Line	Collection fault smart meter	Other 5 smart meters connected to the same pole transformer of the collection fault smart meter	Fault： Smart meter 3 (M3) Success: M4, M23-24, M43-44
Pole Transformer Low Voltage Line	6 Smart meters connected to the same pole transformer.	Smart meters connected to all pole transformers except for the transformer connecting to the data collection fault smart meter.	Fault: M3-4, M23-24, M43-44 Success: All meters except for above.
High Voltage line	All smart meters connected to pole transformers on the failure segment	All smart meters connected to pole transformers on HV distribution lines except for the failure segment.	Success: M229-234, M241-252, M259-360 (B_2 connected meters) Fault: All meters except for above. (B_1 and B_3 connected meters)

*It is assumed that data collection fault in smart meter 3. In the system model, Smart meter 3,4,23,24,43 and 44 are connected to transformer 5 connecting to B_1

In case that data collection for smart meter 3 (M3) would be failed, it is possible to judge whether it is M3 single service outage or an area outage under the pole transformer by alive monitoring executions for other 5 smart meters connected to the same transformer of M3 (M4, M23-24, M43-44). If there is no response from these 5 smart meters, it should be necessary to assume a larger size outage occurrence. In case that single transformer trouble would occur, the "alive monitoring" information for smart meters connected to other pole transformers would be effective. Because data collection for some other smart meters should be conducted at the same time of the data collection for M3, it is possible to confirm "alive monitoring" information for other meters without additional actions. If data collection for other smart meters connected to a pole transformer on the same load bus of M3 was successful, it should be specified that the pole transformer connecting to M3 or same layer problem would occur. On the other hand, all meter data collection would be failed, assumed outage range would be enlarged. Figure

5-15 shows procedures for outage prediction and it is possible to track outage range as this way. Although data traffic including alert messages, recovery requests and their data would increase in outages, this approach mostly use metering data and does not send data packets to communication network except for the first “alive monitoring”.

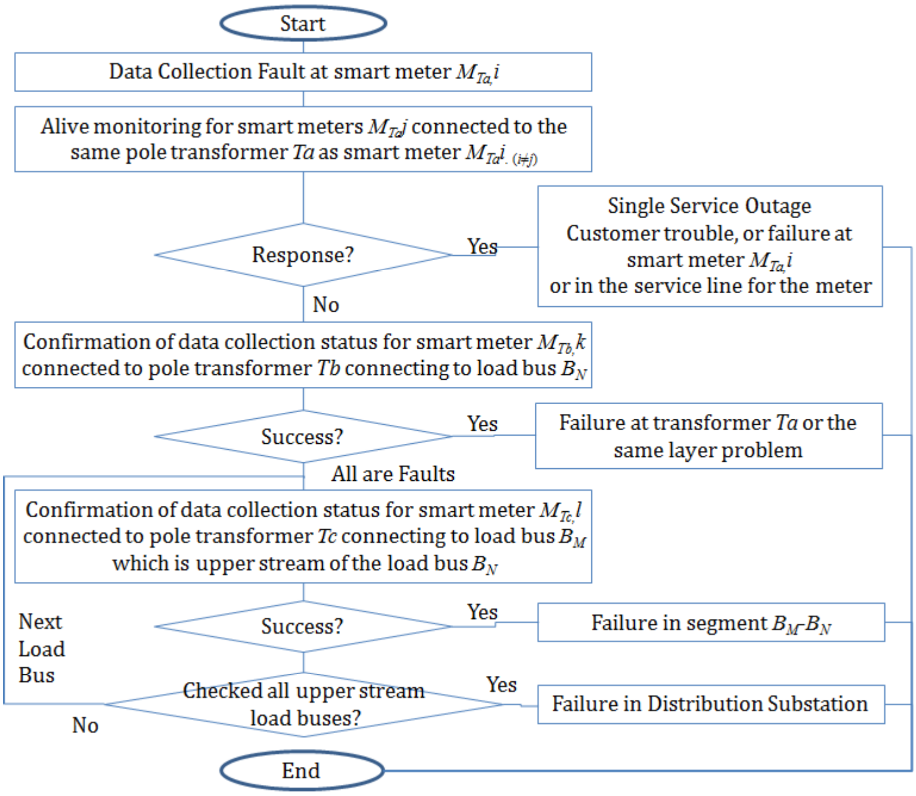


Figure 5-15 Procedures for Outage Prediction

b. Challenges and Effectiveness

As challenges of this approach, it is possible that necessary data for outage prediction might not be collected by previous data collections. In the previous case, when data collections for 5 other smart meters connected to the same transformer of smart meter 5 would be failed, operator should look for the data collection status for smart meters connected to other 19 pole transformers. However no data collection might be conducted to these smart meters. In this system model, it is the case that the number of candidate meters is 19 × 6 = 114 and data collection for these candidate smart meters were not conducted in the same metering timing as smart meter 5. Because it is assumed that data collection timing would be leveled and there are 60 groups in this research, at least one smart meter which is in the same data collection group as smart meter 5 would exist. However, it is realistic that all smart meters might not be leveled completely considering meter installation and removal corresponding to customer contracts. Therefore, multiple times of data collection status data should be utilized for data collection certainty.

Failure occurrence on more upper layer, candidate smart meters which can be utilized for the confirmation of outage prediction would increase than previous case. Therefore, in the system model, outage range should be predicted by the utilization of 30 second later data from a data collection fault. However, the major challenge of this approach should be the time from outage occurrence to data collection fault. With every 30 minutes metering, it might take 30 minutes for single outage occurrence recognition. Also, it takes 5 minutes on average and around 20 minutes at a maximum to recognize an outage under a pole transformer.

It is difficult to solve the problem for initial recognition because it depends on the metering interval in each smart meter, however this approach should be effective to reduce time to recover from the first customer call because such customer call would be one of data collection fault information.

5.4. Summary

In this chapter, the distribution system monitoring measure and the rapid outage area predicting measure were proposed as technologies and measures for optimal power supply and demand and various simulation results were discussed to evaluate these measures.

With respect to the distribution system monitoring measure, this research proposed a new method of distribution system stabilization considering the voltage change problem by many PV systems installation utilizing measured data from smart meters, and some validation works were executed considering future implementations to actual distribution systems through the development of the prototype system. By the validation works, core functions for the future voltage change problem were confirmed and also some important future challenges were clarified. As a technological aspect of information systems, data preparation and I/O time reduction should be focused, in addition to considering speed-up techniques of calculation algorithms such as power flow calculation and active system models calculation. Also as consumer service provision aspects, some consumers' inconveniences such as PV disconnection for preventing voltage violation are needed to consider. It should be necessary to consider compensation measures for these consumers and support functions should be implemented. Also as future works, it is necessary to think about some more constraints required for actual implementation including above mentioned challenges. In addition, optimal distribution network configuration, loss reduction by DGs and PVs should be added to this prototype system to support optimal distribution systems operation.

With respect to the measure for the rapid outage area prediction, this research explored the AMI data utilization for outage management and the approach utilizing smart metering data was proposed with some simulation results. The proposed approach might be useful under some outage occurrence conditions and become the one of support methods for effective outage management. In simulations, by the utilization of metering data, area outages can be predicted in a few minutes later from the outage occurrence only with every 30 minutes metering data, if data collection (transfer) interval would be reduced considering data traffic leveling. The approach was established only with data visualization ideas and most data should be collected with normal metering works and no additional data such as “last gasp” would be required. Therefore, new service installation cost should be small compared with other new system development. Since the installation of AMI requires huge time and investment, it is very difficult to recover the investment only with business efficiency improvement from the manual metering to remote metering. Therefore, AMI data utilization for outage management might be one of effective new services if outage risks would be reduced. In order to improve this approach, actual outage prediction activities in smart meter already installed countries should be researched and practicability of the proposed approach should be discussed with the comparison of outage detection time from the first customer call and the famous outage management indexes such as SAIDI (system average interruption duration index) and SAIFI (system average interruption frequency index) etc.

As mentioned in the opening paragraph in this chapter, beneficiaries of these two measures might be network operators in a direct way. However, future challenges in the network operators should reflect to network utilization cost, solutions or mitigation measures for these challenges gain profitability of competitive power companies, PPS, service providers and service consumers.

Chapter References

[5-1] Study Group of Low Carbon Power Supply System, “Toward the Establishment of Low Carbon Power Supply System,” Study Group Report, July 2009 (in Japanese)

[5-2] Energy Environment Council, "Action Plan to Stabilize Energy Supply-Demand,” November 2011 (in Japanese)

[5-3] G. J. Shirek and B. A. Lassiter, “Solar Plant Modeling Impacts on Distribution Systems PV Case Study,” Rural Electric Power Conference, pp.B5-1-10, April 2012

[5-4] R. K. Varma, J. Berge, I. Axente, V. Sharma and K. W , “Determination of maximum PV solar system connectivity in a utility distribution feeder,” IEEE Transmission and Distribution Conference and Exposition (T&D), pp.1–8 , May 2012

[5-5] T. Tayjasanant and V. Hengsritawat, “Comparative Evaluation of DG and PV-DG Capacity Allocation in a Distribution System,” IEEE International Conference on Harmonics and Quality of Power (ICHQP), pp.293–298, June 2012

[5-6] S. Shao, F. Jahanbakhsh, J. R. Aguero and L. Xu, “Integration of PEVs and PV-DG in Power Distribution Systems using Distributed Energy Storage – Dynamic Analyses,” IEEE PES Innovative Smart Grid Technologies (ISGT), pp.1-6, February 2013

[5-7] R. A. W lling, B. Saint, R. Dugan, J. Burke and L. A. Kojovic, “Summary of Distributed Resources Impact on Power Delivery Systems,” IEEE Transactions on Power Delivery, vol.23, no.3, pp.1636–1644, July 2008

[5-8] D. T. Rizy, H. Li, F. Li, Y. Xu, S. Adhikari and P. Irminger, “Volt/Var Control Using Inverter-based Distributed Energy Resources,” IEEE PES General Meeting, pp.1-8, July 2011

[5-9] K. Kawamura, “Applicability of Demand Response to Voltage Control in Distribution System with large integration of PV - Evaluation of Frequencies and Economic Benefit –,” Y12008, CRIEPI Report, March 2013 (in Japanese)

[5-10] S. Uemura, “Influence of Imbalance Interconnection of Large Penetration of Photovoltaic Generation for Residences on Voltage Management in Power Distribution System,” R11026, CRIEPI Report, June 2012 (in Japanese)

[5-11] “Outage Management,” IEEE Smart Distribution Working Group, 2001 [Online] Available at: http://grouper.ieee.org/groups/td/dist/da/doc/omsapp.ppt

[5-12] H. Tram, "Technical and operation considerations in using Smart Metering for outage management," IEEE PES T&D Conference and Exposition 2008, pp.1–3, April 2008

[5-13] K. Honghai and W. Zhengqiu, "Application of AMR Based on Powerline Communication in Outage Management System," Proceedings of International Conference on Sustainable Power Generation and Supply 2009, pp. 1–4, April 2009

[5-14] Y. Liu and N. N. Schulz, "Intelligent System Applications in Distribution Outage Management," IEEE PES Winter Meeting, vol.2, pp.833–837, January 2002

[5-15] R. Kelley and R. D. Pate "Mesh Networks and Outage Management," White Paper, September 2008

[5-16] Y. Kabasawa, T. Noda, K. Fukushima, and K. Nemoto, "Development of a Distributed Static Synchronous Compensator micro-STATCOM (Part 2)," H11030, CRIEPI Report, September 2012 (in Japanese)

Chapter 6 Evaluation Methods of Smart Grid Components Considering Business Profitability

In this chapter, evaluation methods for the installation effect of technologies and measures which were considered from chapter three to chapter five are proposed.

Firstly, value converting methods for periodical amount are considered because periodical quantification is necessary to evaluate business profitability of Smart Grid critical technologies and measures. Then evaluation methods for the effective installation of critical Smart Grid measures are considered.

6.1. Quantification Method for Periodical Benefits of Smart Grid Realization Activities

In this section, value converting methods for periodical amount and equivalent monetary value are proposed because business profitability should be evaluated on periodical basis such as month, quarter, half year and year with same comparable units.

6.1.1. Quantification of Annual Power Loss Reduction Benefit by Demand Reduction

In this subsection, a quantification approach of the effect of critical technology or measure to realize Smart Grid realization for certain periods is considered. As the example, the power loss reduction effects by demand reduction for the simple distribution system model, which was considered in chapter three, for various periods are considered. This approach is necessary for the evaluation of demand reduction effect by dispersed generation (DG) installation and demand response (DR) program execution etc.

(1) Calculation of Power Loss Reduction Effect in a Day

Let active power loss in branch *i* ($i \in M$ $\{1,2,\ldots,m\}$) be $Ploss_i$. Then accumulated power loss of the system for time period *T* would be the following.

$$\int_0^T \sum_{i\in M} Ploss_i dt \tag{6-1}$$

If one hour average power consumption data could be collected hourly, one day total power loss would be calculated by the sum of 24 sets of hourly data for one day. Let active power loss for time slot k (k =1,…24) be $Ploss_{i,k}$ then, one day power loss would be the following.

$$\sum_{k=1}^{24}\sum_{i\in M} Ploss_{i,k} \tag{6-2}$$

This means that it is possible to calculate one day power loss reduction effect with hourly power consumption data, and then one month and one year power loss reduction effect can be calculated based on a similar way. In order to calculate one day power loss using (6-2), it is necessary to prepare hourly 24 power demand results for one hour time slot. Then, power loss reduction for each time slot would be calculated by power flow calculation and the 24 power loss reduction data for one day would be accumulated. Let active power loss with x % demand reduction be $P(x)loss_{i,k}$, then one day power loss reduction effect for x % demand reduction would be the following.

$$\sum_{k=1}^{24}(\sum_{i\in M} Ploss_{i,k} - \sum_{i\in M} P(x)loss_{i,k}) \tag{6-3}$$

Table 6-1 Simulation Result of One Day Power Loss Reduction Effect by Demand Reduction

TIME	Reduced Effect (p.u.) (30% Demand Reduction)	Reduced Effect (p.u.) (50% Demand Reduction)	Reduced Effect (p.u.) (100% Demand Reduction)
0:00	0.0031	0.0046	0.0060
1:00	0.0027	0.0039	0.0052
2:00	0.0024	0.0035	0.0047
3:00	0.0023	0.0034	0.0045
4:00	0.0023	0.0033	0.0044
5:00	0.0023	0.0034	0.0045
6:00	0.0027	0.0039	0.0052
7:00	0.0035	0.0052	0.0068
8:00	0.0049	0.0071	0.0094
9:00	0.0063	0.0092	0.0122
10:00	0.0070	0.0102	0.0134
11:00	0.0074	0.0108	0.0142
12:00	0.0071	0.0104	0.0137
13:00	0.0075	0.0110	0.0145
14:00	0.0076	0.0111	0.0147
15:00	0.0074	0.0108	0.0142
16:00	0.0072	0.0105	0.0139
17:00	0.0066	0.0097	0.0128
18:00	0.0068	0.0099	0.0130
19:00	0.0064	0.0094	0.0124
20:00	0.0058	0.0084	0.0111
21:00	0.0051	0.0075	0.0099
22:00	0.0047	0.0069	0.0091
23:00	0.0040	0.0059	0.0078
Total	**0.1232**	**0.1800**	**0.2377**

Table 6-1 shows power loss for each time slot and total power loss for demand reduction rates 30%, 50% and 100%. Because the unit of calculated power loss reduction effects is p.u. and this calculation was executed with electricity peak demand (Wh) as

-0.1p.u., let peak demand of a target area be D_{peak}(Wh), then data converting parameter C_{rate} would be the following and it can be used for data convert between p.u. and Wh.

$$C_{rate}=D_{peak}/0.1 \tag{6-4}$$

In addition, let electricity unit price for time slot k be R_k(/Wh), then one day power loss reduction effect B_{date} would be the following.

$$B_{date} = \sum_{k=1}^{24} \left(\sum_{i\in M} Ploss_{i,k} - \sum_{i\in M} P(x) loss_{i,k}\right) \times C_{rate} \times R_k \tag{6-5}$$

(2) Calculation of Power Loss Reduction Effects in a Year

Next, monthly and annual power loss reduction effects are considered.

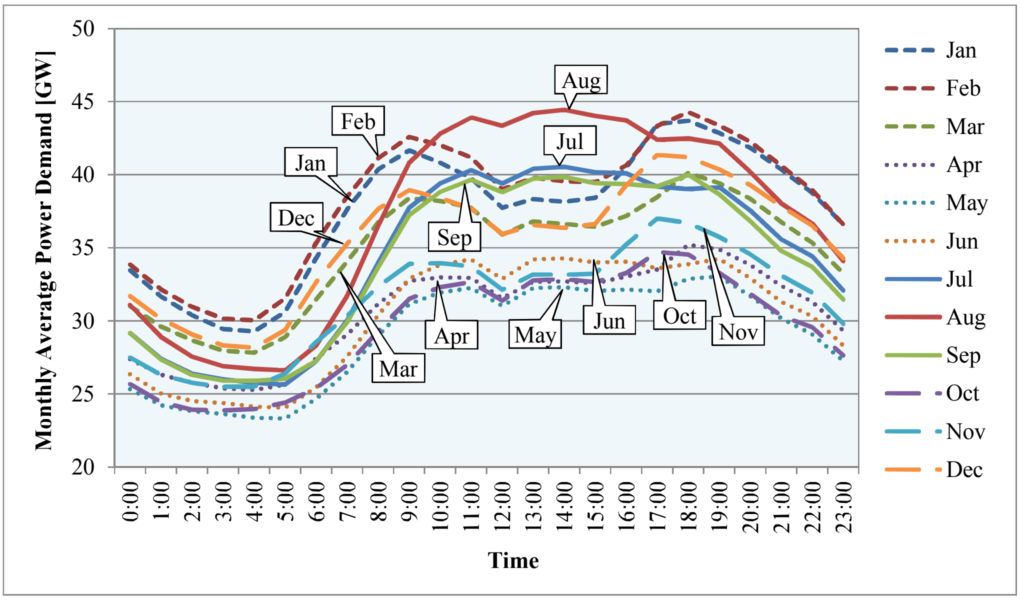


Figure 6-1 Power Demand Curve for Each Month using Data of [6-1]

Figure 6-1 shows average demand curve for each month which was created using data for 2012 at "Past Electricity Demand Data" in Tokyo Electric Power Cooperation [6-1]. Because each month has different characters in quantities and shaping, it should be necessary to consider these patterns of demand curve to calculate monthly power loss effect. Therefore, monthly total demand loss reduction would be calculated using a demand curve pattern of the target month by multiplying the total amount of one day average power loss reduction (Wh basis) by the number of days in the target month. With regard to annual power loss reduction effect, it can be calculated by the sum of monthly power loss for all 12 months in a target year. Therefore, monthly power loss reduction benefit B_{month} ($month$ = 1,2,…,12) and annual power loss reduction benefit B_{year} would be the following equations respectively. In (6-6), *date* is any date in the target month.

$$B_{month} = \sum\nolimits_{d \in date} B_{date} \tag{6-6}$$

$$B_{year} = \sum\nolimits_{month=1}^{12} B_{month} \tag{6-7}$$

Various annual power loss reduction effects were simulated with various setting for demand reductions. As a sample result, Table 6-2 shows the simulation result of power loss reduction effect by 30% and 50% of load reductions.

