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Optimal penetration levels for inverter-based distributed generation considering harmonic limits

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ABSTRACT

The installation of inverter-based distributed generation (DG) has been increasing rapidly in recent years, and specifically, photovoltaic power systems. Such increased penetration will result in increased harmonics which could exceed the IEEE 519 allowable harmonic distortion levels. In this paper, the maximum DG penetration level is determined taking into consideration the IEEE 519 allowable voltage harmonic limits. The proposed study is formulated as a mixed integer non-linear programming (MINLP) problem where harmonics are determined using the decoupled harmonic power flow approach. The maximum DG penetration level based on optimal DG size and location is determined using particle swarm optimization (PSO) algorithm. The proposed formulation is tested on 18-bus and 33-bus radial distribution systems considering ten load and DG scenarios. The results show that by decentralizing the DG capacity, higher penetration levels could be achieved. The limiting effect of preinstalled DG at a certain bus on the overall DG penetration is also analyzed.

1. Introduction

Recently, the penetration level of distributed generations (DG) grows significantly at the distribution level. Integration of small scale DG units such as internal combustion engines, combined cycle, micro turbines, biomass, photovoltaic, wind generation and fuel-cells, in large numbers, can improve the voltage profile, reduce line losses, avoid the construction of new transmission circuits and large power plants, enhance system reliability, and increase overall system efficiency and reduce emissions [1]. Among the various DG interface types, inverter-based DG units are becoming more common since the majority of renewable resources are interconnected to the utility through power electronic converters [2–4]. The inverter-based DG units are designed to operate at unity power factor as per the IEEE Standard 1547 [5].

DG Impact studies have been presented in literature to examine the effect of installing DG on the power system operation [6–9]. In [6], the effect of DG installations on steady state operating conditions such as the system voltage profile, losses and reliability has been discussed. In [7], it shows that DG can impact the fault current levels which in turn will affect the system protection coordination. Power system transient stability can be affected by increased DG penetration levels [8]. The extent to which DG will impact the distribution system depends mainly on the penetration level and type of DG interface [9]. Commonly, utilities conduct a system impact analysis where the DG owners are requested to provide the type, size and location of the DG [10].

Since the system operation is affected by the installation of DG, the allowable DG penetration level satisfying the system limits was optimally determined in [7,9,11,12]. In [7], the maximum DG penetration was determined with consideration of protection coordination. An analytical expression for calculating the acceptable DG penetration to minimize the real power losses is derived in [9]. Similarly, a trade-off between loss minimization and DG capacity maximization was obtained using the ordinal optimization (OO) method taking into account voltage limits and line flow limits in the optimal power flow problem [11]. The estimation of photovoltaic generation penetration levels based on voltage rise and conductor ampacity was studied in [12].

The maximum possible penetration level of DG considering the thermal limits, transformer capacity, voltage limits and short circuit limits on real medium voltage distribution network with already installed DG units was analyzed in [13]. The determination of the maximum DG penetration level based on harmonic limits was analyzed for a simple system having uniform feeder loading, linearly increasing and linearly decreasing loading types [14]. The penetration level is calculated using the 7th and 9th standard harmonic limits individually (based on the IEEE standard 519-1992 [15]) and the results show that the DG penetration level can reach 100% of

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the feeder capacity. A more comprehensive approach to determine the maximum DG penetration level, taking into account harmonics, is considering the use of optimal harmonic power flow. Various harmonic power flow techniques have been proposed in literature and a detailed review of the various harmonic power flow formulations is given in [16,17]. The decoupled harmonic power flow (DHPF) approach is one of the commonly used methods due to its simplicity and capability of handling several harmonic sources simultaneously [18].

In this paper, the maximum DG penetration level and optimal DG locations are determined considering the effect of harmonic distortions caused by inverter-based DG units. The problem is formulated as a mixed integer non-linear programming (MINLP) problem considering the IEEE standard voltage limits, total harmonic distortion limits and individual harmonic distortion limits which are calculated using the decoupled harmonic power flow approach. The proposed formulation is optimized using particle swarm optimization (PSO) algorithm and is tested on 18-bus and 33-bus systems considering ten load and DG scenarios. The effect of the presence of non-linear loads (NLL) and existing DG installations on DG penetration levels is examined. In addition, the optimal penetration levels are determined considering the centralized versus decentralized DG allocation strategy.

2. Problem formulation for maximizing DG penetration

The problem of identifying the optimal locations and sizes of DG units to maximize the overall DG penetration level taking into account harmonics is formulated as a constrained mixed integer non-linear programming optimization problem. The fundamental voltage components are estimated by using the conventional power flow (CPF) method followed by the DHPF algorithm to compute the harmonic components of the voltage. In the fundamental load flow, the DG units generate active power and the DG buses are considered as PQ buses. For the DHPF, the non-linear devices (NLD) such as DG and NLL are modeled as a harmonic current source.

