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博 士 論 文 概 要 書

論 文 題 目

A New Hierarchical Fault Diagnosis Method for
Power Distribution Networks with PV Systems
--- Equivalent-Input-Disturbance-Based Approach---

太陽光発電システムを含む配電ネットワークに関する新しい階層的故障診断手法
― 等価入力外乱手法によるアプローチ ―

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The electrical power system represents not only one of the most complex artificial systems in the world, but also one of the most significant ones in modern society. State monitoring and fault diagnosis are necessary to guarantee its stability and safety. When a fault occurs in power system, it is imperative to limit the impact of outages to the minimum and to restore the faulted facilities as quickly as possible. This requires that the location and type of the fault first be identified. This identification task is referred to as fault diagnosis. Nowadays, severe consequences have been coursed by large-scale blackouts of power system, such as blackouts in the USA, Europe and many other countries in recent years. Moreover, blackouts not only lead to financial losses, but also lead to potential dangers to society and customers. So it is necessary to pay attention to fault and diagnosis.

Centralized fault diagnosis takes place at control centers equipped with Energy Management System (EMS) and supervisory control and data acquisition (SCADA) system using transmitted fault information. The traditional fault diagnosis methods are mainly based on the fusion of sensor information from these systems. However, a natural disaster (earthquake, tsunami, etc.) can significantly reduce the number of functioning sensors, thereby serious degrading the accuracy of fault diagnosis. Meanwhile, photovoltaic (PV) system, as a kind of renewable energy, has been widely installed in the distribution network. With the penetration of grid-connected PV systems, the traditional fault diagnosis encounter an increasing number of bottlenecks, such as island operation, reverse power flow, malfunctions of protective relays and so on.

The doctoral dissertation concerns the above problems and presents a new hierarchical fault diagnosis (HFD) method for power distribution that is based on a hierarchical model and the equivalent-input-disturbance (EID) approach.

1) Construction method of the Hierarchical Fault Diagnosis (HFD) Model is proposed. For a local distribution network, the amount of load nodes is varied from the dozens to thousands and the numbers of sensors are numerous. Due to the complexity of it, a complete mathematical model of an entire distribution system is extremely complicated and contains a huge number of parameters. Since the use of such a model for fault diagnosis involves a time-consuming deduction process, a high-performance microprocessor is needed for real-time diagnosis. Therefore, the HFD model based on power flow calculation approach (Backward and Forward Sweep approach) is set up. In the HFD model, the distribution network is built by first dividing it into multiple Load Clusters (LC) based on the locality and/or logical topology. Each LC contains a number of load nodes. Then the LCs are subdivided successively into smaller LCs. This produces both a multilayer structure and a hierarchical model of the system. Fault diagnosis is carried out from the top down through the layers to gradually pinpoint a fault and to identify its type. Before the construction of HFD model, the power flow parameters need to be calculated in advance. As the distribution feeder in our research is the Low Voltage Network (LVN) and the Backward and Forward Sweep (BFS) power flow calculation algorithm is

suitable for it. Meanwhile, considering the PV system has two operation types: the *PV* specified nodes type and the *PQ* specified node type, thus we improve the BFS algorithm to adapt them. The IEEE 13 bus standard radial feeder is selected to illustrate how to construct a hierarchical model.

2) The Equivalent-Input-Disturbance (EID) approach is applied to a fault diagnosis method for the LC. The parameter fluctuation, measurement noise and the external disturbance always exist in the actual system, beside in the power system. All of them can be regarded as disturbances to the system. Faults of system can be defined as: the disturbances exceed the allowable range of system and break the stability of system. Based on this idea, the (EID) approach, which can estimate the system disturbances, is applied to diagnose the faults. Firstly, the theory basis of EID approach and the definition of EID are presented. According to the characteristics of LC dynamic model, the design method of state observer gain is given out. Secondly, two critical considerations of fault diagnosis method based on EID approach, which are the thresholds of the EIDs and the characteristics of faults are discussed. If the magnitude of EIDs and/or its differential exceed the thresholds, the faults would be occurred. Furthermore, after a fault is located, its type must be determined. This type of fault is determined by monitoring the current of a LC, which is the state of its dynamics. Lastly, the simulation results on the case study are presented to illustrate the effective of the fault diagnosis method.