Table 6-2 Simulation Result of Accumulated Power Loss Reduction Effect by Demand Reduction

Month	Num. of Dates	Loss Reduction Effect Demand Reduction Rate 30%			Loss Reduction Effect Demand Reduction Rate 50%		
		One Day Average (p.u.)	One Month Total (p.u.)	One Month Total (GWh)	One Day Average (p.u.)	One Month Total (p.u.)	One Month Total (GWh)
Jan	31	0.13526	4.19314	1,831.75	0.19752	6.12305	2,674.82
Feb	29	0.13673	3.96525	1,755.64	0.19966	5.79010	2,563.59
Mar	31	0.13788	4.27413	1,715.15	0.20132	6.24100	2,504.43
Apr	30	0.13847	4.15422	1,463.06	0.20220	6.06590	2,136.33
May	31	0.14139	4.38321	1,448.55	0.20643	6.39948	2,114.88
Jun	30	0.14408	4.32226	1,481.58	0.21033	6.30992	2,162.91
Jul	31	0.13419	4.15974	1,686.80	0.19593	6.07370	2,462.92
Aug	31	0.12945	4.01281	1,782.84	0.18902	5.85963	2,603.36
Sep	30	0.13528	4.05829	1,622.69	0.19752	5.92546	2,369.28
Oct	31	0.13325	4.13074	1,433.73	0.19459	6.03214	2,093.68
Nov	30	0.13254	3.97618	1,471.94	0.19356	5.80670	2,149.58
Dec	31	0.13545	4.19906	1,736.26	0.19780	6.13173	2,535.39
Total			**49.82903**	**19,430.00**		**72.75881**	**28,371.19**

(3) Utilization of This Approach to Calculate Power Loss Reduction Effects in Various Situations

The simulation result in 0 is the annual total power loss reduction effect by demand reduction in all consumers uniformly and continuously. This approach can be used for the calculation of power loss reduction effect in various situations by changing its variables and parameters.

By changing the peak demand D_{peak} in (6-4) into the peak demand value for the targeted area, the power loss reduction effect for the targeted area can be calculated. Also, in the area where many Photovoltaic (PV) systems are installed and grid power would be reduced during daytime, power loss reduction effect can be calculated by reducing demand for only a certain time period of a day. In addition, this approach can be used for power loss reduction effect by demand reduction from DR programs which would be only implemented in peak time slots especially in summer or winter seasons, by defining DR implemented timings, period and the number of dates appropriately.

6.1.2. Benefit Quantification of PV Installations

This approach can be used for the calculation of maximum, minimum, average and fluctuation range for the benefit of PV system installation.

(1) PV Capacity and Injected Power at the Slack Bus

Let PV power generation at bus *i* and injected power at the slack bus at time slot of a day s (s=1, 2,…, 24) be $P_{\mathrm{PV}i,s}$ and $P_{\mathrm{SL}\,s}$ respectively, one day total PV power generation $P_{\mathrm{PV}\,date}$ and total injected power at the slack bus $P_{\mathrm{SL}\,date}$ would be the following formulas respectively.

$$P_{\mathrm{PV}\,date} = \sum_{s=1}^{24} \sum\nolimits_{i \in K} P_{\mathrm{PV}\,i,s} \tag{6-8}$$

$$P_{\mathrm{SL}\,date} = \sum_{s=1}^{24} P_{\mathrm{SL}\,s} \tag{6-9}$$

In the same way, monthly total PV power generation capacity $P_{\mathrm{PV}month}$ ($month$ = 1, 2,…, 12), annual power PV generation capacity $P_{\mathrm{PV}year}$, monthly injected power at the slack bus $P_{\mathrm{SL}month}$ ($month$ = 1, 2,…, 12) and annual injected power at the slack bus $P_{\mathrm{SL}year}$ would be the following equations respectively. ($date$: any date in the target month)

$$P_{\mathrm{PV}month} = \sum\nolimits_{d \in date} P_{\mathrm{PV}date} \tag{6-10}$$

$$P_{\mathrm{PV}year} = \sum_{month=1}^{12} P_{\mathrm{PV}month} \tag{6-11}$$

$$P_{\mathrm{SL}\,month} = \sum\nolimits_{d \in date} P_{\mathrm{SL}date} \tag{6-12}$$

$$, \qquad P_{\mathrm{SL}year} = \sum_{month=1}^{12} P_{\mathrm{SL}month} \tag{6-13}$$

If electricity price unit would be defined, the revenue of power selling for a day, month and year etc., can be calculated. Also, electricity purchase cost from power companies can be estimated using amount of injected power at the slack bus.

Table 6-3 shows calculation results for average, minimum and maximum PV capacity by the number of PV systems and by the PV penetration levels for the target year. In the same PV penetration level, capacity per PV system would be larger in accordance with the decreased number of PV systems and the fluctuating range also would be large.

Therefore, total fluctuation range also would be large.

Table 6-3 Summary of PV Capacity Deviation

		Penetration Level 5%		Penetration Level 10%		Penetration Level 15%		Penetration Level 20%	
Number of PVs = 10	Ave	1,554.92		3,110.11		4,664.75		6,219.94	
	Min	1,349.57	-13.21%	2,702.54	-13.10%	4,056.75	-13.03%	5,404.64	-13.11%
	Max	1,757.45	13.02%	3,514.76	13.01%	5,277.80	13.14%	7,031.36	13.05%
Number of PVs = 20	Ave	1,554.91		3,109.90		4,664.97		6,219.98	
	Min	1,404.10	-9.70%	2,812.58	-9.56%	4,216.52	-9.61%	5,620.60	-9.64%
	Max	1,704.27	9.61%	3,411.15	9.69%	5,114.03	9.63%	6,814.32	9.56%
Number of PVs = 30	Ave	1,554.93		3,109.91		4,664.66		6,219.78	
	Min	1,431.55	-7.93%	2,860.53	-8.02%	4,293.90	-7.95%	5,724.57	-7.96%
	Max	1,678.50	7.95%	3,356.73	7.94%	5,034.94	7.94%	6,710.17	7.88%
Number of PVs = 40	Ave	1,554.97		3,109.84		4,664.95		6,219.80	
	Min	1,445.48	-7.04%	2,895.28	-6.90%	4,338.45	-7.00%	5,786.26	-6.97%
	Max	1,662.31	6.90%	3,327.25	6.99%	4,985.97	6.88%	6,656.62	7.02%
Number of PVs =50	Ave	1,554.95		3,109.95		4,664.88		6,219.86	
	Min	1,456.81	-6.31%	2,918.03	-6.17%	4,374.45	-6.23%	5,836.49	-6.16%
	Max	1,651.05	6.18%	3,304.40	6.25%	4,954.21	6.20%	6,604.67	6.19%

Table 6-4 shows calculation results for average, minimum and maximum injected active power at the slack bus by the number of PV systems and by the PV penetration levels for the target year. Average values by the different number of PV systems in the same penetration level shows little difference as same as the PV generation capacity. However, the range between minimum and maximum values for penetration level 0% is larger in accordance with the increased number of PV systems, while the range for other penetration level is smaller in accordance with the increased number of PV systems.

Table 6-4 Summary of Slack Power Deviation

		Penetration Level 0%		Penetration Level 10%		Penetration Level 20%	
Number of PVs = 10	Ave	32,069.77		28,782.51		25,565.82	
	Min	29,899.12	-6.77%	26,520.97	-7.86%	23,072.29	-9.75%
	Max	34,247.82	6.79%	31,078.76	7.98%	28,067.56	9.79%
Number of PVs = 20	Ave	32,070.11		28,788.33		25,569.25	
	Min	29,893.99	-6.79%	26,562.67	-7.73%	23,218.82	-9.19%
	Max	34,254.97	6.81%	31,011.45	7.72%	27,948.71	9.31%
Number of PVs = 30	Ave	32,069.60		28,790.40		25,571.71	
	Min	29,890.69	-6.79%	26,604.74	-7.59%	23,305.56	-8.86%
	Max	34,276.87	6.88%	31,011.90	7.72%	27,865.19	8.97%
Number of PVs = 40	Ave	32,069.82		28,790.38		25,571.09	
	Min	29,890.44	-6.80%	26,600.49	-7.61%	23,311.13	-8.84%
	Max	34,249.65	6.80%	31,001.27	7.68%	27,827.09	8.82%
Number of PVs = 50	Ave	32,069.40		28,796.84		25,578.24	
	Min	29,862.78	-6.88%	26,589.00	-7.67%	23,338.62	-8.76%
	Max	34,258.34	6.83%	30,989.87	7.62%	27,808.86	8.72%

While average values of PV power generation by the different number of PV systems in the same penetration level shows little difference, the range between minimum and maximum values is smaller in accordance with the increased number of PV systems.

(2) Active Power Loss

With respect to power loss, the same approach as PV generation capacity can be applied. Let power loss reduction at time slot of a day s (s=1, 2,…, 24) be $P\mathrm{loss}_s$, one day total power loss $P\mathrm{loss}_{date}$, monthly power loss $P\mathrm{loss}_{month}$ ($month$ = 1, 2,…, 12), and annual power loss $P\mathrm{loss}_{year}$ would be the following equations respectively.

$$P\mathrm{loss}_{date} = \sum_{s=1}^{24} P\mathrm{loss}_{s} \tag{6-14}$$

$$P\mathrm{loss}_{month} = \sum\nolimits_{d \in date} P\mathrm{loss}_{date} \tag{6-15}$$

$$P\mathrm{loss}_{year} = \sum_{month=1}^{12} P\mathrm{loss}_{month} \tag{6-16}$$

The loss reduction effects can be calculated by the accumulated loss reduction multiplied by electricity unit price.

Table 6-5 Summary of Active Power Loss Deviation

		Penetration Level 0%		Penetration Level 10%		Penetration Level 20%	
PV	Ave	1,010.92		833.33		727.16	
Num.	Min	870.88	-13.85%	706.30	-15.24%	613.27	-15.66%
10	Max	1,161.12	14.86%	973.79	16.86%	853.25	17.34%
PV	Ave	1,010.96		839.44		730.08	
Num.	Min	871.27	-13.82%	712.24	-15.15%	617.49	-15.42%
20	Max	1,161.65	14.91%	976.90	16.38%	855.75	17.21%
PV	Ave	1,010.92		841.56		732.40	
Num.	Min	870.31	-13.91%	716.11	-14.91%	620.79	-15.24%
30	Max	1,163.51	15.09%	978.65	16.29%	856.65	16.97%
PV	Ave	1,010.94		841.34		731.99	
Num.	Min	870.85	-13.86%	715.32	-14.98%	619.03	-15.43%
40	Max	1,161.93	14.94%	978.47	16.30%	854.26	16.70%
PV	Ave	1,010.91		847.68		739.12	
Num.	Min	870.25	-13.91%	720.40	-15.01%	626.23	-15.27%
50	Max	1,162.94	15.04%	984.97	16.20%	862.69	16.72%

Table 6-5 shows calculation results for average, minimum and maximum active power loss by the number of PV systems and by the PV penetration levels for the target year. Power loss would be reduced with the increase of PV penetration level. With the same PV penetration level, power loss would be reduced slightly with the increased number of PV systems.

6.2. Optimization Method Focusing on Profitability

As the first method for the evaluation of installation effect for Smart Grid critical technologies and measures, profitability priority approach is provided in this section. As a sample approach, the installation effect of consumer-side energy management systems (EMS), discussed in chapter four, is evaluated considering relation between energy management and business profitability using simulations.

6.2.1. Studies for the Relation between Energy Consumption and Productivity

Some statistic researches have been conducted with regard to relation between work environment and work productivity or performance. The literature relating work performance with temperature was analyzed in [6-2], and it found a general decrement in work performance. Also [6-3] explained the importance and needs of the concept of productivity in building environment, and a conceptual diagram was proposed for the evaluation of the effect of indoor environmental quality on productivity.

6.2.2. Formulation of Earning Structure

In 4.2.6, the formulation of earning structure by the implementation of consumer-side EMS was considered. In the consideration, the profitability change would be considered with 1 unit reduction of power consumption such as 1 (˚C) air-conditioner temperature turn up or 10% light turn off etc. Then, let work performance variability of employee i in temperature t (˚C) environment be $L_i(t)$, then total production amount P_{ALL} in temperature t ˚C environment would be as follows.

$$P_{ALL} = P_{AVE} \sum_{i=1}^{n} (1 + L_i(t)) \tag{6-17}$$

where n is the number of employees in the enterprise.

Also as mentioned in 4.2.6, optimal temperature for employee i can be defined as random variable. Therefore, these kinds of variables are treated as stochastic variables and profitability by EMS installation would be analyzed by the Monte Carlo method.

6.2.3. Simulation Approach

In this subsection, the simulation of an optimization approach focusing on the profitability is discussed for the effect of consumer-side EMS and actual simulations are conducted. In addition, results are evaluated for some model cases based on the concept described in 4.2.

(1) Definition of Model Case

The model case described in the previous subsection, which is the first model in 4.2.6 is used for the simulation. A business which outputs would be almost the same in same conditions should be selected, and the productivity difference would be considered by changing air-conditioner settings. The simulation will be executed with some different setting parameters, and then monthly and annual revenue of the business would be calculated. In this research, productivity change would be calculated from June to September for the consideration of cooling demand and from December to March for the consideration of the heating demand based on the normal seasonal requirements in Japan.

(2) Formulation for Productivity Change Simulation

Here, the formulas of benefit quantification of EMS for the simulation model case considered in 4.2.6 are used. The annual revenue R_{year} would be the sum of summer season (June, July, August and September) revenues $R_{6\text{-}9}$, winter season (December, January, February and March) revenues $R_{12\text{-}3}$ and middle season (April, May, October and November) revenues $R_{4,5,10,11}$, and would be formulated as follows.

$$R_{year} = R_{6\text{-}9} + R_{12\text{-}3} + R_{4,5,10,11} \tag{6-18}$$

And let average monthly revenue be $R_{AVE,\ month}$, work performance change rate for employee i in temperature t be $L_i(t)$, and the number of employees be n then, season revenue $R_{6\text{-}9}$, $R_{12\text{-}3}$ and $R_{4,5,10,11}$ would be as follows.

$$R_{6-9} = \sum\nolimits_{month} R_{AVE,month} \sum_{i=1}^{n} (1 + L_i(t)) \tag{6-19}$$

$$R_{12-3} = \sum\nolimits_{month} R_{AVE,month} \sum_{i=1}^{n} (1 + L_i(t)) \tag{6-20}$$

$$R_{4,5,10,11} = \sum\nolimits_{month} R_{AVE,month} \sum_{i=1}^{n} (1 + L_i(t)) \tag{6-21}$$

Because the annual revenue R_{ALL} in this case would be the sum of annual revenue R_{year} and reduction cost $C_{reduction,year}$ and is formulated as follows.

$$R_{ALL} = R_{year} + C_{reductionyear} \tag{6-22}$$

The reduction cost $C_{reduction,year}$ is formulated as follows.

$$C_{reductionyear} = \sum_{month=1}^{12} C_{AVE,month} \cdot e_{month} \tag{6-23}$$

Where $C_{AVE,month}$ is average monthly energy cost, and e_{month} is electricity reduction rate for each month.

In order to clarify EMS installation effect, it is necessary to consider EMS installation and operation cost and payout period in (4-13) as follows,

$$C_I + C_m \times T = (\Delta P_{ma} + \Delta R_{ma}) \times T \tag{4-13}$$

where $\triangle R_{ma}$ is the difference between R_{ALL} and the revenue in the previous year.

(3) Setting parameters and Simulation Scenarios

Here, parameter values are defined for simulations.

a. Setting Parameters

Assuming a general small and medium enterprise (SME), some parameters were defined and showed in Table 6-6. Energy reduction rate per 1(˚C) was defined referring to "Energy Conservation for Office Buildings" provided by the Energy Conservation Center in Japan [6-4]. Energy cost would be reduced with higher temperature settings of air-conditioner in summer season and with lower temperature settings in winter season.

Table 6-6 Setting Parameters for Simulations

The Number of Employees	Average Annual Revenue (United States Dollar (USD))	Electricity Cost Reduction Rate per +1 (˚C)	
		Summer	Winter
50	1,000,000	10(%)	-10(%)

b. Stochastic Variables and Base Populations

W

was defined as a stochastic variable. 50 employees were retrieved from the base population in which each employee had individual preferred work environment temperature which maximized

temperatures conformed to normal distribution.

Figure 6-2 shows normal distribution curves for variance 1.0 and 0.5, and most members are included in the scope of ±3( ) area with variance: 1.0, and ±2( ) area with variance: 0.5. In this research the variance is set at 1.0 as the base variance.

