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Determining Optimal Location and Size of Distributed Generation Resources Considering Harmonic and Protection Coordination Limits

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***Abstract*—In this paper, a new optimization problem is proposed to determine the maximum distributed generation (DG) penetration level by optimally selecting types, locations and sizes of utility owned DG units. The DG penetration level could be limited by harmonic distortion because of the nonlinear current injected by inverter-based DG units and also protection coordination constraints because of the variation in fault current caused by synchronous-based DG units. Hence the objective of the proposed problem is to maximize DG penetration level from both types of DG units, taking into account power balance constraints, bus voltage limits, total and individual harmonic distortion limits specified by the IEEE-519 standard, over-current relay operating time limits, and protection coordination constraints. The DG penetration study is formulated as a nonlinear programming (NLP) problem and tested on the IEEE-30 bus looped distribution network with ten load and DG scenarios. Similarly, feasibility assessment of customer owned DG unit installations considering power quality and protection coordination is also studied. Simulation results show the effectiveness of the proposed approach, which can serve as an efficient planning tool for utility operators.**

***Index Terms*—Distributed generation, harmonic distortion, harmonic power flow, particle swarm optimization, protection coordination.**

I. Introduction

RECENT advancement in research and development on distributed generation (DG) technology such as solar, wind, biomass, fuel cell and micro-turbines has created an important role for DG in the future energy supply due to its improved performance, reliability and flexibility to achieve higher energy efficiency and reduced emission [1], [2]. The DG units are interconnected with the utility grid as per the IEEE-1547 standard [3], [4]. The location, type, and size of DG units are the three main factors that can affect the fault current levels, protection coordination of relays, stability, and power quality [5]–[7] and this can limit the amount of DG penetration.

The DG units may be owned either by utility or by customers [8], [9]. In the case of a utility owned DG installation, the utility has to optimally plan the location and size of the DG units in order to improve network benefits and reliability [10]–[12]. In practice, one is not always able to site DG at the locations determined by an optimization algorithm, however it gives the planner an idea of where DG might be the most beneficial [13]. In the case of customer owned DG installation, the utility planner should conduct a feasibility and assessment study to evaluate any technical issues resulting from the new installation of customer owned DG installation [14].

During the last decade, power electronic converters have undergone a fast evolution due to the development of fast semiconductor switches and also the introduction of real-time controllers that can implement advanced and complex control algorithms efficiently [15]. DG units of the inverter-based type tend to have more impact on the system harmonic levels than synchronous-based DG. The limitations on current and voltage harmonics, which can cause undesirable effects on various power system equipments and the measurement and equipment modelling for harmonic analysis have been given in the IEEE-519 standard [16]. The penetration level of photovoltaic generation in radial distribution system considering the limits on voltage magnitudes and conductor current flow is investigated in [17]. The maximum DG penetration level based on the individual harmonic limit is examined for a simple system in [18]. This approach uses 7th and 9th order individual current harmonic limits given by the IEEE-519 standard and proves that 100% DG penetration is theoretically possible.

On the other hand, synchronous-based DG units has a much more profound effect on protection coordination than inverter-based DG [19]–[21]. In [22], [23], fault current limiters are implemented to mitigate the impact of synchronous-based DG on protection coordination. In [24], the maximum DG capacity for radial distribution systems was calculated considering coordination between recloser and fuse to avoid reliability degradation. Optimal placement of synchronous-based DG, considering the impact on short circuit index level, is solved using particle swarm optimization [25]. An analytical approach to minimize the system losses by installing various type of DG units (PV, wind, fuel cell, and micro turbine based on real and reactive power injection only) is discussed in [26]. However a comprehensive study considering DG type, size, and location simultaneously for maximizing the DG penetration has not been addressed in the literature.

In this paper, an optimization framework is proposed to maximize the DG penetration level in looped distribution systems taking into account power balance, voltage limits, harmonic limits and protection constraints. Since the harmonic distortion is caused by inverter-based DG units and protection coordination failure of directional over-current relays (OCR) are due to the synchronous-based DG units, an algorithm that includes

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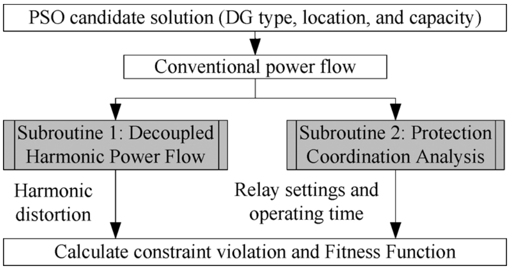

Fig. 1. Framework showing fitness evaluation sequence.

both decoupled harmonic power flow (DHPF) for harmonic estimation and short circuit analysis for protection coordination is embedded within the optimization framework. In the case of customer owned DG installation, the feasibility assessment studies are conducted by the utility planner with the support of the aforementioned optimization tool. The problem is solved using the particle swarm optimization (PSO) algorithm due to the nonlinear and nonconvex nature. The problem is tested on the standard IEEE-30 bus distribution system with ten load and DG scenarios and the maximum penetration level is determined considering both types of DG units and compared with the case of optimizing DG penetration with only inverter-based DG.

