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Research and practice on typical modes and optimal allocation method for PV-Wind-ES in Microgrid

Wanxing Sheng, Ke-yan Liu*, Xiaoli Meng, Xueshun Ye, Yongmei Liu

Power Distribution Research Department, China Electric Power Research Institute, Beijing 100192, People's Republic of China

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ABSTRACT

This study investigates the typical configuration mode and optimal allocation method for photovoltaic (PV), wind generator and energy storage (ES) in Microgrid system. Firstly, the six typical scenarios of the hybrid integration modes are discussed. By considering the objectives of minimum PV-Wind-ES investment cost, minimal expectation of energy not supplied (EENS) and minimal line loss, the proposed optimal allocation of PV-Wind-ES is a multi-objective optimization problem. In order to get a comprehensive solution, an improved NSGA-II algorithm is proposed to solve the multi-objective planning problem. Several experiments have been made on the IEEE 33-bus test case and a real implementation of State Grid Corporation of China (SGCC) with the consideration of multiple DG units and ES. The computational result and comparisons indicate the proposed algorithm for optimal allocation of PV-Wind-ES in distribution system is feasible and effective.

1. Introduction

Distributed generation (DG) technology has become a hot research topic, given increasing global concerns for environmental protection, energy saving issues, increasing penetration of wind power, photovoltaic (PV) power generation and other renewable energy technologies. The DG integration has benefits of expanding capacity of transmission and distribution system, enhancing the reliability of power supply, and solving the problem of power supply for remote rural area. Incorporation of a number of basic technologies including DG, interconnection switches and control systems within a small geographical area forms a small grid, known as Microgrid (MG).

MG offers a number of advantages including enhancements in efficiency, reliability, and the power quality delivered to the load, enabling high penetration of distribution generation without requiring re-design or re-engineering of the distribution system itself [1]. Overcoming the drawbacks of independent DG operation, MG can operate as a single controllable entity. As a widely technical solution for integrating large scale DG units into power system, the research of MG integration has received extensive attention. As current-control mode DG units, photovoltaic generation and wind turbine (WT) generation have the features of environmental protection and economical efficiency, but also have impact on power grid when they are integrated in a high penetration level. The DG with voltage-control mode, such as diesel generator, energy storage (ES), usually works as stable voltage reference and provides voltage and frequency support in case of off-grid operation. However voltage-control DG is relatively expensive and impacts the system performance when they are connected to the grid. And it cannot be connected to the grid directly without inverters. Therefore, reasonably planning capacity ratio of DG units and finding suitable DG units integration method will be great significant for decreasing investment cost as well as improving the utilization of MG.

There are two operation modes for MG, the grid-connected and islanding modes. In the grid-connected mode, MG can exchange power with utility grid (UG), i.e., distribution power system. In cases involving occurrence of faults in the main grid or suspension of grid operation for maintenance, the MG is switched to the islanding mode, in which the MG is expected to provide sufficient power for loads. In addition, energy storage devices such as batteries and flywheels are employed in order to enhance the stability and efficiency of the MG in this mode. The ES devices are intended to improve the stability by compensating for the slow response of the sources as well as increasing the efficiency and controllability of the MG by becoming charged under off peak conditions, and becoming discharged under peak conditions [2,3].

Some previous researchers have performed optimization and economic analysis to determine optimal allocation for DG units

* Corresponding author. Tel.: +86 13810300290.
E-mail addresses: liukeyan@epri.sgcc.com.cn, polygan123@gmail.com (K.-y. Liu).

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[4–21]. From the perspective of mathematical optimization, DG unit injection is a complex multi-objective optimization problem that presents a challenge to the optimization analysis of a distribution power system. The objectives include optimal energy consumption, the minimum power consumer's electricity purchasing cost and the minimum power loss based on constraints of power grid security and DG power output. Multi-objective economic/emission dispatch algorithms were investigated in references [4,5]. In literatures about optimization methods, multi-objective models of DG planning were optimized by various methods such as simulated annealing technique [6], Tabu search method [7], Tabu search method integrated with genetic algorithm (GA) [8] and Fuzzy optimization method [9]. Recent studies about DG planning model and various algorithms can be listed as follows. Several intelligent optimization algorithms such as GA [10], particle swarm optimization (PSO) [11,12], differential evolution (DE) [13] and artificial bee colony (ABC) [14] are utilized to solve the optimization problem considering minimum costs for network upgrading, operation, maintenance and losses for handling the load growth and maximum DG penetration level. Besides, several sensitivity analysis methods of DG allocation were proposed in [15–17]. In case of multiple conflicting objectives, there may not be a solution which is the best compromise for all objectives. Therefore, a "tradeoff" solution is needed instead of a single solution in multi-objective optimization. In [18], a multi-objective optimization approach based on genetic algorithm was proposed to maximize savings in system upgrade investment deferral, cost of annual energy losses and cost of interruption. In [19], a multi-criteria planning model aiming to minimize the cost and maximize the reliability of generating units was proposed. A multi-objective performance index-based size and location determination of DG was presented with different load models in [20] and a new approach using improved Harmony Search (HS) algorithm was presented in [21].