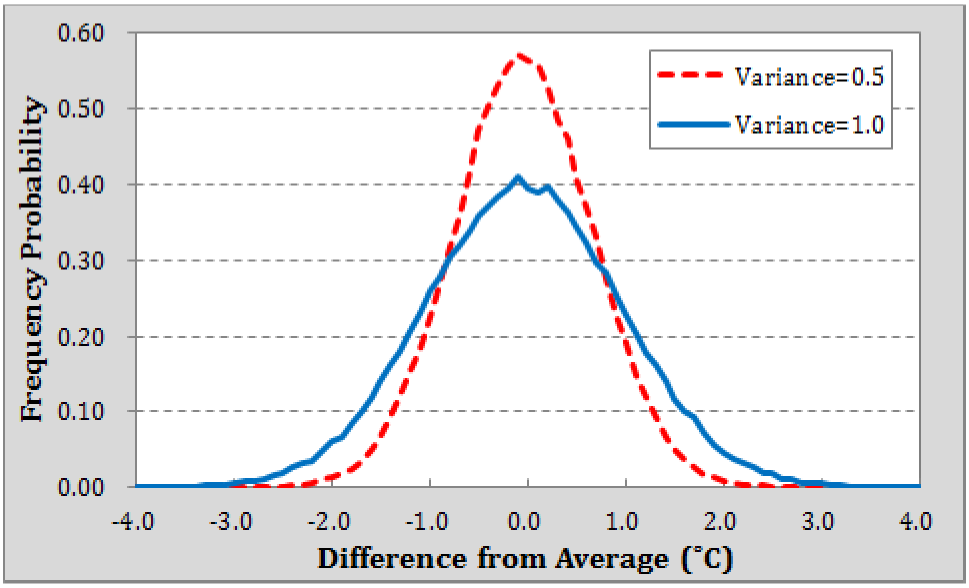


Figure 6-2 Distribution of Employees for the Optimal Work Performance Temperature Difference from Average

In the simulation, 50 employees were selected randomly and the production amount in a certain work temperature environment would be calculated considering performance change for all 50 employees by the work temperature environment. In order to reduce the variability of the simulation, 10,000 times of simulation for each simulation scenario were executed. Table 6-7 shows stochastic variables and base distributions.

Table 6-7 Stochastic Variables and Base Distributions

Stochastic Variables		Work environment temperature which maximizes employee's work performance
Distribution of employees for the optimal work performance temperature: Average	Type	Normal Distribution
	Average ($t_{AVE\_S: Summer}$, $t_{AVE\_W: Winter}$)	26 ˚C(Summer) 22 ˚C(Winter), 27 ˚C(Summer) 21 ˚C(Winter),
	Variance	1.0, 0.5
The number of simulation		10,000 times per scenario

c. Simulation Scenarios

In this research, simulations were executed for several scenarios including 4 patterns of electricity cost for total sales revenue, 4 patterns of work performance reduction rate per 1 (˚C) change, 2 combinations of average temperature which maximized employees' performance, 3 combinations of energy reduction settings and 2 combinations of setting improved temperature. Work performance reduction rates were defined referring to existing researches [6-2][6-3] related to productivity and temperature. Table 6-8 shows setting parameters for simulation scenarios.

Table 6-8 Simulation Scenarios Setting Parameters

Parameter	Values
Rate of Electricity Cost per Revenue	0%, 1%, 5%, 10% (0% model is just used for comparison)
Work Performance Reduction Rate per 1˚C:	0%, 1%, 2%, 3%
Temperature Settings in Work Environment (t_{SET_S}: Summer, t_{SET_W}: Winter)	26 ˚C(Summer) 22 ˚C(Winter), 27 ˚C(Summer) 21 ˚C(Winter), 28 ˚C(Summer) 20 ˚C(Winter)
Setting Improved Temp. for Energy Saving (t_{IMP_S}: Summer, t_{IMP_W}: Winter)	+1 ˚C(Summer), -1 ˚C(Winter) +2 ˚C(Summer), -2 ˚C(Winter)

6.2.4. Simulation Execution and Results Evaluation

Based on simulation scenarios, expected revenues were calculated and results were evaluated.

(1) Revenue Simulation Case for General Enterprise Model in Japan

As the first simulation, the following settings were selected as the base model considering general situation in Japan.

- Average temperature which maximize employees performance:
  26(˚C) (Summer) 22(˚C) (Winter)
- Changed Temperature Settings in Work Environment:
  27(˚C) (Summer) 21(˚C) (Winter)
- Setting improved temperature for Energy Saving:
  +1 ˚(C)(Summer), -1 (˚C)(Winter)
  (Current settings: 26 (˚C) (Summer) 22(˚C) (Winter))

Table 6-9 shows simulation result for the base model. The rate of electricity cost for total revenue is 0(%) means no electricity cost, and therefore expected revenues show the minimum values compared with other same performance decrease rate scenarios. Here, by the reduction of electricity cost, how expected sales revenue would change should be discussed.

The result shows most of expected revenues for the enterprises which rate of electricity cost for total sales 1~5(%) are smaller than the base revenues. Although it depends on the unit price of electricity, if rate of electricity cost was 1~5(%) of total revenue, it would be found that additional benefit by the electricity cost reduction would be small, so cost reduction benefit would be canceled easily if productivity would decrease by the energy reduction. On the other hand, in enterprises which energy cost is 10(%) of total revenue, expected revenue would be increased even if 1(%) of performance would be decreased.

Table 6-9 Simulation Results

(T_{AVE_S} =26 ˚C, T_{AVE_W} = 22 ˚C VARIANCE $Σ^2$=1.0 T_{SET_S}=27 ˚C, T_{SET_W}= 21 ˚C T_{IMP_S}=+1 ˚C, T_{IMP_W}=-1 ˚C)

Rate of Electricity Cost for Total Revenue (%)	Performance Decrease Rate for 1 ˚C (%)	Maximum Expected Revenue (USD)	Minimum Expected Revenue (USD)	Average Expected Revenue (USD)
0%	0%	1,000,000	1,000,000	1,000,000
0%	1%	996,148	990,836	993,337
0%	2%	991,922	981,676	986,673
0%	3%	987,244	971,346	980,014
1%	0%	1,001,000	1,001,000	1,001,000
1%	1%	996,635	991,734	994,333
1%	2%	992,579	982,117	987,667
1%	3%	988,450	973,559	981,023
5%	0%	1,005,000	1,005,000	1,005,000
5%	1%	1,000,804	995,644	998,335
5%	2%	996,745	986,963	991,651
5%	3%	991,889	977,753	984,969
10%	0%	1,010,000	1,010,000	1,010,000
10%	1%	1,005,871	1,000,926	1,003,334
10%	2%	1,002,569	991,672	996,657
10%	3%	997,532	982,453	989,996

Gray colored cells mean calculated revenue is more than the base revenue

(2) Revenue Simulation Case for Excess Energy Consumption Enterprise Model

It is expected that EMS benefit should be large for enterprises which energy saving activities have not been addressed so far. For this type of simulation, the model which air-conditioners had excess settings was used.

Table 6-10 shows the simulation result for the model which has excess energy utilization settings. In this case, current work environment temperature settings were 25(˚C) in summer season and 23(˚C) in winter season and both were changed to 26(˚C) and 22(˚C) respectively. Because work environment temperature would be the average temperature which maximizes employees' performance, in most cases expected revenues would increase and EMS installation and operation cost should be able to be covered. Generally expected revenues would be reduced with performance decrease rate, however the result showed revenues with high performance decrease rate had large values in this case. This is because the current setting generates bad impact largely compared with low work performance decrease rate and these bad impacts would be improved by the new optimal setting.

Table 6-10 Simulation Results

(t_{AVE_S} =26 ˚C, t_{AVE_W} = 22 ˚C Variance σ^2=1.0 t_{SET_S}=26 ˚C, t_{SET_W}= 22 ˚C t_{IMP_S}=+1 ˚C, t_{IMP_W}=-1 ˚C)

Rate of Electricity Cost for Total Revenue (%)	Performance Decrease Rate for 1 ˚C (%)	Maximum Expected Revenue (USD)	Minimum Expected Revenue (USD)	Average Expected Revenue (USD)
0%	0%	1,000,000	1,000,000	1,000,000
0%	1%	1,002,489	997,553	1,000,011
0%	2%	1,005,053	994,875	999,969
0%	3%	1,007,980	992,660	999,992
1%	0%	1,001,000	1,001,000	1,001,000
1%	1%	1,003,261	998,691	1,001,004
1%	2%	1,006,269	996,213	1,001,014
1%	3%	1,008,565	993,309	1,001,024
5%	0%	1,005,000	1,005,000	1,005,000
5%	1%	1,007,581	1,002,713	1,005,008
5%	2%	1,010,245	999,952	1,005,003
5%	3%	1,013,359	997,343	1,005,020
10%	0%	1,010,000	1,010,000	1,010,000
10%	1%	1,012,384	1,007,483	1,010,007
10%	2%	1,016,651	1,005,153	1,010,013
10%	3%	1,017,143	1,002,022	1,010,009

Gray colored cells mean calculated revenue is more than the base revenue

a. Revenue Simulation Case for Excess Energy Saving Enterprise Model

For this type of simulation, the model which air-conditioners have excess settings for energy saving was used.

Table 6-11 shows the simulation result for the model which has excess energy saving settings. In this case, current work environment temperature settings were 27(˚C) in summer seasons and 21(˚C) in winter seasons and both were changed to 28(˚C) and 20(˚C) respectively, although optimal work environment temperatures were 26(˚C) and 22(˚C) respectively. The result shows that expected revenues would decrease except for the scenario which had the rate of electricity cost for total revenue was 10(%) and performance decrease rate for 1(˚C) was 1(%). This means excess energy saving has high possibility of companies' profitability reduction. Although it is important to reduce environmental load for companies' business administration, the balanced energy utilization considering both environmental and business sustainability is essential.

Table 6-11 Simulation Results

(t_{AVE_S} =26 °C, t_{AVE_W} = 22 °C Variance σ^2=1.0 t_{SET_S}=28 °C, t_{SET_W}= 20 °C t_{IMP_S}=+1 °C, t_{IMP_W}=-1 °C)

Rate of Electricity Cost for Total Revenue (%)	Performance Decrease Rate for 1 °C (%)	Maximum Expected Revenue (USD)	Minimum Expected Revenue (USD)	Average Expected Revenue (USD)
0%	0%	1,000,000	1,000,000	1,000,000
0%	1%	989,097	984,058	986,664
0%	2%	978,757	968,476	973,331
0%	3%	967,240	951,800	959,954
1%	0%	1,002,000	1,002,000	1,002,000
1%	1%	991,136	985,820	988,665
1%	2%	980,534	969,940	975,302
1%	3%	969,581	953,401	961,967
5%	0%	1,010,000	1,010,000	1,010,000
5%	1%	999,076	994,396	996,667
5%	2%	988,077	978,177	983,365
5%	3%	977,431	962,659	969,972
10%	0%	1,020,000	1,020,000	1,020,000
10%	1%	1,009,023	1,004,108	1,006,672
10%	2%	998,999	988,746	993,352
10%	3%	987,711	971,920	979,964

Gray colored cells mean calculated revenue is more than the base revenue

(3) Holistic Evaluation of the Simulation Approach

In above simulations, EMS installation and operation costs were not considered. Except for the second model, the benefit should not be enough for covering EMS related cost even in the most effective case, and therefore it should be difficult to get additional benefit for most companies if business productivity would decrease. 1(%) of performance reduction is the same as 0.08 hour (4.8 minutes) work time reduction for 8 hours work per day enterprises, and it means about 5 minutes additional no work time occurrence by the energy reduction leads to bad impact to total profitability for most companies. While detailed researches for the relation between work environment and performance, and energy saving without impact for enterprises' business productivity should be necessary, EMS should be used for a waste energy reduction and optimal settings decision measures.

From the simulation result for the second model, which was excess energy consumption enterprise model, EMS has high possibility to provide various benefits for companies which have conducted insufficient energy saving activities. Because current power utilization amount would be larger than optimal amount in these companies, benefits from energy saving must be generated. Therefore, it should be very important to find optimal settings considering employees and machines performance in consumer-side energy management.

In this time, the impact of the employees’ performance change on an enterprise’s revenue was discussed and evaluated using the simulation approach. Also, similar approach can be used for the impact quantification of the consumers’ purchase behavior change described as the second sample model in 6.3.2. In addition, the proposed approach can be used for the decision of work environment parameters such as optimal temperature settings. By the continuous collection of temperature and performance data, optimal work environment settings can be decided more effectively and accurately.

6.3. Multi-objective Optimization Methods Considering Optimization Problems in Power Distribution Systems

As the second method for the evaluation of installation effect for Smart Grid critical technologies and measures, an effective multi-objective optimization method is considered in this section because most of optimization problems in power systems are constrained multi-objective optimization problems and these objectives have trade-off relationship.

6.3.1. Optimization Problems in Power Systems

In all areas for power systems such as generation, transmission, distribution and consumption of electric power, it is necessary to have appropriate plans and thus it requires optimization tasks under given constraints. In addition, while optimization researches dealt with effective methods for various objectives are important, it should be necessary to clarify the profitability evaluation of the new technology implementation considering the shutdown of existing systems and the re-installation of the new system. Generally, installation benefit and cost have a trade-off relationship. It means that in the effectiveness evaluation of future power system it would be important not only the optimization of installation single objective but also multi-objectives, especially profitability optimization. Therefore, in this research effective multi-objective optimization method not only for a single technological objective but also for cost optimization is considered and proposed.

6.3.2. Single Objective Optimization Problems and Their Studies

Optimization problem is to minimize or maximize objective functions under constraints. Problem resolution by optimization methods is one of important measures in real world. General optimization problem has constrains of inequality, equality and upper and lower limit and is defined as follows.

$$\begin{aligned} & \min\ y = f(x) && \text{(6-25)} \\ \text{subject to}\quad & g_j(x) \leq 0, j = 1,\ldots, q && \\ & h_j(x) = 0, j = q+1,\ldots, m && \\ & l_i \leq x_i \leq u_i\, 0, i = 1,\ldots, n && \end{aligned}$$

where $x = (x_1, x_2,\ldots, x_n)$ is an n dimensional vector, $f(x)$ is an objective function, $g_j(x) \leq 0$ is q inequality constraints and $h_j(x) = 0$ is m - q equality constraints. Functions f, g_j and

h_j are linear or nonlinear real-valued functions. Values u_i and l_i are the upper and the lower bound of x_i, respectively. Recently, population-based descent method has received many attentions, and differential evolution (DE) and particle swarm optimization (PSO) are major representative examples. In these methods, information of populations composed of solutions is utilized for the creation of new candidates to be compared with current solutions [6-5]. The outline of these two major algorithms is described as follows.

(1) Particle swarm optimization (PSO)

PSO is an evolutional computation technique which is inspired by a bird flocking, fish schooling and swarming theory, and utilizes particle swarms flying in problem space, called the hyperspace [6-6]. In the iteration process, each particle evolves into optimal or optimal approximation solution adjusting its velocity by the information of its best location and best neighbor location on its historical data.

If agents included in a population would optimize a certain objective function f, then each agent i memorize its location x_i^t and moving velocity v_i^t at t, the best value of the objective functions $pbest_i$ and its location x_i^* from past experience [6-5].

$$pbest_i = \min_{\tau=0,1,\ldots,t} f(x_i^\tau) \tag{6-26}$$

$$x_i^* == \arg\min_{\tau=0,1,\ldots,t} f(x_i^\tau) \tag{6-27}$$

Also, each agent share the information of the best value of the objective function for agents in the population $gbest$ and its location x_G^*.

$$gbest = \min_{\tau=0,1,\ldots,t} f(x_i^\tau) \tag{6-28}$$

$$x_G^* == \arg\min_{\tau=0,1,\ldots,t} f(x_i^\tau) \tag{6-29}$$

Here, moving velocity of the agent in the time $t + 1$ would be as follows.

$$\begin{aligned} v_{ij}^{t+1} &= wv_{ij}^t + c_1\, rand(x_{ij}^* - x_{ij}^t) \\ &\quad + c_2\, rand(x_{Gj}^* - x_{ij}^t) \end{aligned} \tag{6-30}$$

Where w is inertia weight, $rand$ is uniform random numbers in an interval [0,1], c_1 and c_2 are parameters called "cognitive" and "social" respectively, and represent weight for location search of individual and group best values. Therefore, the approach of the original PSO is called inertia weight approach (IWA) [6-7].

From (6-30), the location of the agent at time $t + 1$ would be as follows.

$$x_i^{t+1} = x_i^t + v_i^{t+1} \tag{6-31}$$

PSO is a one of computational intelligence based techniques, which is not largely impacted by problem size and non-linear characters, and it can provide convergence into optimal solutions even if many analytical methods cannot provide convergence. Therefore, PSO can be used for various optimization problems in power systems.

With respect to PSO, various improved algorithms are proposed. Constriction Factor PSO, M. Clerc and J. Kennedy [6-8] is one of PSO subspecies which utilize constriction factor approach (CFA) controlling the convergence property in PSO and it is reported that the algorithm provides superior results compared with PSO using IWA [6-7][6-9].

(2) Differential Evolution (DE)[6-10][6-11]

DE, proposed by Storn and Price, is one of evolution strategies which is a stochastic direct search method and conducts multi-points search using solution group. Although the control of mutation step size is required in evolution strategy algorithms, DE does not need to control the step size because it adopts a mathematical operation as its mutation using weighted sum of the base vector and the difference vectors. DE's basic strategy can be described as follows.

- **Mutation**

For each target vector $x_{i,G}$, $i = 1, 2, 3, \ldots, N$, a mutant vector is generated according to the following equation.

$$x_{i,G+1} = x_{r1,G} + F(x_{r2,G} - x_{r3,G}) \tag{6-32}$$

where F is a scaling parameter and three individuals $x_{r1,G}$, $x_{r2,G}$, $x_{r3,G}$ are selected at random for $x_{i,G}$ so as not to duplicate each other.

- **Crossover**

Crossover operation is conducted between target vector $x_{i,G}$ and mutant vector $v_{ji,G+1}$, and generates trial vector $u_{i,G+1}$.

$$u_{i,G+1} = (u_{1i,G+1}, u_{2i,G+1}, \ldots, u_{Di,G+1}) \tag{6-33}$$

$$u_{ji,G+1} = \begin{cases} v_{ji,G+1} & \text{if } (randb(j) \leq CR) \text{ or } j = rnbr(i) \\ x_{ji,G} & \text{if } (randb(j) > CR) \text{ and } j \neq rnbr(i) \\ j = 1,2,\ldots,D \end{cases} \tag{6-34}$$

$randb(j)$ is the jth evaluation of a uniform random number generator, CR is the crossover constant determined by the user. $rnbr(i)$ is a randomly chosen index which ensures that $u_{i,G+1}$ gets at least one parameter from $v_{i,G+1}$.

- **Selection**

The trial vector $u_{i,G+1}$ is compared with the target vector $x_{i,G}$ to decide if it should become a member of generation $G+1$.