II. Problem Formulation

The proposed problem is formulated to maximize the overall DG penetration level by optimally selecting the location and size of both inverter-based and synchronous-based DG units using particle swarm optimization (PSO). The constraints of the proposed problem include fundamental frequency real and reactive power balance, RMS voltage limits, individual and total voltage harmonic limits at each bus, relay operating time limits and protection coordination constraints. The fitness evaluation sequence for each PSO candidate solution is shown in Fig. 1.

Initially, the Newton-Raphson based conventional power flow is conducted at fundamental frequency to calculate the fundamental voltage components considering both types of DG units, taking into account the power balance constraints. After running conventional power flow, the sequence has been divided into two parallel subroutines namely decoupled harmonic power flow for harmonic analysis and short circuit studies for protection coordination analysis. In the first subroutine, the result of conventional power flow is used by the DHPF algorithm which estimates the higher order harmonic components with inverter-based DG units. In the second subroutine, the impact of DG units on fault current is considered to optimize the relay settings with protection coordination constraints. The details of the proposed problem formulation are described in the following subsections.

A. Harmonic Power Flow Analysis

Harmonic power flow techniques are useful to estimate the system distortion due to the presence of nonlinear devices [27], [28]. Among various harmonic power flow formulations, the DHPF method is most commonly used due to its simplicity [29]. The subroutine steps involving the decoupled harmonic power flow solution are shown in Fig. 2. Initially, the results

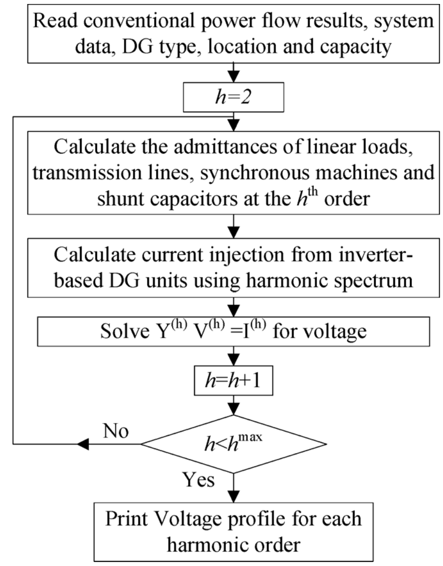

Fig. 2. Flowchart of the decoupled harmonic power flow (Subroutine1).

of conventional power flow, system data and DG type, location and capacity are inputted to DHPF subroutine. In higher order harmonic frequencies, the transmission lines, shunt capacitors, synchronous machines, and linear loads are modeled as an equivalent admittances using the results of the conventional power flow and then a new admittance matrix is formulated. Inverter-based DG units are modeled as harmonic current injecting sources in the DHPF method. On the other hand, the synchronous-based DG units are modeled as a source behind an impedance. Nodal equations are solved for each individual harmonic order h to obtain the harmonic voltage and the result is used to calculate the harmonic distortion [29], [30]. The harmonic admittances of various components can be expressed as follows:

$$y_i^{(h)} = \frac{P_{D,i}}{\left|v_i^{(1)}\right|^2} - j\frac{Q_{D,i}}{h\left|v_i^{(1)}\right|^2} \tag{1}$$

$$y_{ci}^{(h)} = hy_{ci}^{(1)} \tag{2}$$

$$y_{i,i+1}^{(h)} = \frac{1}{R_{i,i+1} + jhX_{i,i+1}} \tag{3}$$

where

$P_{D,i}, Q_{D,i}$	fundamental real and reactive power demand at bus i;
$\lvert v_i^{(1)}\rvert$	magnitude of fundamental voltage at bus i;
$y_i^{(h)}$	admittance of load connected at bus i for hth order harmonic;
$y_{ci}^{(1)}$	fundamental frequency admittance of the capacitor connected at bus i;
$y_{ci}^{(h)}$	shunt capacitor admittance at hth order;
$y_{i,i+1}^{(h)}$	admittance of branch connected between buses i and $i+1$ at hth order.

The harmonic admittances of various elements are used to formulate harmonic admittance matrix $Y^{(h)}$. The fundamental