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Influence of phasor adjustment of harmonic sources on the allowable penetration level of distributed generation

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ABSTRACT

Harmonic distortion caused by increasing size of inverter-based distributed generation (DG) can give rise to power quality problems in distribution power networks. Therefore, it is very important to determine allowable DG penetration level by considering the harmonic related problems. In this study, an optimization methodology is proposed for maximizing the penetration level of DG while minimizing harmonic distortions considering different load profiles. The methodology is based on updating the voltage magnitude and angle at point of common coupling depending on the size of DG to be utilized in the harmonic power flow modeling. The harmonic parameters are determined by using decoupled harmonic power flow method, in which the harmonic source modeling with harmonic current spectrum angle adjustment is embedded, while the nonlinear loads and inverter-based DGs are connected to the distribution power network. The allowable penetration level of DGs is determined based on power quality constraints including total harmonic voltage distortion, individual harmonic voltage distortion, and RMS bus voltage limits in the optimization framework. Fuzzy-c means clustering method is also applied to decrease the computational effort of the optimization process in the long-term load profile. The effectiveness of the proposed method is illustrated on the IEEE 33-bus radial distribution network for different scenarios.

1. Introduction

Distributed generation (DG) has gained great importance with the increasing load demand in distribution power networks. Photovoltaic distributed generation (PV-DG) is one of the most promising DG technologies among the renewable energy resources due to the cost reduction and modular structure [1]. Improving voltage profile, reducing emissions and line losses, enhancing efficiency, reliability, and security can be achieved by the installation of renewable DG units [2]. Interconnection of most of the renewable energy resources into the distribution network through power electronic devices results in extensive use of inverter-based DG [3–5]. However, current and voltage harmonics are caused by the inverter-based interfaces of PV systems [6]. Efficiency and reliability of power system, loads, and protection relays are adversely influenced by these current and voltage harmonics comprising several higher frequency components [7]. The power quality may not be negatively affected by the small penetration of PV-DGs in practical cases [1]. On the other hand, PV-DGs together with the nonlinear loads may contribute to higher values of total harmonic voltage distortion [8].

In the literature, the studies on harmonic power quality problem together with the DG make the power system harmonics concept challenging issue [9–16]. In [9], optimization problem is formulated to determine maximum penetration level of DG based on power quality parameters by using particle swarm optimization. In [10], the worst case conditions among different scenarios are taken into account in terms of power quality parameters in the optimization structure with integrating DG. In [11], the harmonic formation process has been examined by using a general model which is modified from the conventional control structure diagram. According to this study, the magnitude of lower order harmonics increases with the decrease in the output power of PV-DG. In [12], a study regarding the compensation of main voltage harmonics has been performed to enhance the voltage quality in grid-connected micro grids. Waveform distortion observed in the photovoltaic plants has been experimentally evaluated in [13]. In [14], volt/var/THD control is presented by taking into account the reactive power injection and absorption of photovoltaic system when the harmonic distortions exist in the distribution network. An analytical method has been utilized to obtain the maximum DG penetration level in a power system taking into

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account harmonic limits in [15]. In [16], the optimal location and capacity of DG are determined to improve voltage profile and decrease total harmonic distortion and losses in planning of the power network.

In recent years, the impact of harmonic sources on the distribution network is a challenging topic in the literature. In general, nonlinear equipment is modeled as a harmonic current source without considering phase angle in harmonic simulations [9,10]. The magnitude of harmonic current is determined by using a harmonic spectrum which represents the ratio of the harmonic currents to the fundamental current. However, harmonic phase angles should be included in modeling when multiple sources are considered simultaneously [17]. There are a few papers that consider the phase angle modeling of harmonic current sources [18–22]. In [18], the harmonic power quality problems are investigated for a PV installed distribution network with the consideration of current phase angle referencing method while adjusting harmonic angles. In [19], the voltage and current angle referencing methods are described in a detailed manner for calculating power indices in balanced and unbalanced networks and the results show that the both methods give the same values. It is worthy to note that phase angle of harmonic sources plays an important role in power index calculations. The study based on the voltage and current angle referencing methods is also conducted on the power network with multiple harmonic sources in [20]. In [21,22], the importance of phase angles in harmonic simulations is investigated in a distribution network by varying phase angle of harmonic sources and a phasor harmonics index is proposed when multiple harmonic sources exist in the distribution system.