As same as PSO, various improved algorithms have been proposed in DE. Adaptive DE (ADE) is the collective term which shows subspecies of the standard DE algorithm targeting for convergence improvement, and various kinds of ADE algorithms have been proposed. JADE is one of these algorithms and implements a mutation strategy called "DE/current-to-pbest" with optional archive and controls scaling factor and crossover rate in an adaptive manner [6-12]. ε constrained ADE [6-13] is proposed to improve the scheme proposed in JADE and the ε constrained method, which is the algorithm to convert unconstrained optimization method into constrained optimization method using the ε level comparison, is applied.

6.3.3. Multi-objective Optimization Problems and Their Studies

An optimization problem for multiple objectives is called multi-objective optimization problem. In the real world, most optimization problems need to be considered multiple objectives. Generally, multi-objective problems are formulated as follows.

$$\begin{aligned} &\min y_1 = f_1(x), y_2 = f_2(x), \ldots, y_\mathrm{n} = f_\mathrm{n}(x) \\ &\mathrm{s.t.}\, x \in C(x) = \{x \in \Re^k \mid \\ &\qquad\qquad g_1(x) \geq 0, g_2(x) \geq 0, \ldots, g_m(x) \geq 0\} \end{aligned} \tag{6-35}$$

where $\min f_i(x)$ is an objective function and $C(x)$ is constraint conditions. In a single objective optimization problem, the best value is apparent because it is possible to compare between two real numbers in size. However there are trade-off relations among objectives in multi-objective optimization problems generally and thus optimal solution would not be single solution but multiple solutions or infinite population. Therefore, optimal solutions which cannot be improved the value of a certain objective function without degrading some values of the other objective functions would need to be searched and these are called Pareto optimal solutions. If Pareto optimal solutions could be searched, the relation of objective functions would be clarified and better decision making could be made. Pareto optimal solutions can be defined as follows.

If there would be no solution for any x' ($\in C(x)$) to meet the following conditions, feasible solutions x ($\in C(x)$) would be called Pareto optimal solutions.

$$\begin{aligned} &f_i(x') \le f_i(x) \quad (\forall i = 1,2,\ldots,n) \\ &f_j(x') < f_j(x) \quad (\exists j \in \{1,2,\ldots,n\}) \end{aligned} \tag{6-36}$$

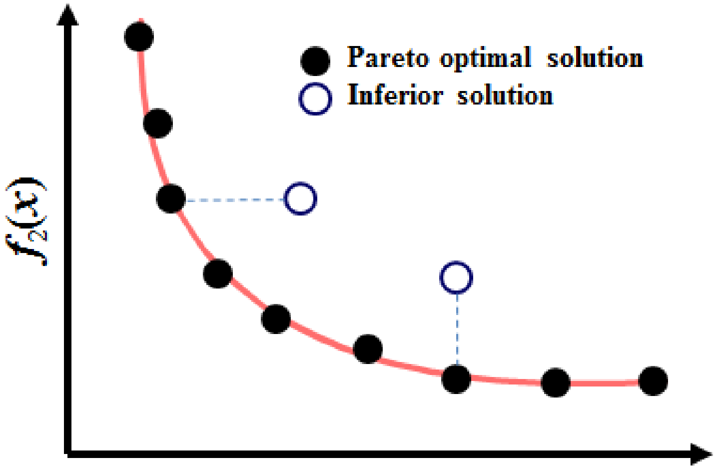


Figure 6-3 Pareto Optimal Solutions

Figure 6-3 shows examples of Pareto optimal solutions for two objectives optimization problem. Filled circles and open circles show Pareto optimal solutions and inferior solutions respectively. The surface formed by Pareto optimal solutions is called the Pareto front and generally three aspects need to be considered to evaluate Pareto front [6-14]. The first one is the "convergence", minimizing the distance from search results to the Pareto frontier. The second is "uniformity", maintaining uniform solution distribution. And the last one is "extensity", maximizing the extent of solutions following the Pareto frontier.

Recently, the multi-objective evolutional algorithm (MOEA) becomes the active area of research and recent researches focused on the methodology for fast and effective Pareto front provision. Major MOEA methods includes multi-objective particle swarm optimization[6-15][6-16][6-17][6-18], Pareto Envelope based Selection (PESA [6-19] and PESA-II [6-20]) based on Pareto Archived Evolution Strategy (PAES) [6-21], and improved PESA-II (IPESA-II [6-14]). These methods are briefly described below.

(1) PAES

The algorithm of PAES starts from initialization of a current solution. Firstly, the current solution is copied and the mutation is executed, and then the generated candidate solution is compared with the current solution. If neither solution dominates, the candidate solution is compared with the population of non-dominant solutions previously archived. Then, one solution which does not dominate others in the least crowded area of the archive is disconnected.

(2) Multi-objective PSO

The superior performance of PSO has been utilized not only for the single objective optimization but also for multiple objectives optimization in various researches. Reference [6-15] proposed a multi-objective optimization PSO (MOPSO) algorithm which allows the PSO algorithm to deal with multi-objective optimization problems using an external memory, called the “repository” and [6-16] introduced a clustering technique which divides particle swarm population, and comparison results with other multi-objective PSO algorithms for some test functions were reported. Also, as application examples for power systems, both [6-17] and [6-18] proposed improved approaches of the multi-objective optimization methods for the optimization in energy management system for factories, and voltage and reactive power control, respectively.

(3) PESA, PESA-II and IPESA-II

PESA [6-19] is the multi-objective optimization algorithm integrating the ideas of strength Pareto evolutionary algorithm (SPEA) [6-22] and PAES [6-21] are two major multi-objective optimization methods. PESA uses a population (archive) which stores an approximation to the Pareto front and an internal population which has candidate solutions same as SPEA, and also maintains hypergrid division which can trace the crowded factor of different areas in the archive as same as PAES. PESA-II [6-20] is the improved version of PESA and mating-selection processes were implemented not in individual based but in region based. Firstly, a hyperbox is selected and then an individual which is the result of evolutional operations is randomly selected from the hyperbox. IPESA-II [6-14], is an improved version of PESA-II with three improvements: the maintenance method of the archive, individual maintenance around boundary and the selection of the hyperbox by the crowded factor.

6.3.4. Effective Optimization Method in Power Distribution Systems

Some preparation tasks for exploring effective optimization method in power distribution systems are conducted, including problem definition, procedure clarification and data preparation.

(1) Definition of a Problem

Many researches have been conducted to solve optimization problems in power system area. Major areas include power system planning and operation, environmentally constrained economic dispatch, state estimation and optimized power flow [6-23]. For the versatile and essential point of view, benefits or effects maximization of approaches for low-carbon power systems and cost minimization for these approaches should be fundamental trade-off relation objectives. In order to enhance existing power systems into new advanced systems, it must be necessary to achieve both new additional benefit provision to consumers and cost recovery of the investment at the same time. Therefore, this kind of problems is defined as the multi-objective problem in this research.

Author's group has researched power loss minimization problems in order to evaluate optimized installation of DGs for low-carbon society. In these researches, it is found that inadequate DG installation would cause power loss increase while effective DG installation would contribute to the realization of very low power loss distribution systems [6-24]. Therefore, an optimal DG installation is one of critical problems for advanced low-carbon power systems considering most of renewable energy source (RES) generations, however the correct evaluation of these DGs installation should be the balance of various impacts including cost. In the view of above consideration, this paper dealt with optimal DG installation problem considering power loss and cost minimizations. In particular, simulations of power loss and cost reduction by DG location and capacity for a distribution system model are executed and then are evaluated to find the optimal solutions.

(2) Procedure Clarification

Multi-objective optimization would be important in future power systems, because the enhancement of power systems would not be realized only by technical advantages, such as improvement of power supply stability with a large number of RES installations, but their cost effectiveness considering added-values would be essential. In most countries and regions, power systems are already one of social infrastructures and provide values to consumers with reasonable price. Therefore, consumers would not pay additional costs without significant additional values and then multi-objective optimization methods for evaluating the cost effectiveness of enhanced technologies should be critical.

The procedure to find effective solution method for multi-objective optimization problems in power systems is described below. The bi-objective optimization problem of DG allocation with optimal power loss and cost mentioned in above is considered as the base problem in this paper.

a. Distribution Model

Considering optimal DG allocation problems, it is necessary to define a target system model firstly. Because many DGs are planned to install into distribution systems in Japan, a model distribution system composed of buses and branches should be defined. In order to calculate power loss in the distribution system model, power flow calculation is necessary, thus active and reactive loads, complex voltage and current at each bus, and branch parameters such as reactance and susceptance are also needed to be prepared. In addition, preconditions and constraints are also necessary to be defined. Constraints can influence the results in optimization problems, thus it is necessary to define specific constraints in power systems especially. These specific constraints include power flow laws, voltage upper and lower limits, and apparent current upper limit, etc.

b. Effective Single-objective Optimization Method in Power Systems

For the target distribution system with allocated DGs, major single objective optimization algorithms should be used to understand their effectiveness for optimization problems in power systems. As mentioned in above, recently, the population-based descent method has received many attention, thus DE and PSO are selected as base single optimization algorithms in this research.

In order to evaluate the effectiveness, the number of iterations required for the convergence to the optimal value in an Optimal Power Flow (OPF) problem can be utilized. With respect to the optimal value compared by some candidate algorithms, the pre-calculated exact solution is used. As candidate algorithms, not only original DE and PSO algorithms, but also subspecies of these algorithms are considered. Then, the best algorithm in these simulations will be selected as the best single objective optimization algorithms for optimization problems in power systems.

c. Enhancement of the Effective Single-objective Optimization Method for Multi-objective Optimization Problems in Power Systems

Multi-objective optimization algorithm is considered on the enhancement of the effective single -objective optimization algorithm selected in the previous step. Considering the enhancement of the effective single objective optimization method, various hybrid approaches using proven major multi-objective algorithms should be discussed. In case that Pareto front would be evaluated on “convergence”, “uniformity” and “extensity” three aspects, assumed that each multi-objective optimization method had specific ranges in which high quality Pareto front is provided by pre-conducted basic researches and simulations. Therefore, it is expected that the hybrid approach of proven multi-objective algorithms can provide an effective Pareto front for the multi-objective optimization problems in future power systems. Then, the algorithm which finds the best Pareto front in the aspects of “convergence”, “uniformity” and “extensity” will be selected as the best multi-objective optimization algorithm.

(3) Data Preparation

Some predefined data for simulations are provided. The data include target distribution system model and defined data, constraints, and cost related data.

a. Distribution System Model

As a distribution system model for simulations, the wiring diagram of grid in [6-25], which is the same 126 buses radial distribution system model as used in chapter three and showed in Figure 3-6.

The bus number 126 is the slack bus and it is found that the slack bus provides active power of P=4.4239(p.u.) and reactive power Q=3.1053(p.u.) for the total load of P=4.2300(p.u.) and Q=2.8870(p.u.). Therefore, total power loss is calculated as Ploss=0.1939(p.u.) and Qloss=0.2183(p.u.) and power loss rate for injected power at slack bus are P: 4.383(%), Q: 7.030(%), respectively. Parameters for the system model such as branch attributes, load at bases were also referred to [6-25].

b. Constraint Definition for Optimization Problem

With respect to the installation of DGs, the following constraints are defined.

a. The number of installation DGs is 2, 3 and 4.

b. DG would be installed at one of the buses.

c. One DG would be installed per one part where the load would be installed in the same range.

Table 6-12 shows capacity constraints for each DG and slack bus.

Table 6-12 Capacity Constraint for Each DG and Slack Bus

	Max. P (p.u.)	Min. P (p.u.)	Max. Q (p.u.)	Min. Q (p.u.)
DG	4.0	0.0	2.0	0.0
Slack Bus	6.0	1.0	6.0	1.0

c. Cost Related Data

As an additional objective, “

multi-objective optimization. Table 2 shows installed DGs and cost parameters used in the

lation. In the table, “ .5 (p.u.)” means that required cost per DG capacity 1 (p.u.) is 0.5 (p.u.)

Table 6-13 Installed DGs and Cost Parameters

	The Number of DGs	2	3	4
DG-1	DG location	7	5	5
	Fixed/Variable cost for P p.u.	0.0/0.5	0.0/0.5	0.0/0.5
	Fixed/Variable cost for Q p.u.	0.0/0.4	0.0/0.4	0.0/0.4
DG-2	DG location	16	13	13
	Fixed/Variable cost for P p.u.	0.0/0.5	0.0/0.5	0.0/0.5
	Fixed/Variable cost for Q p.u.	0.0/0.4	0.0/0.4	0.0/0.4
DG-3	DG location		18	18
	Fixed/Variable cost for P p.u.		0.0/0.5	0.0/0.5
	Fixed/Variable cost for Q p.u.		0.0/0.4	0.0/0.4
DG-4	DG location			55
	Fixed/Variable cost for P p.u.			0.0/0.5
	Fixed/Variable cost for Q p.u.			0.0/0.4
Slack Power	Fixed/Variable cost for P p.u.	0.0/0.3	0.0/0.3	0.0/0.3
	Fixed/Variable cost for Q p.u.	0.0/0.0	0.0/0.0	0.0/0.0

d. Calculation Result of Power Flow by Interior Point Method

Before the discussion using simulations, OPF calculation for the defined problem is executed using an interior point method to know exact optimal solutions. Table 6-14 shows calculation results of the OPF. The leftmost column shows the name of installed DG and DG location, active and reactive power capacities are provided by the number of total DG in the distribution model. For example, when the number of installed DGs is 2, the location of the DG-1 is Bus7 and active and reactive powers are 1.983168(p.u.) and

1.022116 (p.u.), respectively.

Table 6-14 Results of OPF by PSO

	No. of DGs	2	3	4
DG1	Location	7	5	5
	Capacity (*P*)	1.983168	1.157973	0.854512
	Capacity (*Q*)	1.022116	0.447595	0.244404
DG2	Location	16	13	13
	Capacity (*P*)	1.261669	1.393307	1.295070
	Capacity (*Q*)	0.882551	0.976911	0.910799
DG3	Location		18	18
	Capacity (*P*)		0.688242	0.688242
	Capacity (*Q*)		0.473893	0.473893
DG4	Location			55
	Capacity (*P*)			0.400341
	Capacity (*Q*)			0.267712
Slack Power	Capacity (*P*)	1.000000	1.000000	1.000000
	Capacity (*Q*)	1.000000	1.000000	1.000000
Minimum Power Loss(*P*)		0.01484	0.00952	0.00817

6.3.5. Simulation of Single-objective Optimization

For the exploring effective methods for optimization problems in power systems, the effective single-objective optimization problem is considered.

(1) Application of Proven Optimization Algorithms

The following major algorithms are prepared to conduct simulations and each algorithm is named after considering its characteristics, base algorithms and objective function for clear identification.

- Original PSO [6-8] (“IWA-PSO-OPF”)
- Constriction factor PSO [6-9] (“CFA-PSO-OPF”)
- Original DE [6-10] (“ODE-OPF”)
- Adaptive DE [6-13] (“ADE-OPF”).

(2) Simulation Results of Single-objective Algorithms

Simulation results of the convergence status for single -objective optimization algorithms are provided. Utilized algorithms are assumed to be effective for the power system problems. In each simulation process, if the new solution would be predominant compared with the current solution, the optimal solution is replaced and the non-dominant process is discarded. The number of iterations is 100 and the number of populations (swarms or archives) is 20 in each simulation result.

a. PSO

Firstly, the simulation using “IWA-PSO-OPF” was executed. Figure 6-4 shows the simulation result for the convergence status of optimal value by “IWA-PSO-OPF”. Predominant values are converged with around 60 iterations for 2 and 3 DGs and around 90 iterations for 4 DGs.

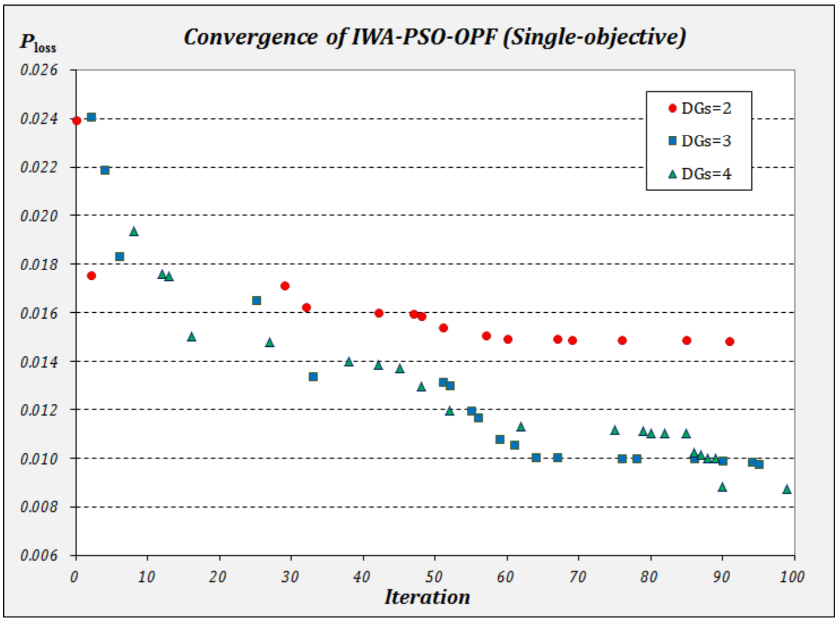


Figure 6-4 Simulation Results for the Convergence Status of Optimal Value by “IW -PSO-

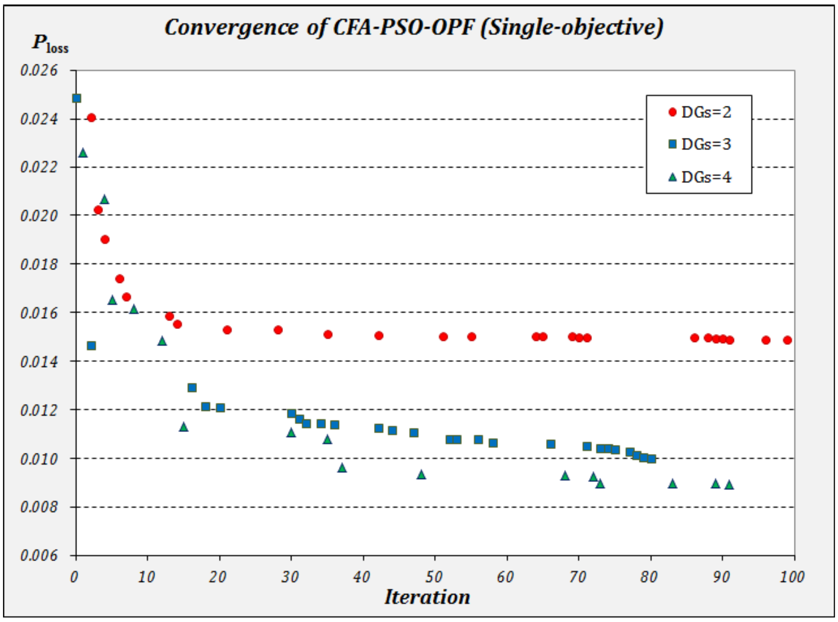


Figure 6-5 Simulation Results for the Convergence Status of Optimal Value by -PSO-

Then, the simulation using "CFA-PSO-OPF" was executed. Figure 6-5 shows the simulation result for the convergence status of optimal value by "CFA-PSO-OPF". Predominant values are converged with around 20 iterations for 2 DGs and around 80 iterations for 3 and 4 DGs. However, convergence rates to optimal values for all 3 patterns are fast compared with "IWA-PSO-OPF", and it is found that better approximation optimal could be retrieved with small number of iterations.

b. DE

Next, the simulation using "ODE-OPF" was executed. Figure 6-6 shows the simulation result for the convergence status of optimal value by "ODE-OPF".

