Energy 96 (2016) 614–624

Contents lists available at ScienceDirect

Energy

journal homepage: www.elsevier.com/locate/energy

A multi-level approach to active distribution system planning for efficient renewable energy harvesting in a deregulated environment

Bo Zeng*, Junqiang Wen, Jinyue Shi, Jianhua Zhang, Yuying Zhang

State Key Laboratory of Alternate Electrical Power System with Renewable Energy Sources, North China Electric Power University, Beijing 102206, China

ARTICLE INFO

Article history:
Received 27 December 2014
Received in revised form
16 December 2015
Accepted 17 December 2015
Available online 4 February 2016

Keywords:
Active distribution system
Renewable distributed generation
Active network management
Multi-level programming
Deregulated market

ABSTRACT

Increasing penetration of renewable distributed generation accentuates the need of active distribution system. However, under the unbundling environment, the conflicting interests between different market participants create hurdles for efficient exploitation of renewable energy sources. To address this issue, we develop a multi-level optimization approach for active distribution system planning, with the purpose of best coordinating the target of renewable energy harvest with the benefits of individuals. The proposed model considers the decision-making of utility under the constraints by the reaction of distributed generation owner as well as the system operational characteristics. It collectively determines the optimal solution concerning network reinforcement, reserve and renewable generation deployment. Furthermore, demand response has been considered as an additional active network management scheme in this work and the uncertainties of renewable generation and load responsiveness are also accounted for. Numerical results based on a 33-bus distribution system verify the effectiveness of the proposed method.

1. Introduction

The accelerating growth of energy usage and environmental concerns calls for the unprecedented emphasis on renewable energy utilization throughout the globe [1]. According to the target announced by the Chinese government, renewable energy sources are expected to contribute over 15% of the domestic consumption by the end of 2020 [2]. To achieve such a goal, the local-based distributed generation technologies have gained rapid development in the past decade as most of them harness renewable energies.

With the continuous insertion of DG, the way of electricity delivery is evolving from today's passive unidirectional flow networks to active distribution systems (ADS) [3]. However, due to its stochastic nature, the improper displacement of renewable DG (RDG) can lead to unfavorable effects, such as increased energy losses, voltage quality deterioration, etc. [3]. As such, the optimal allocation of RDG in ADS has become a major focus of researches [4]. In Ref. [5], an analytical method is proposed for renewable distributed generation integration. A probabilistic model for distributed wind generation planning is presented in Ref. [6], in which the operational control is especially considered. The impact of low-voltage network constraints to the effectiveness of DG planning is investigated in Ref. [7]. Due to the intrinsic limitation of single-objective formulation, the authors of [8] also proposed a multi-objective optimization model for RDG planning. The cost-savings attributed to both energy losses and reliability of the system are taken into account. Similar studies can be found in Ref. [9], which also takes the reconfiguration option into account. In above studies, the possible network reinforcement to be incurred during the process is not included. To fill in this gap, the work of [10] developed an integrated model, which integrated RDG and network planning together under the same framework.

For all of above works, the emphasis is given on the coordination between RDG and network in terms of capacity. In this regard, the authors implicitly assume of a centralized context, wherein distribution companies (DISCOs) both own and operate the DG assets. Nevertheless, with the unbundling of power sector in the worldwide, this prerequisite may not stand. The deregulation policies enable new entities to participate in the power system investment and specify market players their scopes of responsibilities. Under such environment, for example, the DG development may be permitted only undertaken by private entities, while the duty of DISCOs includes only the investment and operation of distribution

* Corresponding author. Tel.: +86 10 84150264.
E-mail address: alosecity@126.com (B. Zeng).

http://dx.doi.org/10.1016/j.energy.2015.12.070
0360-5442/

grid. The inherent controversy in the interests of different players would greatly invalidate the methodologies presented above.

To address this issue, the authors in Ref. [11] employed the multi-objective optimization to compromise the benefits of utility and the DG owner (DGO), thus guaranteeing the final decision to be a win–win strategy. Likewise, in Ref. [12], an index called 'minimum acceptable rate of return' was defined and introduced as an additional constraint into the presented model. The method provides the solutions with the maximum profits to DISCO while keeping the economic returns attractive to DGO. Moreover, a bilevel programming approach also has been used in Ref. [13], wherein the problem is modeled as a Stackelberg game.

