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Distribution system reconfiguration for energy loss reduction considering the variability of load and local renewable generation

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ABSTRACT

The interconnection of renewable energy sources with distribution systems is attracting increasing interest because these renewable sources are inexhaustible and nonpolluting. Wind and photovoltaic are among the most mature of these energy sources, and their penetration continues to increase. In this paper a method based on GA (genetic algorithm) is presented to investigate the distribution system reconfiguration problem taking into consideration the effect of load variation and the stochastic power generation of renewable DG (distributed generators units). The presented method determines the annual distribution network reconfiguration scheme considering switching operation costs in order to minimize annual energy losses by determining the optimal configuration for each season of the year. The uncertainties related to DG power and varying load are considered by the creation of a probabilistic generation-load model that combines all possible operating conditions of the renewable DG units with the probability of their occurrence, followed by the incorporation of this model into the reconfiguration problem. The constraints include the voltage limits, the line current limits, the radial topology, and feeding of all loads. In order to evaluate the effectiveness of the proposed method, both balanced and unbalanced distribution systems are used as case studies.

1. Introduction

Demand growth and climate change lead to electricity network congestion [1]. It is estimated that the majority of losses in power systems (generation, transmission, and distribution) come from distribution systems. For example, for a typical system in a developing country, distribution system losses account around 13% of the total energy produced [2]. Thus, loss reduction in distribution systems has constituted one of the most important objectives for researchers and engineers. This reduction of losses can be considered as a source of energy. Typical distribution systems have normally closed sectionalizing switches and normally open tie switches (i.e., to interconnect feeders and allow load transfer among them) [3]. The existence of tie lines has led to the idea of network reconfiguration for loss reduction. Network reconfiguration is the change in network topology by opening the normally closed sectionalizing switches and closing the normally open tie switches [2]. Because changing the network topology affects the power losses, distribution companies strive to find the optimal configuration in such a way that the losses are minimized and the operational constraints are not violated (i.e., voltage and current limits, feeding all loads, and radial structure).

The incorporation of DG (distributed generators) technologies in distribution systems is currently on the rise, and this type of generation is expected to play a major role in system operation [4]. Renewable DG units provide inexhaustible green energy and are attractive for both utilities and customers [5]. Furthermore, one of the main goals of smart grid is to accommodate a wide variety of DG units and storage devices [6].

Many researchers have attempted to minimize losses through network reconfiguration. The methods proposed have advantages and disadvantages, and they can be broadly classified into four categories: heuristics, expert systems, meta-heuristic, and mathematical programming [7]. Heuristic methods are intuitively rule of thumb to limit the search space, such that the expert's knowledge and experience are translated into programming logic to solve problems. However, the optimal solution is not guaranteed [7]. Maintenance of large-scale expert systems has proved to be costly, and the expert system rules are system specific and therefore, change with the system [7]. Meta-heuristic methods such as GAs (genetic algorithms), particle swarms, simulated annealing, and

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tabu searches are more likely to obtain a global optimal solution compared to heuristic methods [7].

A review of the literature shows that most of the work reported in network reconfiguration for loss reduction is based on the assumption that the load is fixed as one snapshot at peak load [2]. This assumption may lead to sub-optimal solution because of the time-varying nature of loads in distribution systems. Few studies have considered variable load demand in the reconfiguration problem [2,3,8,9]. In Ref. [2], the load variation has been assumed to follow a uniform distribution. In Ref. [3], three different load levels during the day (high, medium and low load level values) were used to investigate the interactive effect of operation management of the fuel cell power plants and the reconfiguration problem. In Ref. [8], a typical day load profile is used. In the problem formulation, authors assumed that this daily load profile is repeated during their two years planning horizon. In Ref. [9], a load curve for seasonal, daily, and time of day varying load is used. Although, these papers proposed different ways to take variable load into account, their work did not take DG units into consideration. Furthermore Refs. [2,3], did not take the switching cost into consideration.