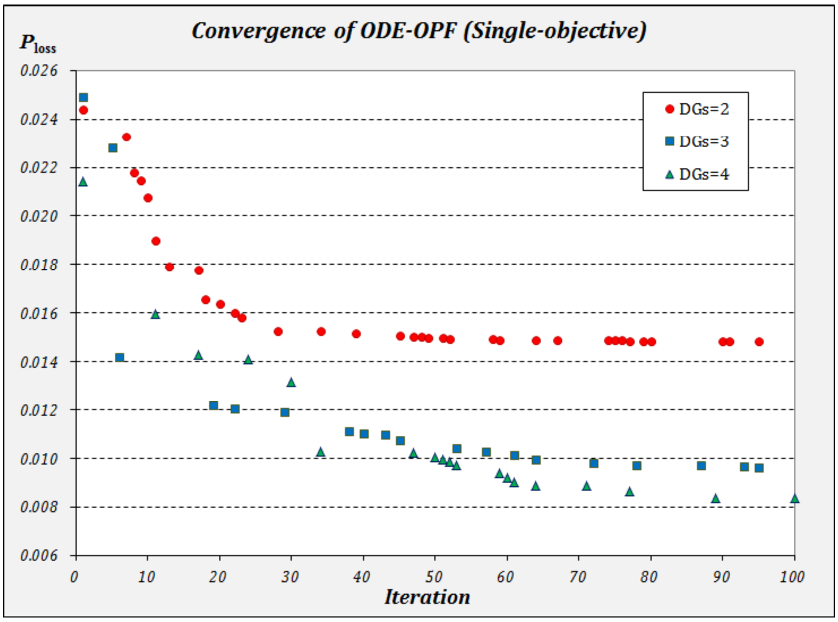


Figure 6-6 Simulation Results for the Convergence Status of Optimal Value by "ODE-OPF"

Predominant values are converged with around 30 iterations for 2 DGs, around 60 iterations for 3 DGs and around 90 iterations for 4 DGs. The performance of "ODE-OPF" is in the same range as "IWA-PSO-OPF" but inferior to "CFA-PSO-OPF".

Finally, the simulation using "ADE-OPF" was executed. Figure 6-7 shows simulation results for the convergence status of optimal value by "ADE-OPF".

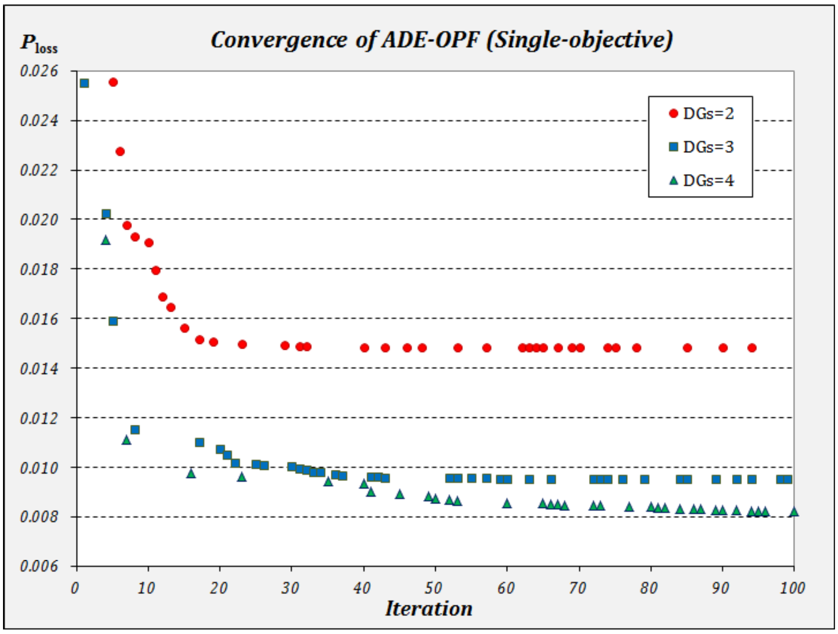


Figure 6-7 Simulation Results for the Convergence Status of Optimal Value by "ADE-OPF"

Predominant values are converged with around 20 iterations for 2 DGs, around 40 iterations for 3 DGs and around 50 iterations for 4 DGs. In addition, convergence rates to optimal values for all 3 patterns are fast compared with other three algorithms, and "ADE-OPF" provides the best performance among 4 algorithms in our simulation results.

(3) Discussion of Simulation Results

Single-objective optimization simulations were executed with PSO and DE algorithms which were assumed to be effective for power system related problems and the adequacy of these algorithms were discussed for power systems. The simulations were presented as follows.

- All 4 utilized algorithms provided good performance for the convergence of predominant solutions and it was confirmed that "CFA-PSO-OPF" and "ADE-OPF", which were subspecies of original OPF and DE algorithms respectively, provided better performance compared with original algorithms.
- "ADE-OPF" which is one of Adaptive DE algorithms showed the highest performance.
- Because the objective function "Power loss minimization by DGs" was a constrained optimization problem, it was confirmed that these four algorithms were able to be used for constrained optimization problems.

6.3.6. Multi-objective Optimization Problems in Power Systems

By the enhancement of the effective single objective optimization method, an effective multi-objective optimization method is considered for the evaluation of future advanced power system.

(1) Enhancement for the Application of Single-objective Optimization Problem

The enhancement of "ADE-OPF" which has confirmed its effectiveness for single-objective optimization problem in power systems is considered to be applied for multi-objective problems.

In the consideration, a methodology which manages multi-objective space efficiently and finds a good approximation set of the Pareto front should be required. Therefore, the utilization of the archive method in the PAES [6-21], which is called the "PAES-Archive method" in this paper, is used for the effective management of solutions generated in multi-objective space by "ADE-OPF".

In order to confirm the applicability of "ADE-OPF" to multi-objective optimization problems, some simulations of hybrid approach of "ADE-OPF" and "PAES-Archive method" were conducted by changing parameters, such as the number of generations and individuals. Figure 6-8 shows a reference example which is one of the simulation results of this approach, with the number of DGs: 3, generations: 40 and individuals: 80.

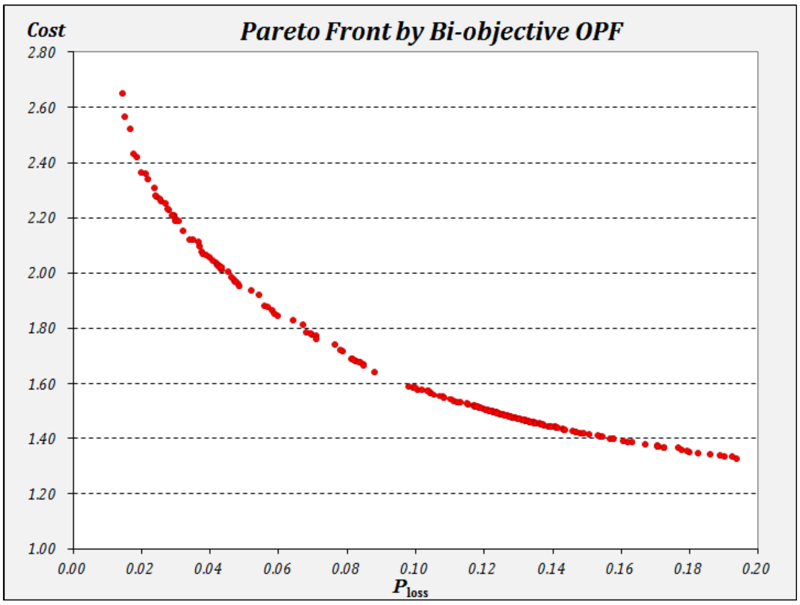


Figure 6-8 Sample Pareto Front by Hybrid Approach of "ADE-OPF" and "PAES-Archive Method"

In this chart, no solution exists in some ranges and solutions are not provided uniformly. Like this chart, it was difficult to obtain a better Pareto front which had enough quality in aspects of “convergence”, “uniformity” and “extensity” in our numeral simulations with these simulations. Although a brief trend of the Pareto front in the optimization problem can be found from this sample chart, in some simulation results, only a few solutions were able to be selected thus Pareto front was not able to be drawn.

(2) 4.2 Challenges in Hybrid Approach of Optimization Methods

In order to solve the challenge in the hybrid approach of “ADE-OPF” and “PAES-Archive method”, another hybrid approach with other multi-objective optimization methods was considered.

a. Utilization of the Adaptive Grid in IPESA-II

Grid division of an objective space was proposed in PESA-II [6-20] to maintain diversity of solutions, and this method has changed the existing individual-based selection process to the area-based selection process. IPESA-II [6-14], which is the enhanced version of PESA-II improved results by changing the adjusting method in the grid environment. Therefore, utilization of the adaptive grid method in the IPESA-II, which is called “Adaptive-Grid method” in this research, is considered for the effective management of solutions generated in multi-objective space by “ADE-OPF”.

b. Pareto front creation with the hybrid approach of “ADE-OPF” and “Adaptive Grid method”

In order to consider the hybrid approach of “ADE-OPF” and “Adaptive Grid method”, some basic simulations were executed by changing some parameters. As the result, the following issue was clarified in our numeral simulations.

- The mating-selecting method utilized in IPESA-II to create solutions in multi-objective space was not able to find Pareto front solutions effectively if enough solutions would not exist in the space.

Therefore, the following conditions were added to the hybrid approach.

- If solutions in adaptive grid in the multi-objective space would be smaller than 2, “ADE-OPF” would be utilized to create solutions in the space, otherwise mating-selection would be utilized.

Since the method was a hybrid approach of "ADE-OPF" and IPESA-II, the method is called the hybrid ADE-IPESA-II (H-ADE-IPESA-II) in this research.

c. Optimization Testing using H-ADE-IPESA-II Method

Using H-ADE-IPESA-II, Pareto front for the multi-objective optimization problem was able to be found effectively.

Figure 6-9 shows the Pareto front of the multi-objective optimization problem which has two objectives of loss minimization and cost minimization with effective DG installation (3 DGs) using H-ADE-IPESA-II. A good set of the Pareto front was provided with respect to "convergence", " . Although the number of DGs for Figure 6-9 is 3, other cases (DGs=2, 4) also provided similar good results.

From the result, H-ADE-IPESA-II which is hybrid approach of Adaptive DE and IPESA-II is one of effective methods for constrained multi-objective optimization problems in power systems.

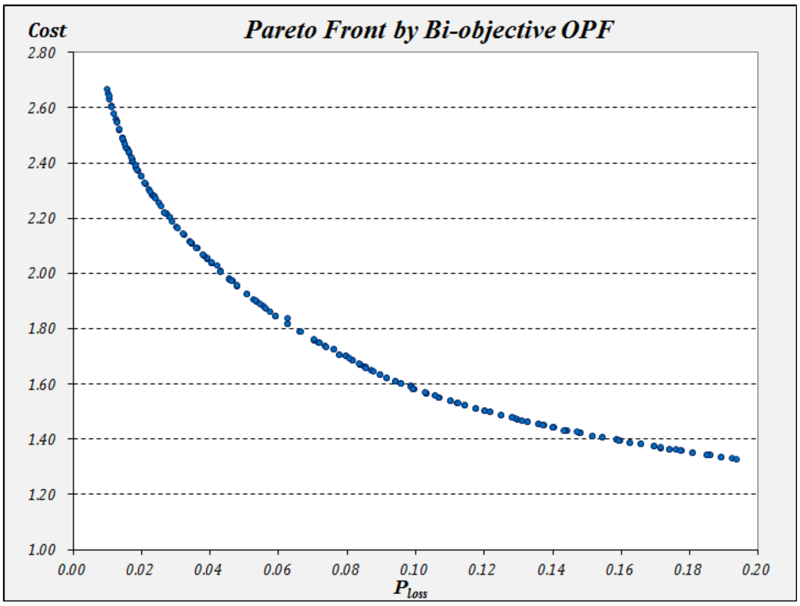


Figure 6-9 Pareto Front of the Multi-objective Optimization Problem Considering Variable Cost Only

(3) Discussion of Multi-objective Optimization Results

Using H-ADE-IPESA-II, various simulation scenarios for the multi-objective optimization problem were executed. Three simulation parameters for the minimization of power loss are considered by the installation of DGs: a. Variable cost; b. Fixed and variable cost; c. Discrete DG capacity.

a. Optimization of power loss and cost by the installation of 3 DGs considering variable cost

Figure 6-9 shows the Pareto front of both loss and cost optimization problem and only variable cost is considered using the proposed H-ADE-IPESA-II.

b. Optimization of power loss and cost by the installation of 3 DGs considering both fixed and variable cost

With respect to objective function for cost, both fixed and variable costs are considered and the Pareto front is created.

Figure 6-10 shows the Pareto front of the multi-objective optimization problem considering both fixed and variable costs. Under the influence of the fixed cost, the set of Pareto front does not converge to a single curve, but shows divided lines.

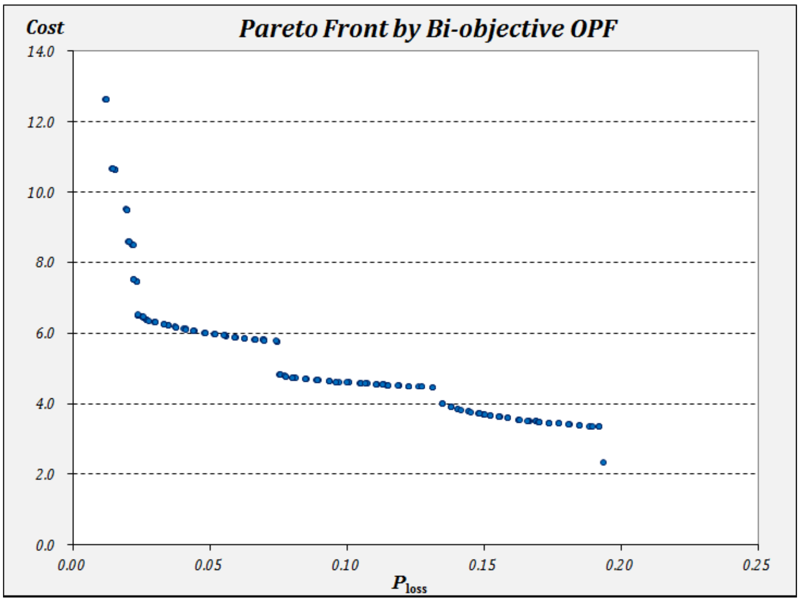


Figure 6-10 Pareto Front of the Multi-objective Optimization Problem Considering Both Fixed and Variable Cost

c. Optimization of power loss and cost by the installation of 3 DGs considering discrete DG capacity

With respect to objective function for loss minimization, discrete DG capacity settings are considerable. Therefore, the Pareto front using discrete DG capacity settings are also considered.

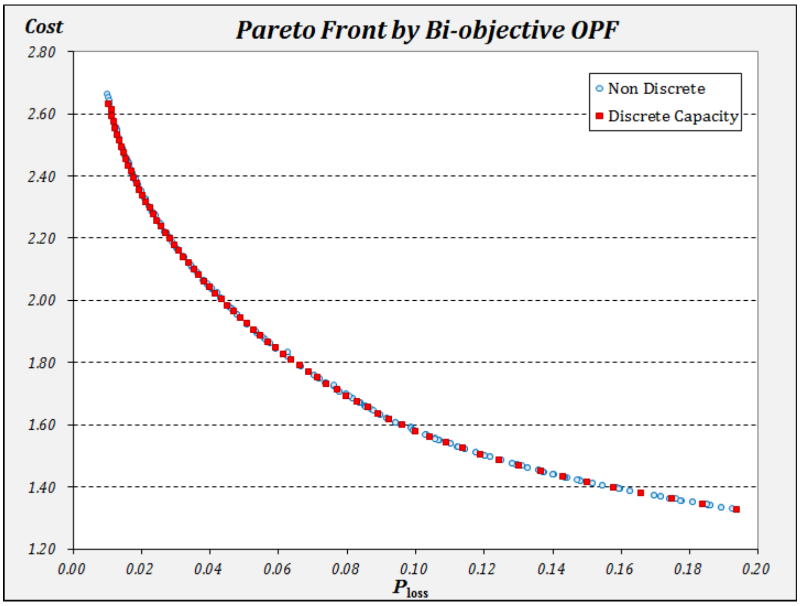


Figure 6-11 Pareto Front of the Multi-objective Optimization Problem Considering Variable Cost Only

Figure 6-11 shows the Pareto front of the multi-objective optimization problem for discrete DG capacity settings with variable cost only. Figure 6-12 shows the Pareto front of the multi-objective optimization problem for discrete DG capacity settings over non-discrete DG capacity setting with both fixed and variable cost. Basically, the Pareto front for the problem with discrete DG capacity settings does not show a clear difference from that with non-discrete DG capacity setting.

