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Planning for distributed wind generation under active management mode

Jietan Zhang [a,*], Hong Fan [b], Wenting Tang [a], Maochun Wang [a], Haozhong Cheng [c], Liangzhong Yao [d]

[a] Qinghai Electric Power Company, Xining, Qinghai Province 810008, China
[b] Electric Power and Automation Engineering, Shanghai University of Electric Power, Shanghai 200090, China
[c] Department of Electrical Engineering, Shanghai Jiao Tong University, No. 800, Dongchuan Road, Shanghai 200240, PR China
[d] Alstom Grid, Stafford ST17 4LX, UK

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ABSTRACT

In the smart grid (SG), the active management (AM) mode will be applied for the connection and operation of distributed generation (DG), which means real time control and management of DG units and distribution network devices based on real time measurements of primary system parameters. In this paper, a novel bi-level programming model for distributed wind generation (DWG) planning under AM mode is put forward. The model takes the maximum expectation of net benefit of DWG as the upper level program objective, and takes the minimum expectation of generation curtailment as the lower level program objective. The impact of active management algorithm on improvement of branch power flow and node voltage is taken into account. A hybrid algorithm combining the plant growth simulation algorithm (PGSA) with probabilistic optimal power flow (POPF) algorithm is presented to solve the optimal planning of DWG under AM mode. The case studies have been carried out on a 33-node distribution network, and the results verify the rationality of the planning model and the effectiveness of the proposed method.

1. Introduction

Currently, most distributed generation (DG) connect with the distribution network based on a so-called "fit and forget" policy, which is consistent with passive network management [1,2]. Under this mode, DG is without control in the operation, the task of balancing supply and demand as well as the task of securing frequency and voltage has been left solely to large production units, and therefore the positive role of DG on improving branch power flow and node voltage is weakened. In some cases the penetration of DG must be controlled strictly, and the benefit and extension of DG have been confined.

Fortunately, smart grid (SG) has the potential to mitigate some of the difficulties that are posed by high levels of DG [3–9]. The ultimate smart grid defined by Gharavi and Ghafurian [10] as an electric system that uses information, two-way, cyber-secure communication technologies, and computational intelligence in an integrated fashion across electricity generation, transmission, substations, distribution and consumption to achieve a system that is clean, safe, secure, reliable, resilient, efficient, and sustainable. Even though there is conflict, the typical core of defining a smart grid consists of a bi-directional power flow, i.e. the consumers are also producing to the grid. SG is capable of delivering electricity from suppliers to consumers via a two-way digital technology, effectively controlling the consumers' energy consumption [11–13].

Active management (AM) is emerging as one of SG operations for the connection and operation of DG. AM means real time control and management of DG units and distribution network devices based on real time measurement of primary system parameters (voltage and current) [14,15]. AM mode takes DG as one component of the distribution network, and active control is taken according to the requirement of the distribution system, that is, DG need to contribute to the task of securing a balance between electricity production and consumer demands [16]. The application of AM is a challenge to the validity of traditional distribution network planning, operation, and commercial practices. Network planning and operation should be synchronous when AM is applied in the distribution network: The determination of the connection capacity of DG should consider different operation situations that will appear in the future as well as the positive effect of AM to improve the technical level of the network.

In this paper, a novel bi-level programming model for siting and sizing of distributed wind generation (DWG) under AM mode is put forward, which breaks the "fit and forget" installation policy of distributed generation in the passive distribution network. The model takes the maximum expectation of net benefit of DWG as the upper level program objective, and takes the minimum expectation of generation curtailment with voltage and thermal constraints as the lower level program objective, taking into account the impact of active voltage management algorithm on improvement of branch power flow and node voltage. The plant

* Corresponding author.
E-mail address: zhangjietan1980@163.com (J. Zhang).

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growth simulation algorithm (PGSA) combined with probabilistic optimal power flow algorithm (POPF) is applied to solve the optimal planning of DWG under AM mode. The proposed optimal planning approach has been tested on a 33-node distribution system to validate the rationality of the planning model and the effectiveness of the proposed method in the paper.

2. Bi-level planning model for DWG under AM mode

The main barrier for reaching higher levels of DG in distribution networks is the node voltage limit exceeding. Against this background, this paper focuses on three AM schemes that aim to increase the power penetration of DG but maintain the network voltage within the statutory limits [14].

(1) *Power generation curtailment (GC)*: GC controls the voltage by constraining the active power of DG.
(2) *On-load-tap-changer voltage control (OLTC)*: OLTC maintains the network voltages within defined limits by actively changing the tap-changer setting at the primary substation.
(3) *Reactive power compensation (RPC)*: RPC absorbs reactive power at the point of DG connection to mitigate voltage rise.

AM mentioned above belongs to the general optimal power flow (OPF) problems. The main idea of an OPF applied in the context of active distribution networks is to determine the control values of GC, OLTC and RPC schemes that minimize the cost of generation curtailment while satisfying voltage and thermal constraints [17]. In this particular case, the general optimization task is simplified to a problem of minimizing the amount of generation of DWG that has to be curtailed in order to satisfy voltage and thermal constraints.

