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Review Article

Integrating Photovoltaic Systems in Power System: Power Quality Impacts and Optimal Planning Challenges

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This paper is an overview of some of the main issues in photovoltaic based distributed generation (PVDG). A discussion of the harmonic distortion produced by PVDG units is presented. The maximum permissible penetration level of PVDG in distribution system is also considered. The general procedures of optimal planning for PVDG placement and sizing are also explained in this paper. The result of this review shows that there are different challenges for integrating PVDG in the power systems. One of these challenges is integrated system reliability whereas the amount of power produced by renewable energy source is consistent. Thus, the high penetration of PVDG into grid can decrease the reliability of the power system network. On the other hand, power quality is considered one of the challenges of PVDG whereas the high penetration of PVDGs can lead to more harmonic propagation into the power system network. In addition to that, voltage fluctuation of the integrated PVDG and reverse power flow are two important challenges to this technology. Finally, protection of power system with integrated PVDG is one of the most critical challenges to this technology as the current protection schemes are designed for unidirectional not bidirectional power flow pattern.

1. Introduction

The growing power demand has increased electrical energy production almost to its capacity limit. However, power utilities must maintain reserve margins of existing power generation at a sufficient level. Currently, transmission systems are reaching their maximum capacity because of the huge amount of power to be transferred. Therefore, power utilities have to invest a lot of money to expand their facilities to meet the growing power demand and to provide uninterrupted power supply to industrial and commercial customers [1]. The introduction of photovoltaic based distributed generation units in the distribution system may lead to several benefits such as voltage support, improved power quality, loss reduction, deferment of new or upgraded transmission and distribution infrastructure, and improved utility system reliability [2]. PVDG is a grid-connected generation located near consumers regardless of its power capacity [3], is an alternative way to support power demand and overcome congested transmission lines.

The integration of PVDG into a distribution system will have either positive or negative impact depending on the distribution system operating features and the PVDG characteristics. PVDG can be valuable if it meets at least the basic requirements of the system operating perspective and feeder design [4]. According to [5], the effect of PVDG on power quality depends on its interface with the utility system, the size of DG unit, the total capacity of the PVDG relative to the system, the size of generation relative to load at the interconnection point, and the feeder voltage regulation practice [6].

Figure 1 shows a schematic diagram of a grid-connected PV system which typically consists of a PV array, a DC link capacitor, an inverter with filter, a step-up transformer, and a power grid [5]. The DC power generated from the PV array charges the DC link capacitor. The inverter converts the DC power into AC power, which has a sinusoidal voltage and frequency similar to the utility grid. The diode blocks the reverse current flow through the PV array. The transformer steps up the inverter voltage to the nominal value of the grid

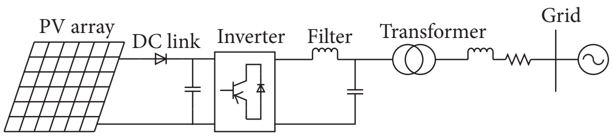

Figure 1: Schematic diagram of a grid-connected PV system.

voltage and provides electrical isolation between the PV system and the grid. The harmonic filter eliminates the harmonic components other than the fundamental electrical frequency.

One of the growing power quality concerns that degrade the performance of power systems is harmonic distortion. The main causes of harmonic distortion are due to the proliferation of power electronic devices like computer, television, energy saving lamps, adjustable-speed drives, arc furnaces, and power converters. Harmonic distortion is also caused by nonlinearity of equipment such as transformer and rotating machines [7]. These harmonic currents may create greater losses in the loads which consecutively require derating of the load, overheating of neutral conductor, overheating of transformer, and malfunction of protective devices [8]. Another power quality problem arises at the interface between PVDG inverters and the grid is harmonic resonance phenomenon. Harmonic resonance phenomena will occur at a resonant frequency where the inductive component is equal to the capacitive component. Harmonic resonance which has been found to be an increasingly common problem at the interface between PVDG inverters and the grid depends on the number of PVDG units. The effect of harmonic resonance not only presents a severe power quality problem but also can trip protection devices and cause damage to sensitive equipment [9].

On the other hand, it is well known that PVDG needs to be installed at the distribution system level of the electric grid and located close to the load centre. Studies are usually conducted to evaluate the impact of PVDG on harmonic distortion, power loss, voltage profile, short circuit current, and power system reliability before placing it in a distribution system. To reduce power losses, improve system voltage, and minimize voltage total harmonic distortion (THD_v), appropriate planning of power system with the presence of DG is required. Several considerations need to be taken into account such as the number and the capacity of the PVDG units, the optimal PVDG location, and the type of network connection. The installation of PVDG units at nonoptimal locations and with nonoptimal sizes may cause higher power loss, voltage fluctuation problem, system instability, and amplification of operational cost [10].