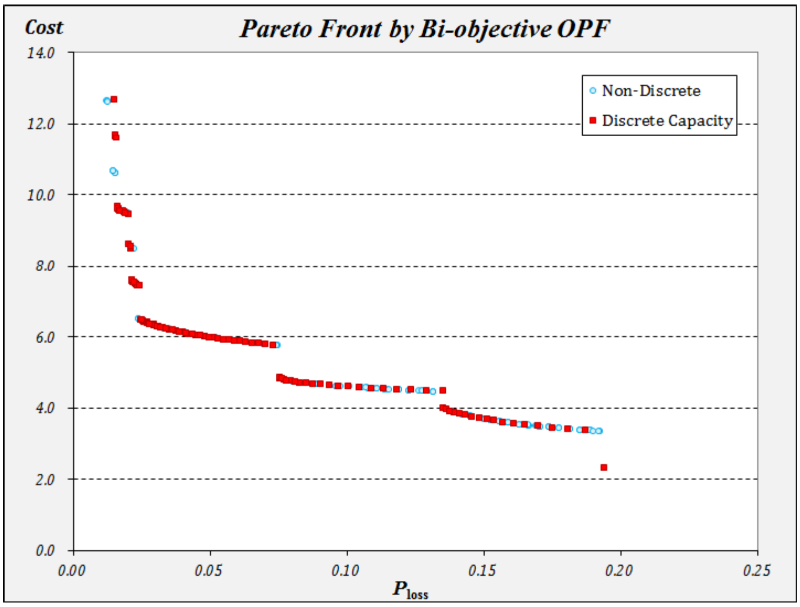


Figure 6-12 Pareto Front of the Multi-objective Optimization Problem Considering Both Fixed and Variable Cost

6.4. Summary

The purpose of this chapter is to provide effective tools for evaluation of Smart Grid critical technologies and measures installation. In the chapter, two types evaluation method are proposed in order to correspond to actual project situations after the provision of value circulation model in Smart Grid and the periodical data preparation methods for business profitability evaluation.

The first one is a method of profitability priority approach and this is appropriate approach for general competitive companies in power market. In this method, an approach to evaluate the impact of energy reduction to the companies' productivity, which has not been considered enough were considered, while many researches for energy reduction effect have been studied. As the result of simulations, it was clarified that energy reduction in a company should not impact to companies' productivity and profitability and power consumers should understand that excess energy saving results in revenue or productivity reduction. Generally impact to energy cost by energy reduction is much smaller than that of profit of the company, so balanced energy utilization considering both environmental and business sustainability.

Another on is a method of both installation effect and money optimization approach which are suitable for regulated area in power market but it can be effective for competitive organizations. Because most of multi-objective optimization tools were prepared for non-constrained problems, it was difficult to have enough results for constrained problems using most of these methods in convergence, uniformity and extensity. Therefore some simulations using various optimization approaches and enough results were able to be provided by the hybrid approach between adaptive DE method and IPESA-II. Although this study deals with only two objectives optimization problems, it is assumed that the approach can be applied to more than three objectives optimization problems and these problems should be conducted in future works. In addition, test data were used in all simulations in this study, but real multi-objective optimization problems should have additional constraints related to electrical and economical aspects. Comparison works between the results of the Pareto frontier provided by the proposed approach and actual decision making and its results in some actual project in the future.

Chapter References

[6-1] "Past Electricity Demand Data," [Online]. Available at Tokyo Electric Power Cooperation web site: http://www.tepco.co.jp/en/forecast/html/download-e.html

[6-2] O. Seppänen, W. J. Fisk and D. Faulkner, "Cost Benefit Analysis of the Night-Time Ventilative Cooling in Office Building," Lawrence Berkeley National Laboratory, June 2003

[6-3] S. Tanabe, M. Haned and N. Nishipana, "Indoor Environmental Quality and Productivity", REHVA Journal, pp26-31, June 2007

[6-4] The Energy Conservation Center, "Japan Energy Conservation for Office Buildings － Major points, measures, and successful cases of energy conservation for office buildings," [Online]. Available at : http://www.asiaeec-col.eccj.or.jp/brochure/pdf/office_building.pdf

[6-5] T. Takahama, "Optimization by Population-based Descent Method － Differential Evolution and Particle Swarm Optimization (集団的降下法による最適化 - 差分進化と粒子群最適化 -)," 2007 (in Japanese) [Online]. Available at: http://www.ints.info.hiroshima-cu.ac.jp/~takahama/documents/pdescent.pdf

[6-6] J. Kennedy and R. Eberhart, "Particle swarm optimization," Proceedings of IEEE International Conference on Neural Networks," vol.4, pp.1942-1948, November 1995.

[6-7] Y. Fukuyama, "Comparative Studies of Particle Swarm Optimization Techniques for Reactive Power Allocation Planning in Power Systems (電力系統の無効電力配分計画問題への PSO の適用比較検討)," IEEJ Transaction on Electrical and Electronic Engineering B, vol.124, no.5, August 2004 (in Japanese)

[6-8] M. Clerc and J. Kennedy, "The Particle Swarm—Explosion, Stability, and Convergence in a Multidimensional Complex Space," IEEE Transaction on Evolutionary Computation, vol.6, no.1, pp.58-73, February 2002

[6-9] R. C. Eberhart and Y. Shi, "Comparing inertia weights and constriction factors in particle swarm optimization," Proceedings of CEC 2000 pp.84-88, July 2000

[6-10] R. Storn and K. Price, "Minimizing the real functions of the ICEC'96 contest by differential evolution", Proceedings of the International Conference on Evolutionary Computation, pp.842–844, May 1996

[6-11] R. Storn and K. Price, "Differential evolution – a simple and efficient heuristic for global optimization over continuous spaces," Journal of Global Optimization, vol.11, pp.341–359, December 1997

[6-12] J. Zhang and A. C. Sanderson, "JADE: Adaptive Differential Evolution with Optional External Archive," IEEE Transaction on Evolutionary Computation, vol.13, no.5, pp.945-958, October 2009

[6-13] T. Takahama and S. Sakai, "Efficient Constrained Optimization by the epsilon Constrained Adaptive Differential Evolution", Proceedings of IEEE Congress on Evolutionary Computation (CEC2010), July 2010

[6-14] M. Li, S. Yang, X. Liu and K. Wang, "IPESA-II: Improved Pareto Envelope-Based Selection Algorithm II," Evolutionary Multi-Criterion Optimization, pp.143-155, March 2013

[6-15] C. A. C. Coello and M. S. Lechuga, "MOPSO: A Proposal for Multiple Objective Particle Swarm Optimization," Proceedings of the IEEE Congress of Evolutionary Computation (CEC'02), vol.2, p1051-1056, May 2002

[6-16] G. T. Pulido and C. A. C. Coello, "Using clustering techniques to improve the performance of a particle swarm optimizer," Proceedings of Genetic and Evolutionary Computation Conference (GECCO'2004)", pp.225–237, June 2004

[6-17] S. Kitamura, K. Mori, S. Sindo and Y. Izui, "改良 MOPSO によるエネルギー供給計画の多目的最適化 (Modified Multi-objective Particle Swarm Optimization Method and its Application to Energy Management System for Factories)", IEEJ Transaction on Electrical and Electronic Engineering C, vol.125, no.1, pp.21-28, January 2005 (in Japanese)

[6-18] K. Iwasaki and H. Aoki, "PSO を用いた多目的最適化手法による電圧無効電力制御 (Voltage and Reactive Power Control Using Multiple Objective Optimization Method with PSO)," Proceedings of the School of Engineering Tokai University, vol.47, no.2, pp.49-54, 2007

[6-19] D. W. Corne, J. D. Knowles and M. J. Oates, "The Pareto envelope-based selection algorithm for multiobjective optimization," Parallel Problem Solving from Nature PPSN VI, pp.839-848, September 2000

[6-20] D. W. Corne, J. D. Knowles and M. J. Oates, "PESA-II: Region-based selection in evolutionary multiobjective optimization," Proceedings of the Genetic and Evolutionary Computation Conference (GECCO) 2001, pp. 283–290, July 2001

[6-21] D. Knowles and D. Corne, "The Pareto archived evolution strategy: A new baseline algorithm for multiobjective optimization," Proceedings of the 1999 Congress on Evolutionary Computation, pp.98 -105, July 1999

[6-22] E. Zitzler and L. Thiele, "Multiobjective Evolutionary Algorithmes: A Comparative Case Study and the Strength Pareto Approach," IEEE Transactions on Evolutionary Computation, vol.3, no.4, pp.257-271, November 1999

[6-23] F. Rivas-Dávalos, E. Moreno-Goytia, G. Gutiérrez-Alcaraz and H. Tovar-Hernández "Multiobjective optimization challenges in power system: The next step forward," Proceedings of the Electronics, Robotics and Automotive Mechanics Conference, pp.681-686, September 2007

[6-24] K. Kuroda, H. Magori, R. Yokoyama, Y. Matsufuji, and T. Ichimira, "Optimal Allocation of Dispersed Generations in Distribution Networks to Realize Low-Carbonate Power System," Power System Technology, vol.36 (12), pp.1-10, December 2012

[6-25] H. Yang, F. Wen, L. Wang and S. N. Singh, "Newton-Downhill Algorithm for Distribution Power Flow Analysis," Proceeding of the 2nd IEEE International. Conference on Power and Energy (PECon2008), pp.1628-1632, December 2008

Chapter 7 Conclusions

This dissertation has presented critical technologies and measures to realize Smart Grid and the quantification and formulation approaches of their effects and values were considered and proposed. In conclusion, achievements of this study and expectations for future research are described in this chapter.

7.1. Achievements of This Study

In this dissertation, effective Smart Grid business models for three major areas, "optimal power supply", "optimal power utilization" and "optimal supply and demand" were proposed with critical composed technologies and measures and their evaluation methods. In the study, technologies and measures which should be improved by the effective utilization of information communication technology (ICT) were focused on especially, and various considerations in the aspect of business profitability were conducted. To show achievements of this study, firstly topics covered in this dissertation are summarized for the evaluation of the completeness of this study and then the Smart Grid value circulation model is provided because all measures composed of Smart Grid should be collaborated each other providing added-values and these collaborations should be critical to realize Smart Grid. After that, achievements and contributions in this study are summarized.

7.1.1. Topics Covered in This Dissertation

Table 7-1 shows actions for critical components in actual Smart Grid projects and their objectives which were provided in chapter two. In the table, topics covered in this dissertation have been changed to Italic bold fonts with underline and topics which are not covered but proposed concepts, techniques or methods in this study can be used for have been changed to Italic bold fonts.

It is found that many critical components in Smart Grid were covered by the topics in this study and thus research topics should be reasonable in the aspect of completeness. Uncovered topics include electric assets and their automation and control, and asset maintenance related topics. These topics are also important to realize Smart Grid and ICT contribution should be expected areas, therefore, these topics should be dealt with in future works.

Table 7-1 Actions for Critical Components in Smart Grid Projects and Their Objectives

Critical Components Technological Countermeasures	**Actions in Smart Grid Projects**	**Objectives**
(1) Optimal Power Supply - ***Dispersed generation (DG)*** - ***Optimal Volt-Ampere Reactive (VAR) control (Step Voltage Regulator (SVR), Static Var Compensator (SVC) Installation)*** - ***Network reconfiguration*** - Autonomous control	- ***Optimal DG installation*** - ***Optimal SVR, SVC installation*** - ***Optimal distribution network reconfiguration*** - Generator operation and maintenance optimization (Asset management Asset life cycle cost management)	- ***Peak power cut/shift*** - ***Power loss reduction*** - Total generation cost reduction - ***Renewable Energy Sources (RES) capacity expansion*** - ***Stable voltage/current*** - Ancillary service cost reduction - Operation and maintenance Cost reduction - Life time cost reduction
(2) Optimal Power Utilization - ***Demand-side efficient energy management (Visualization, device control, demand forecast,)*** - ***Various electricity price program including demand response (DR)*** - Smart equipment and Smart appliance (Autonomous control)	- ***Energy Management System (EMS) (Building-EMS (BEMS), Home-EMS (HEMS), Mansion-EMS (MEMS) and Factory-EMS (FEMS))*** - ***DR*** and Various electricity price system - Smart equipment and appliance Autonomous control -	- ***Electricity saving*** - ***Electricity peak cut*** - ***Electricity cost saving*** - ***CO_2 emission amount reduction*** - ***Optimal electricity price program*** -
(3) Optimal power supply and demand - ***Wide area energy management*** - ***Wide area system, asset and device status management*** - ***Outage area specification*** - Distribution automation (Automatic and remote control) - ***Supply and demand forecasting and adjusting*** (***DG***, Battery, Power storage including electric vehicle (EV), Stationary Power storages, Uninterruptible Power Supply (UPS), ***DR***)	- ***EMS (Community-EMS (CEMS), Wide Area EMS)*** - ***Outage management*** - Asset condition monitoring - Distribution automation - EV integration - System control - ***Aggregator services (BEMS, DR, MEMS etc.)***	- ***Real-time supply and demand balancing*** - ***Outage indexes minimization*** - Operation and maintenance cost reduction - ***Deferred asset investment*** - Deferred inspection interval - ***Efficient management for Small and many loads and power supply asset such as dispersed generators and power storages***

7.1.2. Smart Grid Added-value Circulation Model and Their Optimal Evaluation Method

Through various researches in this study, it was assumed that all measures composed of Smart Grid should be collaborated each other providing added-values because Smart Grid critical technologies and measures contribute not only to the first and major objective but also to other various objectives. For example, it was showed that effective DG installation could reduce power loss and that also contributes to CO_2 reduction by the reduced power in chapter three. DR, which was considered in chapter four, provides incentives such as electricity price down or rebate provision etc., for consumers' power demand reduction, while power companies can defer their installation schedule of power system assets and system operators can maintain system stability by the accumulation of such demand reductions. In addition, as described in chapter five, while power supply network operator's challenges reflect to network utilization fee, solutions or mitigation measures for these challenges gain the profitability of power supply network users. In these ways, added-values of Smart Grid technologies and measures are related each other and these contributions should reflect to various benefits such as incentives for market participants.

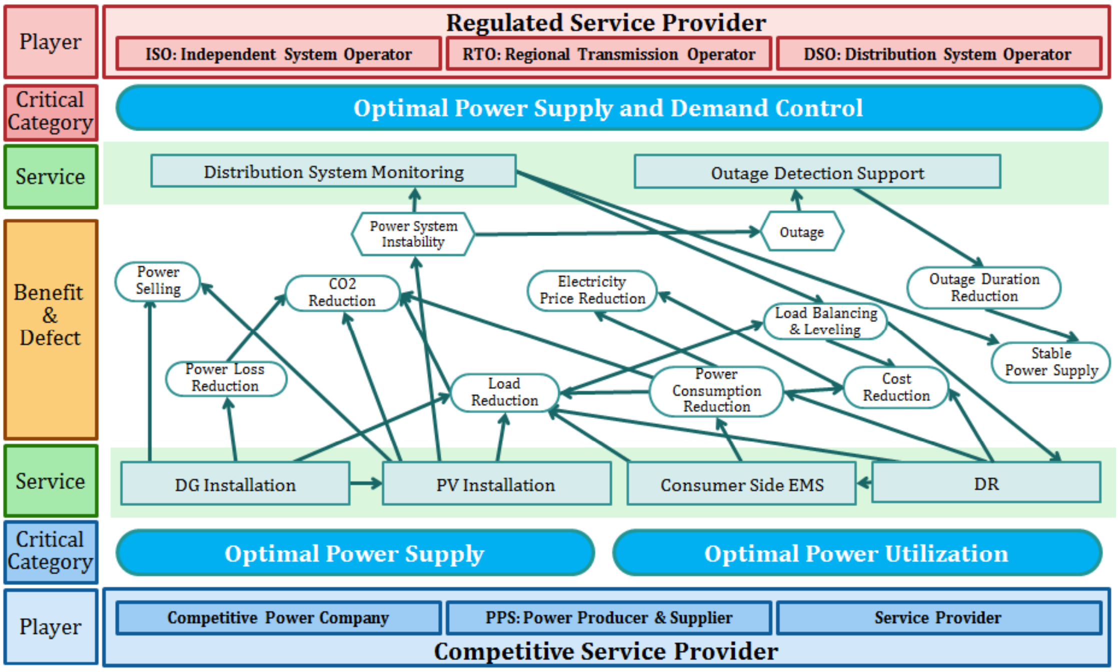


Figure 7-1 Added-value Circulation Model in Smart Grid

Figure 7-1 shows added-value circulation model in Smart Grid and three Smart Grid critical categories, services researched in chapter three to five and some related benefits and defects are described. All values and challenges are related each other and optimized by collaborative operations between regulated service providers and competitive service providers. In the consideration of the profitability of competitive service providers, it is necessary to consider not only the benefit of service providers but also defects of the service for regulated service providers. Solutions or mitigations for these defects would convert to benefits of regulated service providers and these benefits should contribute to mitigated conditions of market participations and would be paid-back to solution providers as the reduction of the market entry fee etc., because regulated service providers are non-profitable organizations.

In electric power business which is one of mature businesses in Japan, it is almost impossible to provide enormous values or benefits only with single technology or solution provision. Therefore combinations of various added-values should be important in the installation of Smart Grid technologies and measures.

7.1.3. Summary of Achievements and Contributions

In this subsection, achievements in this study are summarized per chapter and then major contributions of this dissertation are described.

In chapter two, critical components of Smart Grid were decided from activities in Smart Grid demonstration projects in the United States. In the consideration, candidates of Smart Grid critical component technologies and measures were extracted focusing on their benefit in order to consider their profitability. In addition, selected candidates were evaluated whether ICT utilization could contribute effectively.

From chapter three to chapter five, detailed considerations for Smart Grid critical components defined in chapter two were conducted such as reorganization of the components, effect quantification of Smart Grid technologies and measures, and proposal of effective business models.

In chapter three, optimal power generation technologies and measures in demand-side were considered and the installation effect of DG were simulated and evaluated. In the chapter, an approach to decide optimal location and size of DGs for the power loss minimization and also an evaluation method of installation effect of Photovoltaic (PV) generation systems which are expected as future main RES generation systems were proposed.

In chapter four, optimal power utilization technologies and measures in demand-side were explored and EMS and DR which are receiving big attention in Japan recently were evaluated. In the chapter, effect formulation and evaluation were conducted and general business models for both solutions might be difficult to be effective in consideration of Japanese environment. Therefore, it is also discussed effective business models and their effect quantification.

