Electrical Power and Energy Systems 101 (2018) 13–24

Contents lists available at ScienceDirect

Electrical Power and Energy Systems

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

Rapid assessment of maximum distributed generation output based on security distance for interconnected distribution networks

Jia Liu[a,*], Haozhong Cheng[a], Pingliang Zeng[b], Liangzhong Yao[b]

[a] Department of Electrical Engineering, Shanghai Jiao Tong University, Shanghai 200240, China
[b] China Electric Power Research Institute, Beijing 100085, China

ARTICLE INFO

Keywords:
Interconnected distribution networks
Distributed generation
Maximum output assessment
Security distance
N-1 contingencies

ABSTRACT

Security distance provides a quantitative approach to assess the N-1 security and its margin of distribution systems. In order to support system N-1 secure operation, distributed generations (DGs) should be used in terms of capacity credit (CC). Considering the conductor thermal constraints and voltage constraints after a substation transformer or feeder N-1 contingency, this paper proposes a rapid maximum output assessment method for DGs. With the proposed method, the system operators can better guarantee system security in the presence of active management. The concept of security distance for distribution networks is primarily decomposed into two parts: feeder security distance (FSD) and transformer security distance (TSD). Considering the correlation between the wind speed and illumination intensity, the combined output characteristics of DGs are achieved using the defined wind-photovoltaic conversion coefficient based on coordinate conversion. Then, the initial maximum DG output on each feeder section is approximately calculated by initial FSDs and TSDs. On these bases, the maximum output assessment method is proposed under uncertainties associated with DGs, loads and contingencies. Moreover, several related issues are further discussed: (a) discussion of the proposed use of DGs in terms of CC, (b) consideration of demand response in the proposed method, and (c) feasibility of the proposed method to N-2 contingency analysis. In the end, the proposed method is successfully applied to the expanded IEEE RBTS-Bus4 and a real urban distribution networks and the results verify its high performance when compared to the normal optimal method from static and dynamic views.

1. Introduction

In recent years, with distribution generations (DGs), such as wind turbine generators (WTGs) and photovoltaic generators (PVGs), and new types of loads injected into the distribution system, the various uncertainties bring inevitable concerns over the secure operation of the distribution network [1]. Although the power injection can decrease net losses, improve power qualities and reduce carbon emissions, the outputs of DGs have the obvious characteristic of fluctuation, which are sensitively affected by climate and environmental factors. When the outputs of DGs exploited in a distribution system are unacceptable, the economic and secure operation of the system would be greatly influenced. Thus, there is an imperious demand for a rapid method to calculate the maximum DG output, which would be a critical problem to ensure the security and asset efficiencies of distribution systems.

In order to investigate the impacts and optimal operation problems of the exploited DGs, a variety of studies have been carried out in literatures [2–10]. A novel real-time testing of the optimal power flow (OPF) technique for the distributed power flow management (PFM) problem in an online operational mode is employed to manage the thermal constraints [2]. Ref. [3] investigates an effective method to formulate the distribution OPF based on message passing interface. In [4], the interruptible generator contracts and power reduction commands are proposed to increase the wind-power penetration on condition that the security constraints are not violated. Ref. [5] formulates the regulation and load following models, which illustrate the impacts of WTGs on some system requirements. In [6–9], several generation control strategies, including the optimization method, the active and reactive power operating point, the bi-level control system and the multi-stage output control in distribution PFM, are proposed and various case studies are used to illustrate the effectiveness of these approaches. Ref. [10] presents an alternative strategy for the coordinated output control of DGs in the presence of PFM under DG proliferation.

Considering uncertainties brought by DG outputs, all the above studies help a lot in the assessment of maximum DG output under different circumstances. However, because these works do not take N-1 security guideline into consideration, the output results obtained from these methods may not meet the secure demand for system operation.

* Corresponding author.
E-mail address: liujia911011@126.com (J. Liu).

https://doi.org/10.1016/j.ijepes.2018.03.018
Received 25 February 2017; Received in revised form 19 November 2017; Accepted 11 March 2018

As a key criterion for distribution system operation, N-1 security must be guaranteed. On the other hand, modelling of uncertainties should take a substation transformer or feeder N-1 contingency in distribution systems into account. To guarantee system security, the maximum generated power of DGs allocated in distribution networks may be changed when contingencies occur. Moreover, due to a large-scale nonlinear optimization process, the computation efficiencies of the existing assessment methods for maximum DG output are low. The larger the scale of a distribution system is, the lower the efficiency of computation is. Thus, a rapid method to calculate the maximum DG output for practical distribution systems considering N-1 security is urgently required.

The use of DGs to support system capacity has drawn increasing attention, and the concept of capacity credit (CC) has been developed to DGs to quantitatively evaluate their contribution to adequacy of supply [11,12]. Moreover, numbers of CC assessment indices for DGs, such as equivalent firm capacity, equivalent conventional capacity and guaranteed capacity, are adopted in [13] to assess the CC systematically. Recently, the network capacity support from demand response (DR) was investigated [14], and the impacts of the different operating parameters of DR on their contribution to adequacy of supply in terms of a transmission network were studied [15]. Ref. [16] assesses the post-contingency reliability of smart distribution networks in the presence of DR. The contributions of DR to support planning of smart distribution networks are verified in [17]. The flexibility offered by distributed energy solutions such as DR or DGs could help defer or even avoid costly irreversible network upgrades, thus potentially reducing capital costs [18]. As a result, with the consideration of the interactions between DGs and DR, DR may impact the use of DGs in terms of CC to guarantee system N-1 security.

