Graduate School of Advanced Science and Engineering
Waseda University

博 士 論 文 概 要
Doctoral Thesis Synopsis

論 文 題 目
Thesis Theme

Study on Hybrid Control Design based on Fuzzy Logic for Photovoltaic Solar Systems

太陽光発電システムのためのファジー論理に基づくハイブリッド制御設計に関する研究

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In recent years, because the fossil-fuel resources are likely going to be exhausted, and the environmental preservation is an important problem; the use of renewable-energy sources is currently a salient advance and also becomes more popular in many countries. Wherein, photovoltaic (PV) solar systems, that have outstanding features such as an unlimited power and environmentally friendly resource, are playing an ever-increasingly significant role in supplying electricity. For example, PV energy systems are applied in the automatic irrigation system in agriculture, household uses and especially in remote areas, street signal and light systems in public services, electricity generation stations, space satellites in universe engineering and so forth. Commonly, PV systems have two modes in operation; that is the stand-alone PV system and the grid-connected PV system. In detail, the stand-alone PV system uses the energy obtained from solar panels to supply to the load and/or energy storage system (ESS), and its operation is independent of the electric grid. So one of the most important control objectives in this PV system is how to obtain optimally the DC power from PV arrays in varying weather conditions. Whereas, the grid-connected PV system is normally used in distributed power generation systems; therefore, the main control goal for this PV system is how to deliver effectively the active and/or reactive output power(s) of the DC-AC inverter to the utility grid.

To achieve a good efficacy in operating a real PV energy system, two major effect factors should be examined thoroughly. Namely, the first one is impacts of weather parameters. Another is effects of the power-electronic converters, controllers, ESS and loads utilized in the designed PV system. Obviously, the weather condition is out of the user's control and usually alters continually, so control methods used in PV energy systems should be researched and developed thoroughly to achieve the best efficacy as possible. Moreover, since characteristics of PV array are highly affected by weather parameters, and the power-electronic converters, loads and electric grid are the nonlinear and complex objects, fuzzy logic, an intelligent control algorithm based on heuristics from experts' experiences, is suitable for developing the novel hybrid controllers to improve significantly the overall effectiveness of PV systems.

Motivated by the above reviews, this Doctoral thesis focuses on developing the efficient controllers based on fuzzy logic for PV solar systems to reduce thoroughly the nonlinear effects of weather parameters, power-electronic converters, load and grid on PV systems. In detail, the thesis has three key study parts as follows. The first part is a study about an improved maximum power point tracking (MPPT) algorithm to obtain optimally the power from PV array in varying weather conditions. Then, an active and reactive power control based on the feedback linearization technique for the three-phase grid-connected PV inverter is studied in the next part. And the last part introduces a coordinated-control strategy to adjust fittingly the total active output power injected into a local grid from a large-scale solar farm, consisting of many PV agents and battery banks at agents, in order to support grid-frequency regulation. In all the three study parts, fuzzy logic controllers are developed newly and combined appropriately with related conventional methods to enhance noticeably performance and adaptability of the proposed hybrid controllers.

The first study part presents an enhanced Incremental Conductance - Maximum Power Point Tracking (INC-MPPT) algorithm based on fuzzy logic for PV systems. The demonstrative stand-alone PV system consists of the solar array with a nominal power of 320*W*, a non-inverting buck-boost DC-DC converter, and a resistive

load. The main PV system's goal is to seek quickly and efficiently the maximum power point (MPP) of the solar array in varying weather conditions. To fulfill well this, the proposed fuzzy-based INC-MPPT algorithm is designed with two sub-controllers. In the first sub-controller, a novel fuzzy logic controller (FLC), comprising 25 association rules, is proposed to enhance effectiveness of the conventional INC-MPPT algorithm. In detail, the proposed FLC adjusts suitably the step-size to improve the response time in seeking the MPP and to eliminate steady-state oscillations around the MPP. Obviously, the main objective of the suggested FLC is to make the step-size to be a variable non-negative value, instead of a fixed positive value in the conventional INC-MPPT method, in order to determine rapidly and accurately the optimal voltage where the PV array operates at the MPP. The other is a proportional-integral (PI) controller with an anti-windup module based on the back-calculation method, and it regulates the operating PV array's voltage to the optimal voltage computed beforehand. Simulations in MATLAB demonstrate that the suggested algorithm fulfills well all the listed goals even if the solar radiation and temperature change suddenly. Additionally, comparisons of simulation results, obtained from the presented algorithm, the conventional INC-MPPT, and an existing fuzzy-based INC-MPPT, show advantages of the proposed algorithm in terms of quick response, accuracy, and fairly small oscillation around the MPP. Besides, the feasibility and effectiveness of the suggested algorithm, including the consideration on effects of the partial shadow condition, are also verified by experiments.