In chapter five, technologies and measures for the optimal power supply and demand were considered, and effective information utilization models for power distribution area were proposed. As the first model, a distribution system monitoring system for a large number of PV installed environment was proposed. In the proposed system, voltage fluctuation at each node of distribution systems was estimated by the power flow calculation using smart meter data. In case that voltage violation would be assumed, the system also provides estimation and simulation functions to evaluate effectiveness of countermeasures to avoid these problems. As the second model, outage detection system using smart meter data was also proposed because data sensing devices in low voltage (LV) distribution systems are not installed sufficiently at present and thus it is difficult to detect outages in LV distribution systems. As the result, the proposed approach would not be a method for the first outage detection for a single outage however it should be an effective method to detect area outages and be a support tools for the status confirmation when a customer would notify an outage occurrence.

In chapter six, evaluation methods for installation effects of technologies and measures from chapter three to chapter five were considered and proposed. Firstly, value converting methods for periodical amount and equivalent monetary value were proposed because business profitability should be evaluated on periodical basis such as month, quarter, half year and year with same comparable units. Then, two evaluation methods for the installation effect of Smart Grid critical technologies and measures were proposed. The first one is a method of profitability priority approach and this is appropriate for general competitive companies consuming a lot of electric power. The other is a method of both installation effect and cost optimization approach, because most of installation technologies and measures in power systems consider multi-objectives which has trade-off relationships such as installation.

Major contributions of this dissertation are as follows.

- The major benefit of information utilization in future power system is to realize optimization of whole power systems by optimal operation and control of power system components by analysis and utilization of various status information collected accurately and rapidly as numeral data. This study considered holistic optimization of power systems in demand-side and proposed evaluation methods not only for individual and static installation effects but also holistic and periodical installation effects of Smart Grid component technologies and measures to solve current limitations in power systems and to improve performance of these technologies and measures.

- In order to be provided Smart Grid component measures continuously, business profitability of these component measures without dependency of subsidies or preference treatments should be necessary. This dissertation not only provided quantification methods of generation values but also proposed the value circulation model between supply and demand sides. In addition, it is showed that value exchanges between them were possible virtually with ICT and environmental conditions activating values were also provided.

- In order to reform existing power systems, which is one or important social infrastructure into advanced power systems, "Smart Grid", the collaboration of electric engineering with technologies and knowledge in various areas should be essential. Therefore, this study has adopted integration approaches among various academic and business areas. As mentioned in above, ICT and business profitability are major integration and collaboration areas in this dissertation. All approaches and methods in this study were focused on the ICT utilization and business profitability, the expansion of ICT application areas should contribute to improvement of electric power business efficiency and effectiveness and consideration of business profitability using various concepts and theories in economics, business administration and social science etc., should be contribute to realistic and practicable approaches in real business.

7.2. Avenues of Future Research

In this study, benefit formulation and quantification of Smart Grid measures and benefit expansion models were considered based on the hypothesis that continuous business profitability by the Smart Grid realization measures should be required because continuous technical innovations and investments to both supply and demand sides should be necessary. Japanese power market, which is the main target of various Smart Grid measures proposed in this study, is on the start stage of smart meter installation, and utilized models and data should be clarified step-by-step and stored gradually. Therefore, it is necessary to improve various methods and models considered in this study continuously with new enhanced data and models.

(1) Expansion of Actual Data Utilization in Benefit Calculation of Smart Grid Measures

In Japan, presently it might be difficult to get most of actual data required for benefit calculation methods proposed in this study. Also standard power supply system models with adequate information for reasonable calculation used in proposed methods should not be clear because it is the first stage for the Smart Grid implementation.

Therefore, it is necessary for benefit calculation models proposed in this study to conduct simulations using actual data as many as possible to improve the accuracy of the models. In addition, by the cause consideration of gaps between simulation and actual results, proposed models also should be improved considering additional constraints and assumptions which should be contributed to improving the accuracy of the simulation results. In the consideration, it is important to define reasonable data amount and accuracy because these should influence to the cost for the measures although these are contribute to accuracy of the simulation results Again, business sustainability should be the most important to realize Smart Grid.

(2) Data Assumption in Introductory Process

For the realization of Smart Grid, many and various technical measures should be implemented collaborate each other taking long time. Even smart meter installation, this is the first step of Smart Grid realization, it is expected it takes more than ten years in Japan. Most of proposed models and measures in this study assume that smart meters and sensors are fully installed in the simulation target areas and data using these models and measures are available. Therefore, it should be necessary to use various assuming or estimating data during the implementation stage of Smart Grid and reasonable data preparation methods should be discussed. In addition, it should be necessary to consider evaluation methods and measures during the implementing stage of Smart Grid.

(3) Information Utilization of Power System for the Other New Service Businesses

In order to reform the current power system which is already one of the important social infrastructures, into Smart Grid, long term and huge investment should be required and also new added values which surpass the investment largely would be essential. As one of effective ideas, new services which utilize information used for basic power supply services, such as metering data, should be considered more. In this study, new services using metering data were proposed such that optimal DG allocation, impact evaluation of many PV systems installation environment, the distribution system monitoring method in a large number of PV systems installed environment and the outage area detection support method utilizing metering collection status information. These new services using already collected data do not require additional data collection mechanisms and thus the service preparation cost can be reduced. Considering the encouragement of lower energy pricing, it should be critical for energy supplier to provide new services using existing data as well as efficiency improvement of existing services.

Recently, various industries such as healthcare, finance and transportation etc., have succeeded to generate huge benefit by the expansion of ICT utilization. However in electric power supply systems, which large scale and concentrated power generation plants have provided electricity to consumers in one way through also large scale transmission and distribution systems, it looks the information utilization level is limited, especially in the power systems control area. This is because current high performance power systems in Japan have been developed with asset (hardware) based autonomous control technologies. Therefore, it opens up a lot of possibilities for generating a large scale of benefit in electric power industry by the expansion of ICT utilization areas. In the near future, available status information should increase dramatically by the smart meter penetration and other sensor technologies, these high frequent, rapid exchanging and many area covered metering information should be the first “Big Data” in Japan. To transform these “Big Data” into new values is one of critical challenges and this is the next key factor to realize Smart Grid.

APPENDICES

APPENDIX A – Publications and Presentations

Refereed Papers

[1] **Ken Kuroda**, Tomiyasu Ichimura and Ryuichi Yokoyama, "A Hybrid Multi-objective Optimization Method Considering Optimization Problems in Power Distribution Systems," Journal of Modern Power Systems and Clean Energy (MPCE) (ISSN: 2196-5420, Journal no.40565)(Accepted)

[2] **Ken Kuroda**, Tomiyasu Ichimura and Ryuichi Yokoyama, "Benefit Evaluation Approach of Consumer Side Energy Management Systems Focusing on Enterprise Productivity," Journal of Clean Energy Technologies (ISSN: 1793-821X), vol.3, no.4, pp.254-260, July 2015

[3] **Ken Kuroda**, Hideki Magori, Ryuichi Yokoyama, Yuichi Matsufuji and Tomiyasu Ichimura, "Optimal Allocation of Dispersed Generations in Distribution Networks to Realize Low-Carbonate Power System," Journal of Power System Technology (ISSN 1000-3673), vol.36 (12), pp.1-10, December 2012

[4] **Ken Kuroda**, Tomiyasu Ichimura, Hideki Magori and Ryuichi Yokoyama, "A New Approach for Optimal Location and Sizing of Distributed Generation using an Exact Solution Method," International Journal of Smart Grid and Clean Energy (ISSN: 2315-4462), vol.1, no.1, pp.109–115, September 2012

[5] **Ken Kuroda**, Ryuichi Yokoyama, Daisuke Kobayashi and Tomiyasu Ichimura, "An Approach to Outage Location Prediction Utilizing Smart Metering Data," Asia Modeling Symposium (AMS) 2014, September 2014

[6] **Ken Kuroda**, Hideki Magori, Ryuichi Yokoyama, Daisuke Kobayashi and Tomiyasu Ichimura, “An Evaluation Method for the Impact of PV Installations into Distribution Systems,” The 2014 IEEE Innovative Smart Grid Technologies (ISGT) Asia Conference, pp.470-475, May 2014

[7] **Ken Kuroda**, Tomiyasu Ichimura and Ryuichi Yokoyama, “Critical Factors and ICT Contribution for Accelerating Smart Grid Realization,” The International Conference on Electrical and Electronics Engineering, Clean Energy and Green Computing (EEECEGC) 2013, pp.207-219, December 2013

[8] **Ken Kuroda**, Yuichi Matsufuji Tetsuya Kashiwagi, Tomiyasu Ichimura and Ryuichi Y , “An Approach of Distribution Systems Stabilization for a Large-scale PV Systems Installation Environment,” IEEE The 4th European Innovative Smart Grid Technologies (ISGT Europe), pp.1-5, October 2013

[9] **Ken Kuroda**, Hideki Magori, Tomiyasu Ichimura and Ryuichi Yokoyama, “Basic Consideration of Power Loss Reduction Effect by Electricity Demand Reduction,” The 1st International Smart Grid Conference & Exhibition (ISGC&E) 2013, pp.254-259, July 2013

[10] **Ken Kuroda**, Tomiyasu Ichimura and Ryuichi Yokoyama, “An Effective Evaluation Approach of Demand Response Programs for Residential Side,” The 9th IET International Conference on Advances in Power System Control, Operation and Management (APSCOM) 2012, pp.1-6, November 2012

[11] **Ken Kuroda**, Tomiyasu Ichimura, Yuichi Matsufuji and Ryuichi Yokoyama, “Key ICT Solutions for Realizing Smart Grid,” IEEE International Conference on Smart Grid Engineering (SGE’12), pp.1-8, August 2012

Oral Presentation

[12] **Ken Kuroda**, Tomiyasu Ichimura, Hideki Magori and Ryuichi Yokoyama, "Basic Consideration for Optimal Allocation of Shared Dispersed Generation in Many Small Dispersed Generations Installed Environment (小規模分散電源大量導入環境における共用分散電源の最適配置に関する基礎検討)," The 2013 IEEJ Annual Meeting Record, 6-149, March 2013 (in Japanese)

Other Papers

[13] Tomiyasu Ichimura, Masahiro Maeeda, Kunio Fukumoto, **Ken. Kuroda** and Ryuzo Fukunaga, "Approach to Energy Management for Companies," FUJITSU Scientific & Technical Journal (ISSN: 0016-2523), vol.50, no.2, pp.41-48, April 2014

[14] Yicheng Zhou, Jie Zhang, **Ken Kuroda** and Tomiyasu Ichimura, "Branch Parameter Estimation for Distribution System (配電系統の系統パラメータ同定の一手法)," The 2014 IEEJ Annual Meeting Record, 6-129 (in Japanese), March 2014

[15] Yicheng Zhou, Jinhua She, **Ken Kuroda**, Junichi Yokoyama and Tomiyasu Ichimura, "Prioritization of Maintenance Tasks for Transmission Lines Based on Index of Degree of System Influence (系統影響度指標による送電線メンテナンス優先順位決定手法)," Proceedings of the 24th Annual Conference of Power & Energy Society, IEE of Japan, pp.11-7-12, August 2013

[16] Yicheng Zhou, **Ken Kuroda**, Junichi Yokoyama and Tomiyasu Ichimura, "時間帯別電気料金設定に関する基礎的検討（１）　ーコストベースのアプローチー," The 2013 IEEJ Annual Meeting Record, 6-073, March 2013 (in Japanese)

[17] Tomiyasu Ichimura, **Ken Kuroda**, Hideki Magori and Ryuichi Yokoyama, "A New Approach for Leveling Maintenance Cost in Electric Utilities," The 9th IET International Conference on Advances in Power System Control, Operation and Management (APSCOM) 2012, pp.1-7, November 2012

[18] Tomiyasu Ichimura, **Ken Kuroda**, Hideki Magori and Ryuichi Yokoyama, “Quadratic Programming Problem for Determining Electric Power Asset to be Replaced in Leveling of Replacement Cost,” The International Conference on Electrical Engineering (ICEE) 2011, July 2011

[19] Tomiyasu Ichimura, **Ken Kuroda**, Hideki Magori and Ryuich Yokoyama, “A priority decision method to replace electric power equipment in leveling replacement cost (電力設備更新コスト平準化に向けた優先順位決定方式),” 31st Joint of Technical Meeting on Power Engineering & Power Systems Engineering, IEE of Japan, pp.1-6, September 2010

[20] Tomiyasu Ichimura, **Ken Kuroda**, Kenichi Yamagishi, Wataru Kawai, Kazuya Sasaki and Ryuichi Yokoyama, “Integration Approach of Multiple Risk Values for Assets in Power Systems,” The International Conference on Electrical Engineering (ICEE) 2010, pp.1-6, July 2010

[21] Tomiyasu Ichimura, **Ken Kuroda**, Kenichi Yamagishi, Wataru Kawai and Kazuya Sasaki, “Calculation method of electric demand cost using measurement results of power flow (潮流実績を用いた電力需要原価の算定手法),” The 2010 IEEJ Annual Meeting Record, 6-063 March 2010 (in Japanese)

[22] Tomiyasu Ichimura, **Ken Kuroda**, Kenichi Yamagishi, Wataru Kawai and Kazuya Sasaki, “Utilization of an asset information base for advanced power transmission asset management”, IEEJ-EIT Joint Symposium on Advanced Technology in Power Systems, November 2009

APPENDIX B – Smart Grid Definition by METI (in Japanese)

“次世代エネルギーシステム、いわゆるスマートグリッドは、最新のIT技術を活用して電力供給、需要に係る課題に対応する次世代電力系統とされる概念である。一般に再生可能エネルギー等の分散型電源の大規模導入に向けて、従来からの大規模電源と送配電網との一体運用に加え、高速通信ネットワーク技術等を活用し、分散型電源、蓄電池や需要側の情報を統合々活用して、高効率、高品質、高信頼度の電力供給システムの実現を目指すものとされる。

APPENDIX C – Distribution System Model Parameters in [3-12]

Branches parameter

F	T	R	X	F	T	R	X	F	T	R	X	F	T	R	X
126	1	0.00125	0.0018	32	33	0.00304	0.00278	62	65	0.00087	0.00103	96	97	0.00067	0.00061
1	2	0.00031	0.0005	4	34	0.0047	0.0043	63	66	0.00043	0.00041	96	98	0.00088	0.00081
2	3	0.00285	0.00261	4	35	0.00153	0.00181	64	67	0.00056	0.00052	14	99	0.00134	0.00158
3	4	0.00143	0.0013	35	36	0.00076	0.0007	9	68	0.00234	0.00277	99	100	0.00053	0.00049
4	5	0.00078	0.00092	35	37	0.0012	0.00142	68	69	0.00035	0.00034	99	101	0.00086	0.00102
5	6	0.00063	0.00074	37	38	0.00056	0.00051	10	70	0.00113	0.00133	101	102	0.00094	0.00086
6	7	0.0012	0.00137	37	39	0.00086	0.00079	70	71	0.00056	0.00052	102	103	0.0013	0.00119
7	8	0.00089	0.00105	37	40	0.00105	0.00124	70	72	0.00078	0.00092	102	104	0.00059	0.00054
8	9	0.00123	0.00145	40	41	0.00075	0.00068	72	73	0.00065	0.0006	103	105	0.00088	0.00081
9	10	0.00087	0.00103	40	42	0.00063	0.00058	72	74	0.00089	0.00082	101	106	0.00153	0.00181
10	11	0.00112	0.00132	5	43	0.00124	0.00114	72	75	0.00056	0.00052	106	107	0.00069	0.00063
11	12	0.00093	0.0011	5	44	0.00089	0.00082	72	76	0.00089	0.00092	106	108	0.00075	0.00069
12	13	0.00065	0.00078	5	45	0.00034	0.00031	11	77	0.00135	0.00124	15	109	0.00109	0.001
13	14	0.00086	0.00102	6	46	0.00106	0.00097	12	78	0.00096	0.00088	16	110	0.0021	0.00192
14	15	0.0025	0.00296	7	47	0.00096	0.00113	78	79	0.00068	0.00062	17	111	0.0013	0.00119
15	16	0.00342	0.00405	47	48	0.00075	0.00069	13	80	0.0012	0.0011	111	112	0.00056	0.00052
16	17	0.00068	0.0008	47	49	0.00103	0.00122	80	81	0.00056	0.00052	18	113	0.00148	0.00136
17	18	0.00083	0.00098	49	50	0.00087	0.0008	14	82	0.00087	0.00103	18	114	0.00087	0.00103
18	19	0.0012	0.00142	49	51	0.00097	0.00115	82	83	0.00142	0.0013	114	115	0.00171	0.00157
19	20	0.0014	0.00166	51	52	0.00113	0.00103	82	84	0.00086	0.00102	115	116	0.00092	0.00084
1	21	0.0021	0.00249	51	53	0.00078	0.00092	84	85	0.00076	0.0007	115	117	0.00121	0.00111
21	22	0.00086	0.00078	53	54	0.00065	0.0006	85	86	0.00045	0.00042	116	118	0.00062	0.00057
21	23	0.00124	0.00147	53	55	0.00121	0.00143	85	87	0.00069	0.00063	114	119	0.00135	0.0016
23	24	0.00056	0.00051	55	56	0.00132	0.00121	84	88	0.00105	0.00096	119	120	0.0012	0.0011
23	25	0.0014	0.00166	56	57	0.00069	0.00063	84	89	0.00088	0.00105	119	121	0.00221	0.00262
25	26	0.00071	0.00065	57	58	0.00079	0.00072	89	90	0.00065	0.0006	121	122	0.00067	0.00062
25	27	0.00135	0.0016	56	59	0.00023	0.00021	90	91	0.00105	0.00096	121	123	0.00083	0.00076
27	28	0.00065	0.00059	57	60	0.00065	0.00061	90	92	0.00037	0.00034	19	124	0.00056	0.00052
27	29	0.00078	0.00072	58	61	0.00057	0.00052	91	93	0.00057	0.00052	8	125	0.00462	0.00423
27	30	0.00053	0.00048	55	62	0.0011	0.0013	89	94	0.00078	0.00092				
2	31	0.0023	0.0021	62	63	0.00096	0.00088	94	95	0.00093	0.00086				
3	32	0.0021	0.00249	63	64	0.00211	0.00193	94	96	0.00113	0.00134				