In addition, most of the work reported assumes that the output of DG units is dispatchable and controllable [10]. Few studies have considered the uncertainties in the power output from renewable DG units in network reconfiguration [11–13]. In Ref. [11] the representation of non-dispatchable DG units was simplified based on the assumption that each DG unit delivers half of its rated real power (utilizing capacity factor). This assumption is inaccurate because DG output may be higher or lower than the half of its rated real power. In Ref. [12], the effect of coordinating reconfiguration and voltage control on increasing the maximum allowable DG penetration at a given node was studied. In this work, a random simulation approach is used as a means of including the time-varying effect of bus loads and wind-based DG output on Volt/Var control. The uncertainty of the loads and DG output during each hour are modeled based on 100 randomly selected values using data available from SCADA (Supervisory Control and Data Acquisition). For each feeder configuration, the randomly selected cases (24 h $\times$ 100 cases per hour) are simulated based on load flow in order to calculate the average number of voltage control actions and maximum DG integration. This process is repeated for different configurations that are generated through particle swarm optimization in order to obtain the highest available DG penetration at the candidate bus. Ref. [13] used GA to solve the planning problem in a distribution system with the use of topology changes (installing new switches or reconfiguring the system with existing switches), DG installation, the rewiring of specific lines, and the addition of new load points. They generated nine scenarios with different load and generation values by multiplying the nominal generation and load values by factors that represent the planner's expectation. The authors did not propose a new reconfiguration algorithm but used a heuristic algorithm from a previous work. The work reported in Refs. [11–13] also covered only balanced distribution systems.

The goal of the work presented in this paper is therefore to propose a reconfiguration method for both balanced and unbalanced distribution systems in a manner that will include:

1. Load variation by considering the hourly change during the day, daily change during the week, weekly change during the month and finally monthly change during the season.
2. The uncertainty associated with renewable DG resources by considering all possible operating conditions of the renewable DG units with the probability of their occurrence.
3. The switching operation cost to allow the reconfiguration scheme to balance/improve the benefit from system loss reduction against the cost of switching.

The paper is organized as follows. Section 2 presents the models used for the system components (loads and DG units), and the combined generation-load model. The formulation of problem is explained in Section 3. Sections 4 and 5 present the results of a simulation conducted in order to validate the proposed algorithm, and Section 6 provides conclusions and summarizes the main contributions of this research.

2. Modeling of loads and DG units

In this paper, DG units are modeled as PV(photovoltaic) modules, wind turbines, and biomass DGs, which are the most commonly used DG units in distribution systems. Other DG types can be modeled with similar approaches. This paper is using the models proposed in Ref. [14] and is described in the next subsections.

2.1. Generation modeling

2.1.1. Renewable DG units

For this research, the wind speed and solar irradiance for each hour of the day are modeled by Weibull and Beta PDFs (probability density functions) respectively, using historical data [14]. When the wind speed and solar irradiance are modeled for each hour, the probabilistic function of the output power can be generated. The probabilistic model for wind and PV-based DG units' output power is described as follows [14]:

- The entire year is divided into 4 seasons, and each season is being represented by a day within that season.
- The day which is representing the season is further subdivided into 24 one-hour time segments each referring to a particular hourly interval of the entire season.
- The mean and standard deviation for each time segment are calculated utilizing the historical wind speed and solar irradiance data.
- The Weibull and Beta PDFs are generated for each hour using the mean and standard deviation for each segment.
- In order to integrate the output power of wind turbines and PV modules as multistate variables in the formulations, the continuous PDF of each is divided into a proper number of states. In this research, the output power of the wind turbine and PV modules for each hour of the day is divided into 12 and 10 states respectively. Then the probability of each wind speed and irradiance state is calculated.
- The corresponding output power of the wind turbine and PV module in each state is calculated using the wind turbine power performance curve and PV module characteristics.

Therefore, 24 PDFs (i.e., one PDF for each hour of the day hours) are calculated for each season. These PDFs are repeated for all of the season days in order to represent the variable behavior of wind and PV-based DG units during that season.

2.1.2. Biomass DG units

For this research, biomass DG output power is assumed to be constant (non-intermittent) at its rated power [14]. However, each utility can easily adjust this biomass DG output level in the reconfiguration algorithm based on its own reliability levels and policy.

2.2. Load modeling

The load profile is assumed to follow the IEEE-RTS (Institute of Electrical and Electronics Engineers Reliability Test System) 8760 hourly load model. The hourly, daily, and weekly load variation