2. Power Quality Impact of PVDG

The integration of PVDG in power systems can alleviate overloading in transmission lines, provide peak shaving, and support the general grid requirement. However, improper coordination, location, and installation of PVDG may affect the power quality of power systems [11]. Most conventional power systems are designed and operated such that generating stations are far from the load centers and use the transmission and distribution system as pathways. The normal operation of a typical power system does not include generation in the distribution network or in the customer side of the system. However, the integration of PVDG in distribution systems changes the normal operation of power systems and poses several problems which include possible bi-directional power flow, voltage variation, breaker noncoordination, alteration in the short circuit levels, and islanding operation [2, 6]. Therefore, studies are required to address the technical challenges caused by DG integration in distribution systems. The interconnection device between the DG and the grid must be planned and coordinated before connecting any DG [12].

2.1. Harmonic Impact of PVDG. Harmonic is a sinusoidal component of a periodic wave or a quantity which has a frequency that is an integral multiple of the fundamental frequency [13]. Harmonic distortion is caused by the nonlinearity of equipment such as power converters, transformer, rotating machines, arc furnaces, and fluorescent lighting [7]. PVDG connected to a distribution system may introduce harmonic distortion in the system depending on the power converter technology. A power quality study was performed on a PV system to estimate the effect of inverter-interfaced PVDG on the quality of electric power [14]. The experimental results indicate that the values of total harmonic distortion THD_i depend on the output power of the inverter. This dependence decreases proportionally with reduced power converter rating.

Another factor that influences harmonic distortion in a power system is the number of PVDG units connected to the power system. The interaction between grid components and a group of PVDG units can amplify harmonic distortion [15]. In addition, PVDG placement also contributes to harmonic distortion levels in a power system. DG placement at higher voltage circuit produces less harmonic distortion compared with PVDG placement at low voltage level [16]. On the customer side, the increasing use of harmonic-producing equipment such as adjustable speed drives may create problems, such as greater propagation of harmonics in the system, shortened lifetime of electronic equipment, and motor and wiring overheating. In addition, harmonics can flow back to the supply line and affect other customers at the PCC. Therefore, harmonic mitigation strategies for power systems must be measured, analyzed, and identified [1].

2.2. Harmonic Resonance in a Power System with PVDG. Resonance occurs in a power system when the capacitive elements of the system become exactly equal to the inductive elements at a particular frequency. Depending on the parallel or series operation, it may form parallel or series resonance. At a given location, when a system forms a parallel resonance, it exhibits high network impedance, whereas for a series resonance, it presents a low network impedance path [17].

With increasing PVDG penetration in the power grid, harmonic resonance is becoming a crucial issue in power systems [18]. Harmonic resonance can occur at the interconnection point of individual or multiple PVDG units to the grid because of impedance mismatch between the grid and the inverters. Dynamic interaction between grid and inverter output impedance can lead to harmonic resonance in grid current and/or voltage which occurs at certain frequencies. The effect of harmonic resonance presents severe power quality problems such as tripping of protection devices and damage to sensitive equipment because of overvoltage or overcurrent [18].

A study investigated the harmonic interaction between multiple PVDG units and a distributed network and found that high penetration levels of PVDG units increase harmonic emission significantly even though the PV inverters each meet IEC 61000-3-2 specifications. Parallel and series resonance phenomena between the network and PV inverters were found to be responsible for unexpected high current and voltage distortion levels in the network [19].

2.3. Effect of PVDG on Voltage Variation. The operating voltages in a distribution system are not always within required voltage ranges because of load variations along the feeders, the action of tap changers of the substation transformers, and the switching of capacitor banks or reactors. This results in voltage variations, which may be defined as the deviations of a voltage from its nominal value [19]. Disturbances classified as short-duration voltage variations are voltage sag, voltage swell, and short interruption, whereas disturbances classified as long-duration voltage variations include sustained interruption, undervoltage, and overvoltage [20].