3) With the PV systems installed in the distribution network as distributed generators, many new challenges are brought to the tradition relay protection system. In particular, with the PV system injecting the power, the feeders get active. The island effects, reverse power flow would be appeared. Moreover, the short circuit fault current of feeders will be changed and it will make the relay malfunction. The general block diagram for a PV grid-connected system is introduced and the characteristics of PV output are also presented. Based on the PV output power data collected from the PV systems installed at Honjo campus of Waseda University, evaluate the influence of different kinds of penetration level of PV on the distribution network such as the voltage variation, reverse power and etc.. Moreover, the fault diagnosis method based on EID approach for the LC with PV system connected is proposed. The different of fault diagnosis for the LC without PV connected is the output fluctuation of PV impacts on the fault diagnosis. To eliminate the influence of PV, a fault signal is abstracted from the EID by removing the fluctuation caused by the PV system. We measure the PV system output variation and estimate the EID of PV to the LC, then eliminate it before fault diagnosis. The simulation on a case study shows our method can eliminate the influence of PV and identify the faults on LC successfully. Comparing with other methods, our method does not need to install any new device or modify the setting of existing device. It can save the cost for power grid upgrade when installing a large scale of grid-connected PV systems.

4) In order to make the procedure of Hierarchical Fault Diagnosis Method easy to understand, the IEEE 37 bus standard model is used as an example. Firstly, construct the hierarchical model of the system and design an EID estimator for the dynamic model of LC in each layer. Secondly, monitor Layer 1 of the hierarchical model by estimating the EID of LC in a real-time fashion. If a fault occurs at any LC, then go to the next layer of the LC. If the LC only contains one node and can not be divided any more, then we can pinpoint the fault node. Lastly, determine the type of fault by analyzing the amplitude and phase of the estimated state of the smallest LC containing the fault. Note that, if a cluster containing a fault has only one node, then the location of the fault is determined in that step and the type is determined in the next step; there is no need to always descend to the lowest layer. There are many reasons for performing a fault diagnosis. For example, a supervisor might want to know if it is safe for one of the power plants in a large system to supply power to the loads it services. In this case, diagnosis should start at the layer containing that plant. On the other hand, for maintenance, a supervisor might need to check if there is a fault in a particular area. In that case, the diagnosis should start at the relevant layer. Hierarchical fault diagnosis provides the flexibility needed to handle a variety of diagnostic needs.

Comparing the HFD method with conventional methods revealed the following advantages.

1) The HFD method only requires a small amount of information system. Furthermore, the HFD method successively breaks down a large system into smaller and smaller subsystems at lower levels. This reduces the complexity involved in modeling and shortens the computing time needed for fault diagnosis, while requiring less information.

2) The HFD method diagnoses faults layer by layer, and the dynamic model of a cluster in a layer has only *one* state. Furthermore, the HFD method only needs to diagnose clusters that might have a fault. Due to the small size of each model and the limited number of clusters that need to be dealt with, the computational complexity is reduced remarkably. As a result, the computations are very fast.

3) The HFD method the precision of fault diagnosis depends on the accuracy of the local model. In other words, even if a higher-level model is not very accurate, as long as it detects a fault, the models at lower layers can be used to obtain exact information on the fault.

4) The HFD method not only determines whether or not a fault has occurred, but can also assess the damage caused by a fault at different levels of the system. The infinity and Euclidean norms of the EIDs of different layers can be used to assess the damage caused by faults at different levels. More specifically, the infinity norm is related to maximum power, and the Euclidean norm is related to total energy.