As a next step of the first study part, the second study part discusses about two techniques based on the feedback linearization (FBL) method to control the active and reactive output AC powers of three-phase grid-connected PV inverters, which input is the DC power obtained from PV arrays as referred in the first part. Wherein, the first control scheme is an application of the direct FBL approach. The other is an appropriate combination of the FBL and fuzzy logic (FBL-FL), and is the main proposed method in this part. In the FBL-FL hybrid technique, a unique FLC, consisting of 25 association rules, is designed to improve efficacy of the linear PI control method used in the direct FBL technique. In detail:

i. The FLC fine-tunes automatically and properly for the gain factors of integral modules in the linear PI method. This helped enhance considerably the transient response (response time, overshoot) of the output powers, especially when the reference values are varied noticeably and abruptly.
ii. Additionally, the FLC also adjusts suitably the final virtual-control signals to reduce efficiently the steady-state fluctuations in the output powers, especially in the parametric uncertainty condition.

In this study part, the illustrative PV inverter utilizes a three-level DC-AC converter, an R-L filter and a $250V/10kV$ transformer to inject the energy, obtained from PV arrays with a nominal power of $100kW$, into the $10kV/60Hz$ three-phase electric grid. The two FBL-based control schemes are designed with per-unit values of the relevant system parameters in order to simplify the tuning process of coefficients of controllers. Numerical simulations in MATLAB show that the two FBL-based schemes perform well in regulating independently the active and reactive output powers to the reference values in both the step and ramp functions, even within the parametric uncertainties and the unbalanced grid voltage condition. Moreover, comparisons of simulation results, obtained from the two FBL-based structures and the traditional PI control, illustrate advantages of the proposed FBL-FL technique in terms of fast response, small overshoot, acceptable steady-state fluctuation and robustness.

Also, the stability for the proposed FBL-FL hybrid method is analyzed and proved according to the theory "Affine Parameter-Dependent Lyapunov Functions" applied for the second-order systems.

As a combination and development from the first two study parts which are applied in a local solar-energy agent, the last study part introduces a novel coordinated-control strategy based on fuzzy logic to inject efficiently the total active power from a grid-connected large-scale PV farm, consisting of many local solar power agents and the battery bank to store energy at each agent, into a local electric grid with supporting the regulation of grid frequency. Wherein, this part has three major objectives as follows:

a) The total output active power from the PV farm supplied to the grid is tuned suitably to ensure the grid frequency in acceptable ranges. Two tolerable ranges used for frequency deviation are ±0.2 *Hz* in transient states and ±0.05 *Hz* at steady states, where the nominal grid frequency is 60 *Hz*.
b) At each local PV power agent, state-of-charge (SOC) of the battery bank is governed in the safe ratio range of [0.2 0.8] to improve durability of the battery bank. Also, steady-state SOC of the battery bank is regulated to a desired ratio value of 0.5 if the frequency deviation is in the so small range of ±0.05 *Hz*.
c) The two above objectives listed in a) and b) of the suggested fuzzy-based strategy have to be validated well even if the AC-system load, solar radiation and temperature unexpectedly change.

To achieve all the above aims, the proposed strategy which is designed according to the two-level control structure, consists of a central coordinating controller and local controllers at PV power agents. In detail, the central controller uses a frequency regulation module based on a newly designed FLC, comprising 49 rules, to determine the adjustable value for updating the reference value of total active power needed from the solar farm; and then appropriately coordinates the individual reference value for the local controller at each PV agent. As well, each local controller drives the power-electronic DC-DC converters connected with four PV arrays, bidirectional DC-DC battery charger and three-phase DC-AC inverter installed at the PV agent to deliver the active power to the grid accurately according to the individual reference value obtained from the central controller. Besides, in each local controller, a prediction module based on simulation with the mathematical model of PV panel is utilized to forecast the maximum power from PV arrays, and a control method for regulating SOC of the battery bank in both transient and steady states to ensure durability of the battery bank is also implemented. To study about the grid-frequency deviation, the local grid can be modeled as one or some synchronous generator(s), including the speed governor(s), and the AC-system load(s) connected to the three-phase AC bus. Simulation results in MATLAB demonstrate that the proposed strategy has good performance in injecting the output active power from the PV farm into the grid with regulating the grid frequency in tolerable ranges even if the AC-system load, solar radiation and air temperature suddenly vary. Moreover, the efficacy in regulating grid frequency of the suggested fuzzy-based strategy is also compared with the conventional control strategy which uses the full MPPT mode.

