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Stochastic operational scheduling of smart distribution system considering wind generation and demand response programs

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ABSTRACT

In this paper a stochastic operational scheduling method is proposed to schedule energy and reserve in a smart distribution system with high penetration of wind generation. The wind power and demand forecast errors are considered in this approach and the reserve is furnished by both main grid generators and responsive loads. The consumers participate in both energy and reserve scheduling. A Demand Response Provider (DRP) aggregates loads reduction offers in order to facilitate small and medium loads participation in demand response program. The scheduling approach is tested on an 83-bus distribution test system over a 24-h period. Simulation results show that the proposed stochastic energy and reserve scheduling with demand response exhibits a lower operation cost if compared to the deterministic scheduling.

Introduction

The upgrading of power system toward a smart grid is being developed to improve reliability, facilitate the integration of different types of renewable energies, and improve load management. With the development of the smart grid, more Distributed Energy Resources (DER) are deployed such as distributed wind and solar units, as well as technologies for expanded demand side management programs.

Demand response (DR) is one of the key approaches that can fully be enabled by smart grids. DR is a set of actions taken to reduce consumer electricity consumption when contingencies, such as unit outage or unpredictable change in demand or renewable generation, occur that threaten supply demand balance. Moreover, if market conditions that raise electric supply costs occur, DR is one of the best solutions. In other words, DR programs and tariffs maybe designed to improve the reliability of the electric grid or to lower the use of electricity during peak hours, thus reducing the total system operation costs.

Wind power generation is one of the most important renewable resources used in many countries to replace conventional power plants and reduce greenhouse gas emissions [1]. However, since wind generation can only be controlled by "spilling wind" and its power output cannot be forecasted with great accuracy, a significant increase in the prediction of the power produced from wind energy has a considerable impact on the way in which scheduling and dispatch are carried out. This increased uncertainty must be considered when determining the requirements for spinning reserve (SR) in order to protect the power system against sudden load and wind generation changes or a combination of both [2].

Determining the optimal amount of reserve that must be provided as a function of the system conditions is thus an important and timely issue. Moreover, the reserve scheduling is simultaneously carried out with energy scheduling [3]. There are two types of methods used for reserve scheduling in the literature: specifically deterministic and stochastic methods. In the deterministic approach, the amount of reserve requirement in each period is determined before the energy and reserve scheduling [4,5]. Generally, the amount of reserve is determined considering the capacity of the largest online generators, load demand and the percentage of renewable generation. Some previous researches evidence that the probabilistic nature of renewable generation and load demand can be considered for scheduling reserve [1]. In the stochastic approach, the amount of reserve requirement is settled during the energy and reserve scheduling procedure [6–8]. The situation (e.g. unpredicted generators outage and wind power and load demand fluctuations) in which the reserve is needed in order to compensate the power generation shortage is generally modeled by scenarios and the amount of reserve is determined according to the probability of each scenario.

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A stochastic model of wind power generation based on an optimal power flow scheduling/dispatching program has been presented in [9]. This model incorporates the error in wind power forecasts by using a relative frequency histogram or probability. In [10], a differential evolution algorithm for integrated energy and spinning reserve dispatch with uniform prices has been proposed. In [11], covariant matrix adaptation with evolution strategy using mean learning technique has been proposed to solve an economic dispatch problem and to find the optimal scheduling/allocation of energy and spinning reserves among thermal and wind generators. The uncertainty of wind power generation has been modeled by Weibull probability density function. However, the objective function has been considered such as in a deterministic method. A probabilistic approach to investigate the multi-objective distribution feeder reconfiguration considering wind turbines has been presented in [12]. This probabilistic method considered the uncertainty regarding the load demand forecast errors as well as the wind turbines output power variations. In [13], a stochastic joint energy and spinning reserve market clearing model has been proposed based on a multi-objective mixed integer nonlinear programming with three objective functions. Wind power generation uncertainty and demand response programs are not considered in this work. A stochastic bidding strategy of a microgrid in a joint day-ahead market of energy and spinning reserve service has been proposed in [14] in which uncertainty of renewable DG units' output power and load demand has been taken into account.

Today, ancillary services (such as voltage control, reactive power contribution and reserve capacity) are procured by the Transmission System Operator (TSO), largely from large power producers, to manage the system as whole. With the introduction of distributed generation and information and communication technologies, in future, it will be essential that also DSO will leave the actual passive management philosophy and become active in the management of the distribution system, thus also participating in procurements of ancillary services [15]. Moreover, DSOs are also responsible for ensuring that the dispatch of generation and allocation of reserves is correctly managed in order to maintain the power flows on distribution network within security and operational limits. Thus, active DSOs should be allowed to coordinate new system services such as ancillary services from Distributed Energy Resources (DER) [15].