The aim of this study is to investigate the harmonic influences on the allowable DG penetration level in the distribution network by including inverter-based DG and nonlinear loads having the harmonic spectrum with magnitudes and phase angles. The novelty of current this paper lies in considering harmonic spectrum current angle adjustment in harmonic analysis and taking into account the bus voltage magnitude and phase angle changes with the real and reactive power flow in distribution network. Moreover, instead of considering different load conditions separately, the planning horizon is included in the optimization framework and the impact of planning horizon result is presented to compare with that of single load profile in the present study. In the literature, harmonic analysis is implemented either by considering the adjustment of harmonic spectrum phase angle [17–20,23] or ignoring the adjustment [9,10,24]. In this study, the DG harmonic spectrum as presented in [10,25] is utilized, whereas the nonlinear load data are taken from [24] as an example. But nevertheless, the proposed method can be applied to any DG and nonlinear load harmonic spectrums. The harmonic current magnitudes are updated based on the size of DG and corresponding voltage phasors obtained from fundamental frequency power flow. The harmonic current spectrum phase angles are adjusted by utilizing voltage angle referencing based method.

The paper is organized as follows: first, the voltage magnitude and phase angle at the point of common coupling (PCC) of the power network, where the DG is integrated, are updated by solving the power balance equations at the fundamental frequency depending on the size of DG to be utilized in harmonic power flow modeling. The harmonic parameters are determined by using decoupled harmonic power flow method, in which the voltage angle referencing method and the harmonic source modeling without harmonic current spectrum angle adjustment are included, while the nonlinear loads and inverter-based DGs are connected to the distribution power network. Fuzzy-c means clustering method is also applied to decrease the computational effort in the optimization process under long-term load profile. Genetic Algorithm (GA) and Interior Point (IP) optimization methods are utilized to obtain the allowable penetration level of DGs based on power quality constraints consisting of total harmonic voltage distortion (THDV), individual harmonic voltage distortion (IHDV), and RMS bus voltage (Vrms) limits by considering different load profiles in the optimization framework. The effectiveness of the proposed method is tested on the IEEE 33-bus radial distribution network for different scenarios.

2. Modeling of harmonic power flow

In this study, the decoupled harmonic power flow is used to determine the voltage harmonics because of its feasibility and convergence ability in complex systems [9]. According to this method, the conventional power flow is achieved in the fundamental frequency, and harmonic analysis is utilized in the higher frequencies. The harmonic current injection matrix of nonlinear load and DG and the harmonic bus admittance matrix are built in each frequency separately. Thus, simulation time is shortened by considering the harmonic couplings as negligible [24]. Besides nonlinear loads, inverter-based DGs are also modeled as harmonic source according to the decoupled harmonic power flow method [9,10].

The bus voltage angles and magnitudes are changed by the inclusion of DG systems. For this reason, the corresponding bus voltage magnitudes and angles are updated by solving power balance equations at fundamental frequency to be utilized in harmonic power flow in this study.

2.1. Bus voltage magnitudes and angles after the interconnection of DG

The synchronism between the utility grid and the inverter-based DG system is associated with the time interval, which is until the integration of renewable agent into the power system [26]. However, the steady-state change in voltage magnitude and angle at PCC after the interconnection process should be taken into account for carrying out harmonic power flow analysis. An example is given with and without DG integration in order to illustrate this change in voltage magnitude and angle at PCC as demonstrated in Fig. 1 [27].

According to Fig. 1, the power generation at bus k is modeled as a synchronous generator, meanwhile the generation at load bus i is represented as DG unit. P_{ki} and Q_{ki} represent the active and reactive powers flowing through the $k$ith branch, respectively. While R_{ki} and X_{ki} are resistance and reactance of the line, I_{ki} is line current flowing from bus k to bus i. As illustrated in the figure, S is the switch interfacing the DG to the power network. Power flow analysis, which is known as the backbone of power system analysis and design, is required to illustrate the changes in voltage magnitude and angle at PCC in case of switching on the DG. The active and reactive power balance equations at bus i are given as follows:

$$P_{G,i} - P_{D,i} - \sum_{k=1}^{Nbus} |v_i^1||v_k^1||y_{i,k}^1| \cos(\delta_{i,k}^1 - \theta_i^1 + \theta_k^1) = 0 \qquad (1)$$

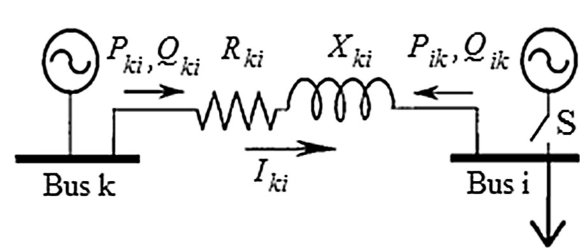

Fig. 1. $k$ith branch of a distribution power network.