Traditional distribution networks are mainly based on radial topology structure. However, more interconnections of feeders are implemented in urban areas. Furthermore, with the concept frame of smart distribution grid proposed, distribution automation is rapidly developed in medium-voltage distribution systems, which makes the remote control much faster [19,20]. The real-time information of feeder loads can be measured by feeder terminal units [21]. The above progresses in the distribution system make it possible for loads to transfer from one feeder to another and to be re-distributed among substations. This indicates that the capacities of transformers in different substations can reserve for each other [22].

The conventional approaches to illustrate the N-1 security and load shedding strategies are based on N-1 simulation method [23,24]. However, the speed to sequentially testify N-1 security of each component is severely limited, which may not be suitable to be utilized in practical application. Moreover, because the distribution network operator (DNO) has the burden to accommodate the numerous uncertainties, fluctuations or contingencies and guarantee the N-1 secure operation of distribution systems, it is hard for DNOs to observe the real-time N-1 security margins and control the appropriate penetration capacities of loads and DGs through the existing approaches. Thus, a region-wise approach known as distribution system security region (DSSR) is proposed to illustrate N-1 security, which has the advantages of high efficiency and visualization. The DSSR is defined as a set of all operating points guaranteeing the secure operation when a substation transformer or feeder faults [25–27].

Therefore, the DSSR theory can be an effective tool to evaluate real-time secure operation level by calculating security distance in advance. Besides, DNOs can visually observe the security margin of the current operating point and directly obtain overall security information of the distribution system. However, there is no printed literature reporting the N-1 security illustration of distribution systems in the presence of DGs by utilizing DSSR theory, so it is a meaningful but neglected problem for us to research how to quickly assess the maximum DG output guaranteeing system N-1 security, voltage constraints and asset efficiencies in an interconnected distribution network. The main contributions of this paper include:

- A novel assessment method for maximum DG output considering N-1 contingencies is proposed, in which the correlations among the wind speed, illumination intensity and load are all formulated in the combined DG-load model.
- Unlike the previous work on maximum DG output assessment that adopted the mathematical optimization method, the proposed method has the advantages of flexibility, efficiency and precision, which is suitable for DNOs to adjust DG output in the presence of active management.

In order to further state the maximum output assessment of DGs considering N-1 security and bus voltage constraints, this remaining paper is organized as follows: based on the concept of DSSR, definitions of feeder security distance (FSD) and transformer security distance (TSD) are described in Section 2. The distance-based maximum DG output assessment is developed in Section 3. The proposed use of DGs in terms of CC for system N-1 secure operation and the potential feasibility of the proposed method incorporating DR and N-2 contingency are discussed in Section 4. The correlated simulation data are generated in Section 5. Numerical results are simulated in Section 6. Finally, Section 7 concludes this paper.

2. Formulations of FSD and TSD

2.1. Concepts of DSSR and its boundary

The N-1 criterion is regarded as a basic guideline for distribution system operation. If a distribution system is N-1 secure, it means that the load of normal areas maintains power supply with all the components satisfying network security constraints when an N-1 contingency occurs [25]. In radial distribution networks, N-1 security only considers the reserve capacity of transformers in the same substation and the NTC after an N-1 contingency is ignored. However, with the network reformation in urban areas, the feeder interconnection is widely implemented and the load can be flexibly transferred among substations. Thus, the substation capacity and feeder configuration should be simultaneously considered when guaranteeing N-1 security in interconnected distribution networks. Two types of contingency scenarios, feeder contingency and substation transformer contingency, are preliminarily considered in this paper.

DSSR is defined as an operating space made up of innumerable operating points satisfying substation transformer and feeder N-1 contingency constraints [27]. Here, the operating point refers to an n-dimensional vector composed of feeder section loads, which are defined as equivalent loads formulated by loads that have the same restoration or transfer path. The basic constraints of DSSR are the conductor thermal constraints after a feeder or substation transformer N-1 contingency. These constraints can be mathematically formulated as

$$\Omega_{DSSR} = \left\{ W_f \;\middle|\; \begin{array}{l} S_F^i = \sum\limits_{j=1} S_{f,tr}^{i,j} \\ S_{f,tr}^{i,j} + S_F^j \leqslant S_{F,max}^j \\ S_{T,tr}^{m,n} = \sum\limits_{i\in\Phi^{(m)},j\in\Phi^{(n)}} S_{f,tr}^{i,j} \\ S_T^m = \sum\limits_{i\in\Phi^{(m)}} S_F^i \\ S_{T,tr}^{m,n} + S_T^n \leqslant S_{T,max}^n \end{array} \right. \tag{1}$$

where Ω_{DSSR} represents the DSSR; W_f is the operating point; S_F^i is the load of feeder section F_i; $S_{f,tr}^{i,j}$ is the load transferred from F_i to F_j when F_i faults; $S_{F,\max}^j$ is the capacity of F_j; $S_{T,tr}^{m,n}$ is the load transferred from transformer T_m to T_n when T_m faults; S_T^m is the load of transformer T_m; $S_{T,\max}^n$ is the transformer T_n capacity; $\Phi^{(m)}$ is the set of feeder sections