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Increasing PV hosting capacity in distorted distribution systems using passive harmonic filtering

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ABSTRACT

Adding new capacity expansion alternatives using distributed generation (DG) technologies, particularly penetration of renewable energy, has several economical, and technical advantages such as the reduced system costs, the improved voltage profile, lower line loss and enhanced system's reliability. However, the DG units may lead to power quality, energy efficiency, and protection problems in the system when their penetration exceeds a particular value, generally called as the system's hosting capacity (HC) in the literature. In this paper, the HC determination of a distorted distribution system with Photovoltaic (PV)-based DG units is handled as an optimization problem by considering over and under voltage limitations of buses, current carrying capabilities of the lines, and harmonic distortion limitations as constraints. It is seen from simulation results that the HC is dramatically decreased with the increment of the load's nonlinearity level and the utility side's background voltage distortion. Accordingly, a *C*-type passive filter is designed to maximize the harmonic-constrained HC of the studied system while satisfying the constraints. The results indicate that higher HC level can be achieved using the proposed filter design approach compared to three conventional filter design approaches as voltage total harmonic distortion minimization, line loss minimization and power factor maximization.

1. Introduction

Distributed generation (DG) technologies are small-scale dispersed sources of electric power, which are placed close to the loads being served [1–3]. Many DG technologies exist such as photovoltaic (PV) cells, wind turbines, biomass, small hydro, microturbines, fuel cells, and others. DG technologies have been widely practiced in the distribution systems since they provide technical benefits for the power networks such as voltage profile improvement, system reliability and security enhancement, power loss reduction, and energy efficiency increase. Furthermore, energy crisis caused by the shortage of the traditional energy resources such as natural gas and petroleum, and the expanded interests to global warming and climate change have forced all the stakeholders including planners of distribution companies to focus on the widely employement of the DG technologies using environmentally friendly renewable energy resources [4]. Socially, renewable energy-based industries are more labor-intensive compared to fossil fuel-based technologies because of their continued development process. Hence, the investment in the DG technologies may represent a real opportunity to meet the load growth by adopting low-cost, low-carbon, and high-efficient capacity expansion alternatives [5,6].

In the past, the grid interconnected DG units were weaker to cause a significant disturbance in the distribution system. Currently, with the notable progress in systems integration with dispersed generation units, this situation is changing, and the dream of 100% penetration is getting closer. However, excessive penetration or inappropriate DG capacities may produce undesirable effects in the electrical systems such as power quality, energy efficiency, and protection problems [7,8]. The possible amount of DG penetration that can safely be handled by grids is called as hosting capacity (HC). Hence, specifying the appropriate penetration of DG units without violating the hosting limit is a principal factor for increasing the benefits gained from them. Accordingly, opti-

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mal planning, placement, and sizing of DG units in the distribution networks are considered in many works [9,10].

In the literature, different design goals are considered for the optimal planning problem of DG units such as the reduction of the system power losses [11], reactive power management [12], voltage profile enhancement [13], system security and reliability improvement [14], and maximizing of the DG penetration. Usually, the conventional design constraints are related to the voltage limitations represented by the voltage variation range and overvoltages, or current limitations posed by the allowable loading capabilities of the lines/cables and transformers, or DG limitations represented by their types, numbers, sizes, and economics. However, with the increase of power electronic-based loads (nonlinear loads) and using of large-scale grid-connected DG units; today's power systems suffer from harmonic pollution represented by harmonic voltage and current distortions. Increased levels of harmonic pollution can cause excessive losses or heating of all kinds of equipment as supply lines, transformers, power factor correction capacitors and induction motors; reducing their lifetimes [15]. Besides, they can reduce the energy transfer efficiency or transmission power factor [16,17]. To overcome these harmonics related problems, the international standards such as IEEE Standard 519 and IEC 61000-3-2 provide limits for individual and total harmonic distortion of PCC voltages and currents [18].