Through above reviews, it can be seen that some pilot works have been done concerning ADS planning in the unbundling cases. Nevertheless, in all these literature, the analyses taken were merely restricted to controllable generation, whereas the renewable-based generation technologies were barely considered. In fact, incorporating renewable generation may significantly complicate the problem. On the one hand, although developed by DGO, the variability associated with renewable generation necessitates ancillary services for guaranteeing system security and quality of service. However, as the investment of these devices (e.g. spinning reserve, etc.) are undertaken by DISCO, whether or not the utility consents to do so would affect the operation efficiency of RDG units. On the other hand, in existed studies, most of the planning models that formulated are generally premised on a "fit-and-forget" routine, and the operational characteristics of the system were neglected. However, in order to fully exploit the benefits of renewable generation, the active network management becomes an essential choice [14]. In this case, the active distribution system planning cannot rely on snapshot analysis, but needs to further incorporate its operational characteristics [15].

In this study, a multi-level approach for active distribution system planning is proposed in order to promote renewable energy harvesting in the deregulated environment. Compared to the works in Refs. [11–13], the main contributions of this paper can be summarized as follows:

1) A novel multi-level optimization model is developed to formulate the problem, wherein the operational characteristics are properly coordinated in the planning setting.
2) The proposed model uses a new environmental-embedded economic objective function and considers various issues (i.e. network upgrade, RDG and reserve allocation) together.
3) Demand response is considered as an additional active management option in our method and the uncertainties associated with load responsiveness are also accounted for.

The methodology that proposed in this study can be relevant for real applications. Take China for example. At present, a series of guidelines have already been performed which required the utility to provide open access to DG connection without charge [16]; besides, the popularization of smart metering in end-users facilitates the exploitation and management of demand-side resources [17]. The above facts laid solid technical basis for the implementation of the proposed method. On the other hand, according to the directive of power market reform in China, the government is expected to play a more active role in power system planning [18]. As such, the interests of all market participants may be better protected without bias and their communication could be also enhanced. This creates another favorable condition for the actual use of the method in practice.

The remainder of this paper is organized as follows. Sections 2 and 3 describes the modeling of active management schemes and generation resources. The detailed formulation of planning model and the solution methodology are presented in Sections 4 and 5, respectively. This is followed by a case study in Section 6. Finally, some concluding remarks are provided in Section 7.

2. Modeling of active management schemes

In a broad sense, active management refers to an ex-ante and positive paradigm for the management of distribution network and its connected devices which were once operated without visibility [19]. Over the past decade, a variety of active management options have been deployed in the demonstration projects [3]. However, we herein mainly focus on three of those, i.e. generation curtailment (GC), power factor control (PFC) and demand response (DR). The implementation of such actions would bring a series of operational constraints to be described next.

2.1. Generation curtailment

The violation of power flow constraints has been viewed as a prime barrier for reaching higher penetration of RDG [4]. However, this can be avoided by active power flow control via generation curtailment [19]. The generation curtailment is upper bounded by the potential output of generating units, which leads to the following constraint

$$0 \le P^{\mathrm{cur}}_{g,t} \le \eta_{g,\max} P^{\mathrm{pot}}_{g,t} \quad \forall g \in \Omega_{RG}, \ \ \forall t \tag{1}$$

where $\eta_{g,\max}$ is the ratio of maximum power curtailment to the potential output of the unit $P^{\mathrm{pot}}_{g,t}$ that may be otherwise delivered from bus g.

2.2. Power factor control

According to the directive of Chinese grid code [16], RDG can be used to provide reactive power support to the grid under necessary circumstances. This is generally actualized by controlling the power factor of DG units. However, the variation of power factor must always keep within the permissible range

$$\varphi_{g,\min} \le \varphi_{g,t} \le \varphi_{g,\max} \quad \forall g \in \{\Omega_R \vee \Omega_{RG}\}, \ \ \forall t \tag{2}$$

2.3. Demand response

Demand response is considered as an available option which produces outcomes equivalent to the supply-side generation [20]. For simplicity, only one type of demand-side resources, storage managed load [21], will be focused here.

Regarding such loads, the total energy to be delivered is basically a constant over an interval (e.g. one day), but there is flexibility in its timing. This can modeled as a virtual 'energy storage' unit with bi-directional power output, which yields the following constraints

$$P^{dr}_{\min} \le \left|P^{dr}_{k,t}\right| \le \varpi^{sml}_{k}, \quad \forall k \in \Omega_D, \ \ \forall t \tag{3}$$

$$\sum_{t=1}^{T} r_t \left(P^{dr}_{k,t}\right)^{+} = \sum_{t=1}^{T} r_t \left(P^{dr}_{k,t}\right)^{-} \quad \forall k \in \Omega_D \tag{4}$$

$$\left(P^{dr}_{k,t}\right)^{+} \cdot \left(P^{dr}_{k,t}\right)^{-} = 0, \quad \forall k \in \Omega_D, \ \ \forall t \tag{5}$$

$$0 \le \sum_{t=1}^{T} \left(\kappa_{k,t} \middle| \left|P^{dr}_{k,t}\right| \ne 0\right) \le \kappa_{k,\max}, \quad \forall k \in \Omega_D \tag{6}$$