In the active distribution network with AM, the new role of distribution networks requires unbundling of distribution network services and the development of commercial arrangements within which distribution network operators (DNOs) would carry out their responsibilities with the least cost and the highest efficiency, by using services from a number of potential providers [18]. The fundamental business idea is that the DNO offers an AM service to the DG units allowing them to maximize connected capacity and generated electricity, and the DG owners' income through selling power [19]. The planning objective of DWG is to maximize the expectation of net benefit of DWG by optimizing sites and size of DWG, which is shown as (1):

$$\begin{aligned} Max\,E(B_{\mathrm{N}}) &= Max\,E(B_{\mathrm{SAL}} - C_{\mathrm{CAP}} - C_{\mathrm{OPE}} - C_{\mathrm{CON}} - C_{\mathrm{AM}}) \\ &= Max\left(\sum_{i=1}^{N_{\mathrm{DWG}}}(p_w - c_r - c_{\mathrm{AM}})\cdot E(E_{\mathrm{DWG},i})\cdot PA(r,n) \right. \\ &\quad \left. - \sum_{i=1}^{N_{\mathrm{DWG}}}(c_e + c_f + c_{\mathrm{CON}})\cdot W_i\right) \end{aligned} \quad (1)$$

where B_{N} is the net benefit value of planning scheme; B_{SAL} is DWG owners' earnings from selling power; C_{CAP} is the investment cost of DWG; C_{OPE} is the operation cost of DWG; C_{CON} is the connection cost of DG units; C_{AM} is the cost of active management; N_{DWG} is the number of candidate installation sites of DWG; p_w is the price of wind power; c_r is the unit operation and maintenance cost of DWG; c_{AM} is the per-kWh active management cost of DWG; $E_{\mathrm{DWG},i}$ is the effective power generated by *i*th DWG units; *PA* is the present value factor of uniform annual value; *r* is the discount rate; *n* is the service life of DWG; c_e is the unit equipment investment of DWG, including prime mover, wind turbine, generator, and auxiliary equipment such as reactive power compensation equipment; c_f is the unit installation cost of DWG; c_{CON} is the per-kWh connection charges of DWG units; and W_i is the installed capacity of DWG at the *i*th candidate node.

Siting and sizing of DWG under AM mode is a typical bi-level programming problem, whose upper level program objective is maximum expectation of net benefit of DWG, and whose lower level program objective is minimum expectation of generation curtailment with voltage and thermal constraints. The bi-level programming model can be described as follows:

$$(P_1)\quad \text{Max}\quad F = E(B_N) \quad (2)$$
$$\text{s.t.}\quad 0 \leqslant W_i \leqslant W_i^{\max} \quad (3)$$
$$\sum_{i=1}^{N_{DWG}} W_i \leqslant \rho S_{load}^{\max} \quad (4)$$
$$(P_2)\quad \text{Min}\quad f = \sum P_{Gi}^{cur} \quad (5)$$
$$\text{s.t.}\quad P_{Gi} - P_{Li} - P_{Gi}^{cur} = P_i^{inj}(U,\theta,T) \quad (6)$$
$$Q_{Gi} + Q_{Ci} - Q_{Li} - Q_{Gi}^{cur} = Q_i^{inj}(U,\theta,T) \quad (7)$$
$$S_{ij} \leqslant S_{ij}^{\max} \quad (8)$$
$$U_i^{\min} \leqslant U_i \leqslant U_i^{\max} \quad (9)$$
$$P_{Gi}^{\min} \leqslant P_{Gi}^{cur} \leqslant P_{Gi}^{\max} \quad (10)$$
$$Q_{Ci}^{\min} \leqslant Q_{Ci} \leqslant Q_{Ci}^{\max} \quad (11)$$
$$T_k^{\min} \leqslant T_k \leqslant T_k^{\max} \quad (12)$$
$$Q_{Gi}^{cur} = f(P_{Gi}^{cur}) \quad (13)$$

where $W_i^{\max}$ is the upper limit of installed capacity of DWG permitted at the *i*th candidate installation node; $S_{load}^{\max}$ is the peak load of the distribution system; ρ is the upper limit of the proportion of installed capacity of DWG to the load; P_{Li}, Q_{Li} are the active and reactive load at the *i*th node; P_{Gi}, Q_{Gi} are the active and reactive generation at the *i*th node; $P_{Gi}^{cur}, Q_{Gi}^{cur}$ are active and reactive generation curtailment or increase (if possible) at the *i*th node; Q_{Ci} is the reactive power generated/absorbed by a reactive compensation equipment; P_i^{inj}, Q_i^{inj} are the active and reactive power injection at the *i*th node, T_k is the tap setting of the tap-changer $k; S_{ij}$ is the load flows of branch *ij*; θ is the node voltage angle; and *U* is the node voltage magnitude.

Eq. (2) is the upper level program objective function, that is maximum expectation of net benefit of DWG; Eq. (3) is the installed capacity constraints of DWG at the candidate nodes; Eq. (4) is penetration level limit of DWG. Eq. (5) is the lower level program objective function, that is minimum expectation of generation curtailment. The optimization object need subject to not only power flow equation constraints ((6) and (7)), but also the branch thermal constraint (8) and network voltage limits (9). The amount of active generation curtailed will be limited by the capacity of DG connected (10). Reactive power support is limited by the capacity of reactive compensation equipments installed (11). The tap changer setting will be optimized and can vary within the bounds given by (12). Reactive power curtailment may be correlated with the active power curtailment, which is modeled through (13).

3. Probabilistic optimal power flow under AM mode

3.1. Probabilistic optimal power flow

The upper level program objective function of bi-level DWG planning is in the form of expectation. The simulation method can be used to solve this problem, but it will cost large computational complexity, because every lower level program problem namely the OPF corresponding with every period must be calculated. Furthermore, the operation of distribution network is affected and disturbed by some probabilistic factors, such as the forecast error of load and DWG output. Therefore, it is necessary to introduce the probabilistic optimal power flow (POPF).