Buses parameter

No	P	Q	No.	P	Q	No.	P	Q	No.	P	Q	No.	P	Q
1	0	0	26	0.078	0.045	51	0	0	76	0.049	0.042	101	0	0
2	0.12	0.085	27	0.042	0.025	52	0.009	0.006	77	0.035	0.026	102	0	0
3	0	0	28	0.056	0.042	53	0	0	78	0	0	103	0	0
4	0	0	29	0.023	0.012	54	0.034	0.026	79	0.034	0.024	104	0.035	0.025
5	0	0	30	0.063	0.047	55	0	0	80	0	0	105	0.055	0.042
6	0.35	0.19	31	0.105	0.068	56	0	0	81	0.056	0.044	106	0	0
7	0	0	32	0	0	57	0	0	82	0	0	107	0.078	0.059
8	0	0	33	0.204	0.176	58	0	0	83	0.034	0.021	108	0.032	0.021
9	0.25	0.16	34	0.135	0.098	59	0.053	0.038	84	0	0	109	0.043	0.024
10	0	0	35	0	0	60	0.035	0.02	85	0	0	110	0.013	0.008
11	0	0	36	0.012	0.008	61	0.024	0.015	86	0.022	0.015	111	0	0
12	0.326	0.233	37	0	0	62	0	0	87	0.034	0.021	112	0.047	0.03
13	0	0	38	0.045	0.031	63	0	0	88	0.042	0.031	113	0.076	0.056
14	0	0	39	0.03	0.018	64	0	0	89	0	0	114	0	0
15	0	0	40	0	0	65	0.078	0.054	90	0	0	115	0	0
16	0.103	0.078	41	0.085	0.053	66	0.023	0.015	91	0	0	116	0	0
17	0	0	42	0.026	0.015	67	0.013	0.008	92	0.044	0.035	117	0.039	0.024
18	0	0	43	0.033	0.021	68	0	0	93	0.036	0.022	118	0.056	0.037
19	0.067	0.045	44	0.052	0.034	69	0.035	0.021	94	0	0	119	0	0
20	0.045	0.027	45	0.036	0.025	70	0	0	95	0.065	0.047	120	0.043	0.031
21	0	0	46	0.024	0.016	71	0.024	0.017	96	0	0	121	0	0
22	0.112	0.078	47	0	0	72	0	0	97	0.023	0.015	122	0.035	0.024
23	0	0	48	0.036	0.022	73	0.045	0.032	98	0.071	0.052	123	0.068	0.049
24	0.03	0.018	49	0	0	74	0.032	0.02	99	0	0	124	0.042	0.029
25	0	0	50	0.045	0.034	75	0.025	0.017	100	0.025	0.017	125	0.035	0.023

Buses voltage

No.	A	Angle	No.	A	Angle	No.	A	Angle	No.	A	Angle	No.	A	Angle
1	1.0394	-0.21426	27	1.0363	-0.26533	53	0.99656	-0.69277	79	0.9801	-0.93705	105	0.97524	-1.0092
2	1.0369	-0.27424	28	1.0362	-0.26563	54	0.99652	-0.69297	80	0.97844	-0.96274	106	0.97528	-1.0119
3	1.02	-0.39965	29	1.0363	-0.26571	55	0.99607	-0.70095	81	0.97839	-0.96301	107	0.97518	-1.0124
4	1.012	-0.46142	30	1.0362	-0.26561	56	0.99583	-0.70321	82	0.9759	-1.0039	108	0.97524	-1.0123
5	1.0076	-0.52919	31	1.0365	-0.27765	57	0.99577	-0.70396	83	0.97582	-1.0047	109	0.97327	-1.0466
6	1.0042	-0.58159	32	1.0191	-0.40729	58	0.99574	-0.70428	84	0.97535	-1.0122	110	0.96922	-1.1111
7	0.9986	-0.66039	33	1.018	-0.40906	59	0.99581	-0.70335	85	0.97528	-1.013	111	0.96851	-1.1223
8	0.99491	-0.71551	34	1.011	-0.46813	60	0.99573	-0.70445	86	0.97527	-1.0131	112	0.96847	-1.1228
9	0.9899	-0.7909	35	1.0115	-0.47077	61	0.99572	-0.7045	87	0.97525	-1.0134	113	0.96769	-1.1344
10	0.98678	-0.83725	36	1.0115	-0.4709	62	0.99584	-0.70462	88	0.97528	-1.0127	114	0.96749	-1.1396
11	0.98315	-0.89147	37	1.0111	-0.4777	63	0.99579	-0.70517	89	0.97495	-1.0183	115	0.96722	-1.1423
12	0.9802	-0.93636	38	1.0111	-0.47802	64	0.99575	-0.70565	90	0.97486	-1.019	116	0.96714	-1.1431
13	0.97856	-0.96222	39	1.0111	-0.47816	65	0.99572	-0.70654	91	0.9748	-1.0196	117	0.96714	-1.1432
14	0.9765	-0.99444	40	1.0109	-0.48142	66	0.99577	-0.70534	92	0.97484	-1.0191	118	0.96708	-1.1436
15	0.97334	-1.0456	41	1.0108	-0.48243	67	0.99573	-0.70578	93	0.97477	-1.02	119	0.96711	-1.1453
16	0.96927	-1.1106	42	1.0109	-0.48173	68	0.98975	-0.79369	94	0.97472	-1.0217	120	0.96702	-1.1459
17	0.96861	-1.1213	43	1.0076	-0.52984	69	0.98973	-0.79396	95	0.97461	-1.0225	121	0.96668	-1.1519
18	0.96788	-1.1331	44	1.0076	-0.52989	70	0.98641	-0.84244	96	0.97452	-1.0248	122	0.96664	-1.1523
19	0.96754	-1.1391	45	1.0076	-0.52934	71	0.98639	-0.84261	97	0.97449	-1.025	123	0.96658	-1.1526
20	0.96743	-1.1414	46	1.0042	-0.58195	72	0.98619	-0.84552	98	0.97441	-1.0255	124	0.9675	-1.1395
21	1.038	-0.23791	47	0.99799	-0.66999	73	0.98614	-0.84588	99	0.97593	-1.0026	125	0.99465	-0.71793
22	1.0378	-0.23899	48	0.99795	-0.67047	74	0.98614	-0.84602	100	0.97591	-1.0028	126	1.05	0
23	1.0373	-0.24828	49	0.9974	-0.67924	75	0.98616	-0.84572	101	0.9756	-1.0073			
24	1.0373	-0.24856	50	0.99733	-0.67961	76	0.9861	-0.84597	102	0.97545	-1.0081			
25	1.0367	-0.2587	51	0.99693	-0.68689	77	0.98307	-0.89197	103	0.97533	-1.0088			
26	1.0366	-0.2597	52	0.99691	-0.68704	78	0.98014	-0.93677	104	0.97542	-1.0084			

APPENDIX D – Meter Property Data Used in the Simulation in 5.3

Meter No.	Grp.	Location		Pole Trans.	Bus	Meter No.	Grp.	Location		Pole Trans.	Bus	Meter No.	Grp.	Location		Pole Trans.	Bus
		x	*y*					*x*	*y*					*x*	*y*		
1	12	10	10	1	B1	121	26	40	45	15	B1	241	59	75	10	21	B2
2	20	10	15	1	B1	122	33	40	50	15	B1	242	18	75	15	21	B2
3	25	10	20	5	B1	123	34	40	55	19	B1	243	38	75	20	21	B2
4	10	10	25	5	B1	124	47	40	60	19	B1	244	19	75	25	22	B2
5	38	10	30	9	B1	125	3	40	65	43	B3	245	52	75	30	22	B2
6	6	10	35	9	B1	126	25	40	70	43	B3	246	20	75	35	22	B2
7	13	10	40	13	B1	127	4	40	75	47	B3	247	48	75	40	23	B2
8	42	10	45	13	B1	128	19	40	80	47	B3	248	11	75	45	23	B2
9	31	10	50	17	B1	129	37	40	85	51	B3	249	19	75	50	23	B2
10	11	10	55	17	B1	130	32	40	90	51	B3	250	5	75	55	24	B2
11	60	10	60	41	B3	131	36	40	95	55	B3	251	30	75	60	24	B2
12	29	10	65	41	B3	132	20	40	100	55	B3	252	28	75	65	24	B2
13	1	10	70	45	B3	133	55	45	15	3	B1	253	36	75	80	59	B3
14	26	10	75	45	B3	134	47	45	20	3	B1	254	2	75	85	59	B3
15	18	10	80	49	B3	135	35	45	25	7	B1	255	20	75	90	59	B3
16	46	10	85	49	B3	136	26	45	30	7	B1	256	9	75	95	60	B3
17	54	10	90	53	B3	137	44	45	35	11	B1	257	20	75	100	60	B3
18	50	10	95	53	B3	138	10	45	40	11	B1	258	46	75	105	60	B3
19	11	10	100	57	B3	139	4	45	45	15	B1	259	38	80	10	25	B2
20	7	10	105	57	B3	140	15	45	50	15	B1	260	58	80	15	25	B2
21	1	15	10	1	B1	141	46	45	55	19	B1	261	50	80	20	25	B2
22	10	15	15	1	B1	142	58	45	60	19	B1	262	34	80	25	22	B2
23	23	15	20	5	B1	143	21	45	65	43	B3	263	37	80	30	22	B2
24	12	15	25	5	B1	144	42	45	70	43	B3	264	12	80	35	22	B2
25	59	15	30	9	B1	145	48	45	75	47	B3	265	55	80	40	23	B2
26	53	15	35	9	B1	146	3	45	80	47	B3	266	20	80	45	23	B2
27	35	15	40	13	B1	147	48	45	85	51	B3	267	37	80	50	23	B2
28	44	15	45	13	B1	148	30	45	90	51	B3	268	36	80	55	28	B2
29	9	15	50	17	B1	149	13	45	95	55	B3	269	47	80	60	28	B2
30	16	15	55	17	B1	150	37	45	100	55	B3	270	43	80	65	28	B2
31	2	15	60	41	B3	151	55	50	15	3	B1	271	42	80	70	35	B2
32	50	15	65	41	B3	152	57	50	20	3	B1	272	46	80	75	35	B2
33	48	15	70	45	B3	153	40	50	25	7	B1	273	16	80	80	37	B2
34	48	15	75	45	B3	154	1	50	30	7	B1	274	33	80	85	37	B2
35	20	15	80	49	B3	155	40	50	35	11	B1	275	31	80	90	39	B2
36	28	15	85	49	B3	156	58	50	40	11	B1	276	34	80	95	39	B2
37	34	15	90	53	B3	157	1	50	45	15	B1	277	17	85	10	25	B2
38	49	15	95	53	B3	158	58	50	50	15	B1	278	25	85	15	25	B2
39	34	15	100	57	B3	159	5	50	55	19	B1	279	22	85	20	25	B2
40	13	15	105	57	B3	160	18	50	60	19	B1	280	59	85	25	26	B2
41	13	20	10	1	B1	161	35	50	65	43	B3	281	32	85	30	26	B2
42	22	20	15	1	B1	162	49	50	70	43	B3	282	35	85	35	26	B2
43	35	20	20	5	B1	163	3	50	75	47	B3	283	28	85	40	27	B2
44	21	20	25	5	B1	164	4	50	80	47	B3	284	2	85	45	27	B2
45	32	20	30	9	B1	165	34	50	85	51	B3	285	23	85	50	27	B2
46	26	20	35	9	B1	166	19	50	90	51	B3	286	9	85	55	28	B2
47	35	20	40	13	B1	167	25	50	95	55	B3	287	40	85	60	28	B2
48	4	20	45	13	B1	168	31	50	100	55	B3	288	10	85	65	28	B2
49	33	20	50	17	B1	169	45	55	10	4	B1	289	12	85	70	35	B2
50	13	20	55	17	B1	170	28	55	15	4	B1	290	23	85	75	35	B2
51	58	20	60	41	B3	171	20	55	20	8	B1	291	6	85	80	37	B2
52	56	20	65	41	B3	172	5	55	25	8	B1	292	37	85	85	37	B2
53	60	20	70	45	B3	173	25	55	30	12	B1	293	43	85	90	39	B2
54	51	20	75	45	B3	174	35	55	35	12	B1	294	27	85	95	39	B2
55	25	20	80	49	B3	175	46	55	40	16	B1	295	26	90	10	29	B2
56	49	20	85	49	B3	176	35	55	45	16	B1	296	21	90	15	29	B2
57	60	20	90	53	B3	177	40	55	50	20	B1	297	43	90	20	29	B2
58	16	20	95	53	B3	178	49	55	55	20	B1	298	13	90	25	26	B2
59	11	20	100	57	B3	179	26	55	60	44	B3	299	3	90	30	26	B2
60	42	20	105	57	B3	180	48	55	65	44	B3	300	54	90	35	26	B2
61	2	25	15	2	B1	181	44	55	70	48	B3	301	3	90	40	27	B2
62	21	25	20	2	B1	182	42	55	75	48	B3	302	28	90	45	27	B2
63	42	25	25	6	B1	183	44	55	80	52	B3	303	45	90	50	27	B2
64	7	25	30	6	B1	184	12	55	85	52	B3	304	46	90	55	32	B2
65	7	25	35	10	B1	185	47	55	90	56	B3	305	50	90	60	32	B2
66	18	25	40	10	B1	186	5	55	95	56	B3	306	13	90	65	32	B2
67	24	25	45	14	B1	187	15	55	100	58	B3	307	29	90	70	35	B2
68	34	25	50	14	B1	188	58	55	105	58	B3	308	53	90	75	35	B2
69	19	25	55	18	B1	189	50	60	10	4	B1	309	50	90	80	37	B2
70	18	25	60	18	B1	190	14	60	15	4	B1	310	25	90	85	37	B2

Meter No.	Grp.	Location		Pole Trans.	Bus	Meter No.	Grp.	Location		Pole Trans.	Bus	Meter No.	Grp.	Location		Pole Trans.	Bus
		x	y					x	y					x	y		
71	49	25	65	42	B3	191	12	60	20	8	B1	311	28	90	90	39	B2
72	19	25	70	42	B3	192	15	60	25	8	B1	312	21	90	95	39	B2
73	23	25	75	46	B3	193	56	60	30	12	B1	313	15	95	10	29	B2
74	25	25	80	46	B3	194	16	60	35	12	B1	314	49	95	15	29	B2
75	51	25	85	50	B3	195	16	60	40	16	B1	315	33	95	20	29	B2
76	25	25	90	50	B3	196	43	60	45	16	B1	316	33	95	25	30	B2
77	44	25	95	54	B3	197	40	60	50	20	B1	317	38	95	30	30	B2
78	40	25	100	54	B3	198	47	60	55	20	B1	318	6	95	35	30	B2
79	25	30	15	2	B1	199	46	60	60	44	B3	319	43	95	40	31	B2
80	58	30	20	2	B1	200	19	60	65	44	B3	320	16	95	45	31	B2
81	39	30	25	6	B1	201	50	60	70	48	B3	321	4	95	50	31	B2
82	31	30	30	6	B1	202	44	60	75	48	B3	322	17	95	55	32	B2
83	14	30	35	10	B1	203	54	60	80	52	B3	323	58	95	60	32	B2
84	35	30	40	10	B1	204	14	60	85	52	B3	324	20	95	65	32	B2
85	45	30	45	14	B1	205	22	60	90	56	B3	325	39	95	70	36	B2
86	28	30	50	14	B1	206	34	60	95	56	B3	326	22	95	75	36	B2
87	55	30	55	18	B1	207	22	60	100	58	B3	327	23	95	80	38	B2
88	17	30	60	18	B1	208	13	60	105	58	B3	328	20	95	85	38	B2
89	41	30	65	42	B3	209	35	65	10	4	B1	329	13	95	90	40	B2
90	54	30	70	42	B3	210	38	65	15	4	B1	330	13	95	95	40	B2
91	17	30	75	46	B3	211	9	65	20	8	B1	331	26	100	10	33	B2
92	23	30	80	46	B3	212	4	65	25	8	B1	332	38	100	15	33	B2
93	1	30	85	50	B3	213	39	65	30	12	B1	333	15	100	20	33	B2
94	18	30	90	50	B3	214	51	65	35	12	B1	334	42	100	25	30	B2
95	60	30	95	54	B3	215	39	65	40	16	B1	335	36	100	30	30	B2
96	46	30	100	54	B3	216	26	65	45	16	B1	336	37	100	35	30	B2
97	35	35	15	2	B1	217	12	65	50	20	B1	337	5	100	40	31	B2
98	37	35	20	2	B1	218	30	65	55	20	B1	338	3	100	45	31	B2
99	17	35	25	6	B1	219	59	65	60	44	B3	339	10	100	50	31	B2
100	31	35	30	6	B1	220	47	65	65	44	B3	340	15	100	55	34	B2
101	48	35	35	10	B1	221	23	65	70	48	B3	341	24	100	60	34	B2
102	52	35	40	10	B1	222	30	65	75	48	B3	342	36	100	65	34	B2
103	6	35	45	14	B1	223	33	65	80	52	B3	343	18	100	70	36	B2
104	33	35	50	14	B1	224	41	65	85	52	B3	344	51	100	75	36	B2
105	25	35	55	18	B1	225	3	65	90	56	B3	345	54	100	80	38	B2
106	5	35	60	18	B1	226	39	65	95	56	B3	346	32	100	85	38	B2
107	28	35	65	42	B3	227	54	65	100	58	B3	347	24	100	90	40	B2
108	42	35	70	42	B3	228	21	65	105	58	B3	348	1	100	95	40	B2
109	30	35	75	46	B3	229	8	70	10	21	B2	349	16	105	10	33	B2
110	25	35	80	46	B3	230	26	70	15	21	B2	350	10	105	15	33	B2
111	57	35	85	50	B3	231	47	70	20	21	B2	351	39	105	20	33	B2
112	60	35	90	50	B3	232	22	70	55	24	B2	352	59	105	55	34	B2
113	36	35	95	54	B3	233	25	70	60	24	B2	353	19	105	60	34	B2
114	32	35	100	54	B3	234	45	70	65	24	B2	354	15	105	65	34	B2
115	37	40	15	3	B1	235	27	70	80	59	B3	355	53	105	70	36	B2
116	6	40	20	3	B1	236	44	70	85	59	B3	356	8	105	75	36	B2
117	12	40	25	7	B1	237	31	70	90	59	B3	357	35	105	80	38	B2
118	18	40	30	7	B1	238	11	70	95	60	B3	358	37	105	85	38	B2
119	2	40	35	11	B1	239	17	70	100	60	B3	359	37	105	90	40	B2
120	10	40	40	11	B1	240	6	70	105	60	B3	360	42	105	95	40	B2