2.1. Objective function

The aim is to determine the maximum DG penetration level in terms of the total system capacity. The DG operates at unity power factor and thus there is no reactive power supplied by the DG units [5]. Therefore, the MVA rating of the DG equals to the real power generation. The objective function (F) can be expressed as follows:

$$F = \frac{\sum_{i=1}^{N_{\text{bus}}} \left(b_i * P_{\text{DG},i}\right)}{\text{MVA}_{\text{Total}}} \times 100 \tag{1}$$

where, N_{bus}: number of buses; b_i: binary number where '0' represents no DG and '1' represents presence of DG at ith bus; $P_{\text{DG},i}$: real power installation of DG at bus i (MW); $\text{MVA}_{\text{Total}}$: total system MVA.

2.2. Equality constraints

The system equality constraints are described by real and reactive power flow equations at each bus. In general the real and reactive power equality constraints at bus i can be expressed as follows:

$$P_{\text{G},i} - P_{\text{D},i} - \sum_{j=1}^{N_{\text{bus}}} \left|v_i^{(1)}\right| \left|v_j^{(1)}\right| \left|y_{i,j}^{(1)}\right| \cos\left(\theta_{i,j}^{(1)} - \delta_i^{(1)} + \delta_j^{(1)}\right) = 0 \tag{2}$$

$$Q_{\text{G},i} - Q_{\text{D},i} - \sum_{j=1}^{N_{\text{bus}}} \left|v_i^{(1)}\right| \left|v_j^{(1)}\right| \left|y_{i,j}^{(1)}\right| \sin\left(\theta_{i,j}^{(1)} - \delta_i^{(1)} + \delta_j^{(1)}\right) = 0 \tag{3}$$

where, $P_{\text{D},i}$, $Q_{\text{D},i}$: fundamental real and reactive power demand at bus i; $P_{\text{G},i}$, $Q_{\text{G},i}$: fundamental real and reactive power generation at bus i; $\left|v_{i,j}^{(1)}\right|$: fundamental voltage magnitude at bus i; $\left|y_{i,j}^{(1)}\right|$: magnitude of (i, j)th element of the fundamental admittance matrix; $\theta_{i,j}^{(1)}$: angle of (i, j)th element of the fundamental admittance matrix; $\delta_i^{(1)}$: fundamental voltage angle at bus i.

2.3. Inequality constraints

The inequality constraints are associated with the bus voltage limits, total and individual harmonic distortion levels.

2.3.1. Bus voltage limits

The RMS bus voltage magnitude is limited by its specified lower and upper limit.

$$v^{\min} \le \sqrt{\left|v_i^{(1)}\right|^2 + \sum_{h=2}^{h_{\max}} \left|v_i^h\right|^2} \le v^{\max} \tag{4}$$

where $v^{\min}$ and $v^{\max}$ are the minimum and maximum bus voltage limits and are taken to be 0.9 p.u. and 1.1 p.u., respectively. The superscript h indicates the harmonic order.

2.3.2. Total harmonic distortion limits

The total voltage harmonic distortion is bounded by its maximum acceptable value as specified in the IEEE-519 standard.

$$\text{THD}_{v,i}(\%) = \frac{\sqrt{\sum_{h=2}^{h_{\max}} \left|v_i^h\right|^2}}{\left|v_i^1\right|} \times 100 \le \text{THD}_v^{\max} \tag{5}$$

where $\text{THD}_v^{\max}$ is the maximum permissible voltage harmonic distortion level at any bus and is considered to be equal to 5%.

2.3.3. Individual harmonic distortion limits

The limit on the individual voltage harmonic distortion is specified in the IEEE Std. 519 and the constraint can be expressed as follows:

$$\text{IHD}_{v,i}^h(\%) = \frac{v_i^h}{v_i^1} \times 100 \le \text{IHD}_v^{\max,h} \tag{6}$$

where $\text{IHD}_v^{\max,\text{h}}$ is the maximum permissible voltage individual harmonic distortion level at harmonic order h and is set as 3%.

2.4. Decoupled harmonic power flow

The decoupled harmonic power flow approach is widely used due to its simplicity and convergence capability for large systems [16,18,19]. Following the approach, the conventional power flow is used at fundamental frequency and the nodal method is used for the higher frequency components. At the higher frequency components, the system harmonic admittance matrix is constructed along with the non-linear devices which are represented by a harmonic current injection matrix. The amplitude and phase angle of the non-linear device currents can be calculated for each frequency component using analytical models or estimated from measured non-sinusoidal current waveforms [16]. The hth harmonic load admittance at bus i (y_i^h), shunt capacitor admittance at bus i (y_{ci}^h),