Eventually, in order to achieve an efficient use of DER, DSOs will have to contract energy- and capacity-related products, and it is therefore expected that they will employ market-based mechanisms such as procurement auctions, similar to the ones TSOs are currently using to procure reserves [16].

Making demand side involved in the energy and reserve operational planning has opened a wide range of new possibilities for which demand elasticity has increased [17–19]. In [20], a model to support virtual power plants in DR programs' management has been presented in which all the existing energy resources (generation and storage units) and the distribution network are considered. The result showed that for higher values of network total load demand the use of DR can have a great impact in reducing both electricity prices and operation costs, namely in situations of absence of wind and solar power generation.

To the best of our knowledge, no stochastic energy and reserve scheduling method in distribution system considering uncertainties related to electricity price, wind power and load demand and in which the consumers can provide both energy and reserve services has been reported in the literature. Accordingly, in this paper a stochastic approach for energy and reserve scheduling of distribution systems is presented in which various types of demand response programs are taken into account. The contributions of this paper are highlighted as follows:

- Aggregate real-time price, wind power and load demand uncertainties.
- Consider load demand participation in both energy and reserve scheduling.
- Evaluate stochastic scheduling of energy and reserve in a distribution system.

The rest of the paper is organized as follows: Section 'Demand response programs' describes different types of demand response programs. The uncertainty modeling of electricity prices, wind power and load demand is explained in Section 'Uncertainty modeling'. In Section 'Energy and reserve scheduling', the stochastic scheduling of energy and reserve is formulated. Some simulation results are described in Section 'Case study' and finally the concluding remarks are presented in Section 'Conclusion'.

Demand response programs

In the proposed method, a DR program is provided by Demand Response Providers (DRP) and large individual consumers (e.g. industrial loads) [21,22]. The DRP acts as a medium between Distribution System Operator (DSO) [23] and small customers and enable the participation of small customers in DR programs. DR programs are characterized as load reduction in energy scheduling and reserve capacity in reserve scheduling carried out by DSO [24,25].

Each DRP submits load reduction offers as different price-quantity offer packages. In the price-quantity offer package, the minimum (L^i_{Min}) and maximum (L^i_{Max}) load reduction is determined. Also, the load reduction is divided into several steps each having a specific price. The equations for the ith DRP are the following ones from Eqs. (1)–(4).

$$L^i_{Min} \leqslant l^i_1 \leqslant L^i_1 \tag{1}$$

$$0 \leqslant l^i_j \leqslant \left(L^i_{j+1} - L^i_j\right) \quad \forall j = 1, 2, \ldots, Max. \tag{2}$$

$$DP^E(i,t) = \sum_{j=1} l^i_j \tag{3}$$

$$DC^E(i,t) = \sum_{j=1} o^i_j \cdot l^i_j \tag{4}$$

where l^i_j is the accepted load reduction of DRP i in step j of price-quantity offer package; L^i_j and L^i_{j+1} represent, respectively, the start and end points of step j; $DP^E(i, t)$ and $DC^E(i, t)$ are, the total accepted load reduction quantity and payment for the ith DRP in period t, respectively.

At each hour, the sum of scheduled energy reduction and reserve provided by each DRP should not be greater than its maximum load reduction offer (L^i_{Max}). The reserve prepared by DRPs is calculated as follows:

$$DP^E(i,t) + DP^R(i,t) \leqslant L^i_{Max} \tag{5}$$

$$DC^R(i,t) = DP^R(i,t) \times q^{R,p}(i,t) \tag{6}$$

where $DP^R(i, t)$ and $q^{R,p}(i, t)$ are the scheduled reserved provided by DRP i and the reserve price for being in standby in period t, respectively; $DC^R(i, t)$ is the reserve cost that is paid to DRP.

The equations of individual loads (ILs) participating in both energy reduction and for reserve supply are given as follows:

$$IL^E(b,t) + IL^R(b,t) \leqslant IL^{max}_b(b,t) \tag{7}$$

$$IC^E(b,t) = IL^E(b,t) \times q^{E,I}(b,t) \tag{8}$$

$$IC^R(b,t) = IL^R(b,t) \times q^{R,I}(b,t) \tag{9}$$

where $IL^E(b, t)$ and $IL^R(b, t)$ are, the scheduled load reduction and reserve prepared by individual consumer b in period t, respectively;