In the future developments of this Doctoral thesis, notable issues about coordinated-control strategy, balance of supply and demand of power and power quality in the large-scale electric network, where many distributed PV solar and wind energy agents are integrated, will be examined and researched.

早稲田大学　博士（工学）　学位申請　研究業績書

(List of research achievements for application of doctorate (Dr. of Engineering), Waseda University)

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論文	**＜Journal Papers＞**
○	1. Nguyen Gia Minh Thao, Kenko Uchida, and Nam Nguyen-Quang, “An Improved Incremental Conductance-Maximum Power Point Tracking Algorithm based on Fuzzy Logic for Photovoltaic Systems”, *SICE Journal of Control, Measurement, and System Integration*, Vol. 7, No. 2, pp. 122-131, 20th March 2014, DOI: 10.9746/jcmsi.7.122.
○	2. Nguyen Gia Minh Thao and Kenko Uchida, “Active and Reactive Power Control Techniques based on Feedback Linearization and Fuzzy Logic for Three-Phase Grid-Connected Photovoltaic Inverters”, *Asian Journal of Control*, Vol. 17, No. 5, pp. 1-25, September 2015, published online early view on 10th September 2014, DOI: 10.1002/asjc.998.
講演	**＜International Conference Papers＞**
○	1. Nguyen Gia Minh Thao and Kenko Uchida, “A Novel Fuzzy-based Control Strategy for Grid-connected Large-scale Solar Farm with Supporting The Grid-Frequency Regulation”, *Proceeding of Asian Control Conference 2015* (*ASCC 2015*), pp. 224-231, Kota Kinabalu, Malaysia, 31st May - 3rd June 2015.
○	2. Nguyen Gia Minh Thao and Kenko Uchida, “A Control Strategy based on Fuzzy Logic for Three-phase Grid-connected Photovoltaic System with Supporting Grid-Frequency Regulation”, *Proceeding of International Conference on Intelligent and Automation Systems 2015* (*ICIAS 2015*), paper ID: S0009, Ho Chi Minh City, Vietnam, 6th-7th February 2015.
○	3. Nguyen Gia Minh Thao and Kenko Uchida, “Control The Active and Reactive Powers of Three-phase Grid-Connected Photovoltaic Inverters Using Feedback Linearization and Fuzzy Logic”, *Proceeding of Australian Control Conference 2013* (*AUCC 2013*), pp. 133-140, Perth, Australia, 4th-5th November 2013, DOI: 10.1109/AUCC.2013.6697261.
○	4. Nguyen Gia Minh Thao and Kenko Uchida, “Control The Photovoltaic Grid-Connected System Using Fuzzy Logic and Backstepping Approach”, *Proceeding of Asian Control Conference 2013* (*ASCC 2013*), pp. 1-8, Istanbul, Turkey, 23rd-26th June 2013, DOI: 10.1109/ASCC.2013.6606123.

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講演	5. Nguyen Gia Minh Thao, Kenko Uchida, Kentaro Kofuji, Toru Jintsugawa, and Chikashi Nakazawa, "A Comprehensive Analysis Study about Harmonic Resonances in Megawatt Grid-Connected Wind Farms", *Proceeding of International Conference on Renewable Energy Research and Applications 2014* (*ICRERA 2014*), pp. 387-394, Milwaukee, The U.S., 19th-22nd October 2014, DOI: 10.1109/ICRERA.2014.7016415. 6. Truc Pham-Dinh, Hai Nguyen-Thanh, Kenko Uchida, and Nguyen Gia Minh Thao, "Modified Controls for Grid-Connected Wind-Turbine Doubly Fed Induction Generator under Unbalanced Voltage Dip for Torque Stability and Reduction of Current Harmonic", *Proceeding of SICE Annual Conference 2014* (*SICE 2014*), pp. 1493-1500, Sapporo, Japan, 9th-12th September 2014, DOI: 10.1109/SICE.2014.6935281. 7. Truc Pham-Dinh, Hai Nguyen-Thanh, Kenko Uchida, and Nguyen Gia Minh Thao, "Comparison between Modifications of SFOC and DPC in Control of Grid-Connected Doubly Fed Induction Generator under Unbalanced Voltage Dip", *Proceeding of SICE Annual Conference 2013* (*SICE 2013*), pp. 2581-2588, Nagoya, Japan, 14th-17th September 2013.