Although the attentions of the previous works had been focused on optimal DG allocation in distribution power system, relatively little effort was involved with optimal hybrid integration planning of DG–MG–UG. The typical mode and optimal allocation method of PV-Wind-ES in MG are investigated in this paper. Based on considerations of distribution network outage, grid fault, safe operation of distribution network, the ability of grid connection, decreasing back-up capacity and capital cost, an optimal PV-Wind-ES grouping method was proposed. This method firstly divides PV generators, wind generators and energy storage into groups in terms of actual loads; then some subgroups compose of a PV-Wind-ES MG and connect to the low voltage extended bus; the rest subgroups are integrated into low voltage distribution network directly, thus form a DGs group with certain loads. The number of subgroups of PV, wind and battery as well as the capacity of each subgroup is all obtained by dynamic multi-objective evolutionary algorithm.

The rest of this paper is organized as follows. Section 2 discusses the hybrid integration schemes of DG–MG–UG. The formulation of the proposed multi-objective optimization for DG planning with equality and inequality constraints is established in Section 3. Section 4 describes the proposed INSGA-II method to solve the optimization problem. Sections 5 and 6 provide numerical results and comparisons with the proposed approach using IEEE 33-bus and one real MG demonstration project of China. Section 7 summarizes conclusions and main contributions of the paper.

2. The typical integration schemes of DG–MG–UG

The small and middle scale DG is often directly integrated into distribution network, which is shown in Fig. 1(a). As shown in Fig. 1(a), each DG uses power-type control strategy, and wind and PV operates under the maximum power point track (MPPT) mode. The power output fluctuation of DG units is under the influence of natural conditions changes and the fluctuation frequency. When the penetration level of DG becomes higher, the integration of DG will impact the distribution of power flow, reactive power's adjustment and power quality, which will threaten the safety and stability operation of distribution power system. In this approach, the DG has not the functionality to independently operate in off-grid mode, which means that the DG must exit the integration in case there are faults in UG.

In order to increase the reliability of power supply, energy storage is added in Fig. 1(b). The DG, load and storage forms the independent MG. When there are faults in UG, the voltage-type control strategy of the storage will be applied to provide voltage and frequency support for the island system. Then the island system can operate independently in islanding modes. This centralized scheme has high requirement on the storage capacity, short-time discharge power, unit ramp rate index, etc. At the same time, the construction cost of MG will substantially increase and the system maintenance will also grow accordingly.

Based the above two integration scheme, a hybrid integration scheme is proposed to adapt the advantage of the two schemes, which is shown in Fig. 1(c). Firstly, the DG units have been grouped. Some of them are directly integrated into the distributed system, the other DG units are combined with loads and ES to form MG.

With the consideration of investment cost and various control constraints, the hybrid integrated scheme can have better reliability of power supply. In the scheme, the proportion between DG and MG is kept to allocate wind power and PV, and the load requirement can be satisfied with better diversity, flexibility and adaptability. As shown in Fig. 2, there are six different application scenarios in this DG/MG grouping method, which can be listed as follows:

Scenario 1: PV-Wind-ES MG and DGs group are both in grid-connected mode;
Scenario 2: in case there is breakdown in UG, and PV-Wind-ES MG and DGs group are both in off-grid mode to provide power to loads;
Scenario 3: the ES and DG units in MG are breakdown. The DG units outside the MG are grid-connected;
Scenario 4: PV-Wind-ES MG is in islanding mode, and the DG units outside the MG are in grid-connected;
Scenario 5: PV-Wind-ES MG is in islanding mode, i.e., the utility grid is breakdown and the DG units outside MG is in fault status;
Scenario 6: ES is breakdown or in maintenance, then the utility grid and all DG units provide power to loads.

There is a dynamic transformation among six scenarios in the hybrid DG–MG–UG integration. As shown in Table 1, the PCC can be disconnected in case there is fault inside MG. Then the MG will be in outage status. When the fault is outside MG, MG can be in the offshore status to provide power to load inside its area. The ES periodic charge and discharge will not impact the normal power delivery. The hybrid integration mode is very flexible and can satisfy many operational conditions, which will improve the system stability and reliability. The device statuses of UG, DG and ES are listed in Table 2.

3. Problem formulation

Based on the aforementioned description, the main difference between DG planning and MG planning is in the investment cost and power delivery mode. There is demand of placing ES in MG, and the ES capacity should be in proportion to the configuration of MG. At the same time, the MG construction needs to add