Many studies investigated the impact of the harmonic distortion generated by the DG units on the HC of distribution systems [19–26]. In [19], for radial distribution feeders with different load patterns, closed-form expressions were derived to determine the allowable penetration levels of DG units without exceeding the voltage harmonic distortion limits. In [20], an optimization problem was formulated for estimation of the allowable DG penetration level in the IEEE 18-bus benchmark system, while meeting a restricted voltage range and satisfying IEEE 519 limitations for total and individual voltage harmonic distortion. It was concluded in the same study that adding harmonic limitations in DG interconnection studies is important to restrict the harmonic distortion associated effects. In [21], it was figured out that power factor correction capacitors may lead to resonance hazards in a system with the PV-based DG units; consequently, harmonic filters should be used to increase the harmonic-constrained permissible PV capacities of the systems. Similarly, [22] pointed out that harmonic filters should be employed for the improvement of the maximum allowable DG penetration level. In [23], a DG planning problem based on maximizing the DG penetration level considering the bus voltage limits and the IEEE 519 allowable voltage harmonic limits was solved in the IEEE 18-bus test system for ten loads and DG scenarios. The most significant result obtained in the same study is that decentralization of DG capacity could be used to attain higher DG penetration levels. Furthermore, [24] introduced the harmonic-constrained hosting capacity term, which means the hosting capacity by considering voltage harmonic distortion limits. It proposed a methodology to determine this constrained capacity by regarding the Norton equivalent harmonic model of the system seen from the connection point of the DG unit. Also, it presented the best and the worst conditions of the harmonic hosting capacity when the harmonic currents, which are injected by the utility and the DG unit, are in the same and reverse directions, respectively. In [25], a multi-criteria optimization problem of the simultaneous planning of passive filters and DG units was solved to minimize bus voltage total harmonic distortions, total line loss and investment costs of the filters and DG units. Also, [26] solved the same placement problem for inverter-based DG units and capacitor banks regarding voltage support and loss reduction, and it concluded that harmonic distortion constraints should be included in the planning problems of the inverter-based DG units.

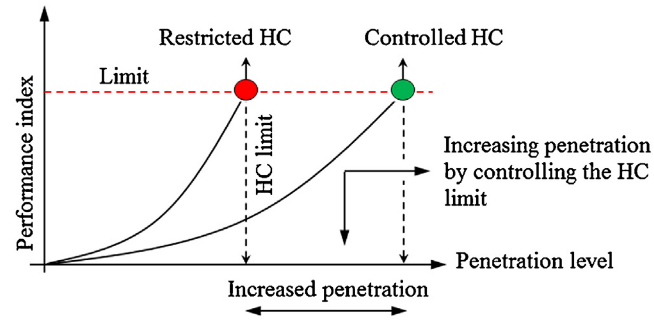

Fig. 1. Conception of the HC.

In this paper, the HC determination of a distorted distribution system containing Photovoltaic (PV)-based DG units is considered as an optimization problem by taking into account over and under voltage limitations of buses, current carrying capabilities of the supply lines, and harmonic distortion limitations such as maximum permissible total and individual harmonic distortion levels of the current and voltage. Thus, in the first part of the paper, for the PV-based DG units, the hosting capacity of a typical two bus distribution system is parametrically analysed under various utility side's background voltage distortion and load's current distortion (or the load's nonlinearity level).

In the second part of this paper, optimal passive harmonic filter design approach is proposed to maximize the hosting capacity while satisfying the above mentioned constraints and the desired power factor level. The proposed approach can be implemented for any kind of filter. However, in this study, the proposed approach is demonstrated with the *C*-type filters since they do not have resonance problem and have low power loss at the fundamental frequency compared to other passive filter types [27–29].

Finally, to show the effectiveness of the proposed filter design approach, the results of the proposed one and three conventional filter design approaches, which are based on voltage total harmonic distortion minimization, line loss minimization and power factor maximization, are comparatively evaluated for the studied system.

2. Methods

In this section, background on the HC control, problem formulations of the proposed and conventional filter designs approaches, and the search algorithm developed for simultaneous sizing of DG unit and the passive filter will be presented.

2.1. Hosting capacity control

Generally, the term "penetration" concerns with the peak load or energy on a yearly time-scale. In this work, the peak instantaneous penetration (PIP) is regarded as the ratio of the DG power to the load's rated power. For a particular system, the PIP ratio is a proper measure for studying the impact of the DG's power on the power quality of the system [30]. In this regards, the HC of distribution networks indicates the DG penetration level that the grid can withstand before violating anyone of the performance indices [31], as illustrated in Fig. 1.

It is seen from this figure that the increment of the DG penetration is limited by performance indices. Under sinusoidal conditions, the first and the most important performance index is the bus voltage, as overvoltage will occur with introducing a DG unit into a particular bus; hence, it should be limited. The second main index is the current carrying capability of the lines/cables, and the third index that may be taken into consideration is the substation transformer's power [32]. However, under non-sinusoidal conditions,