With the growing electricity demand in distribution systems, the voltage tends to drop below its tolerable operating limits along distribution feeders with the increase of loads. Thus, the distribution system infrastructure should be upgraded to solve voltage drop problems [21]. The integration of PVDG units in a distribution system can improve the voltage profile as voltage drop across feeder segments is reduced because of reduced power flow through the feeder. However, if the power generated by PVDG is greater than the local demand at the PCC, the surplus power flows back to the grid. The excess power from DG may produce reverse power flow in the feeder and may create voltage rise at the feeder [22]. Some studies investigated methods of controlling voltage rise caused by PVDG connection into distribution systems. Borges and Falcão (2006) analyzed multiple sources of PVDG together with the operation of voltage regulators and concluded that the power injected by the PVDG unit should be identified to obtain system voltages within the allowed limits at the PVDG connection bus [23]. Chen et al. (2012) presented two voltage control techniques in a distribution feeder through system planning and equipment control [24]. System planning techniques were employed in the system design and planning stages whereas equipment control techniques were used to regulate the bus voltages along a feeder during real-time operation.

With high DG penetration at low voltage level, a violation may occur in the upper voltage limit. Therefore, a solution is needed to reduce the overvoltage caused by DG. Demirok et al. (2010) addressed the overvoltage problem by applying distributed reactive power regulation and active power curtailment strategies at the DG inverters [25]. An approach for charging and discharging control of the storage system (lead-acid batteries) is applied to regulate the storage capacity effectively. An adaptive voltage control scheme which uses an on-load tap changer and automatic voltage control relay was proposed to increase the output capacity of DG without violating voltage limits [24].

3. Maximum Allowable Penetration Level of PVDG

Several studies have been conducted to investigate the impacts of high PVDG penetration in distribution systems by considering various constraints. Kirawanich and O'Connell (2003) performed a simulation to investigate the harmonic impact of a PVDG on a typical commercial distribution system [26]. The results showed that even at the most vulnerable lateral tap points in the system under worst-case conditions, the voltage THD did not exceed the IEEE Standard 519 limit for up to 40% saturation of commercial distribution system with DG units. A similar study performed by Pandi et al. (2013) concluded that the maximum PVDG penetration levels based on an optimal DG size and locations on the 18-bus and 33-bus radial distribution systems are 66.67% and 33.53%, respectively [27].

Other studies focused on the maximum allowable penetration level of DG units by considering the transient stability limit [28]. Azmy and Erlich (2005) investigated the impact of utilizing selected DG units with different penetration levels on various forms of power system stability [28]. The simulation result showed that the voltage deviation decreases significantly with 28.3% DG penetration. Moreover, it is reported that the maximum penetration level of DG, without violating the transient stability limit, is 40% of the total connected load [28].

Another factor that may limit the penetration level of DG in a typical distribution system is the steady-state voltage rise. Celli et al. (2009) developed a method for evaluating the critical value of DG penetration level by considering DG siting and sizing [29]. The result showed that the limit of the DG penetration level in a distribution system was 40% to 50%. A similar study was conducted by Chen et al. (2012) to clarify what would happen to a distribution system if customers were allowed to install DG units freely on their premises and DG units became widespread [30]. The major factor that led to overvoltage and undervoltage was the surplus DG power in localized areas of the secondary network, which caused the tripping of the network protectors.

Germany and Italy have a very strong PV system penetration. By 2012, the installed PV capacity reached 32 GW and 16 GW, respectively. More than 20% of the capacity installed is connected to the distribution voltage network. In Germany—specifically—63% of the PVDG is connected to the household voltage level. The integration of this big amount of PVDG makes challenges to the power system. For example, in case of have a large share of PVDG units that switch off simultaneously may increase the grid frequency up to 50.2 Hz. However, this problem has been addressed in Germany by requiring the back-fitting of installations with a nominal power above 10 kW. In addition to that, voltage regulation within tolerable limits is another challenge faced. Storage has been identified as a possible solution for providing flexibility to the power system and could possibly generate value streams from flexibility. However the feasibility of such a solution is remains challenging. A number of authors assess how storage could overcome the technical challenges of PV integration. For example, the battery can be optimally sized in order to avoid overvoltage caused inverter disconnection [31–36].

4. Optimal Placement and Sizing of PVDG

Voltage variation and harmonic distortion are two major disturbances in distribution systems. The voltage drop occurs because of increasing electricity demand, thereby indicating the need to upgrade the distribution system infrastructure. Studies have indicated that approximately 13% of the generated power is consumed as losses at the distribution level [37]. To mitigate voltage variation and harmonic distortion in distribution systems, several strategies were applied, such as the use of passive and active power filters to mitigate harmonic distortion and the application of custom power controllers to mitigate voltage variation problems. However, these mitigation strategies require investment. Therefore, to improve voltage profile and eliminate harmonic distortion in a distribution system with PVDG, a noninvasive method is proposed, which involves appropriate planning of PVDG units and determining optimal placement and sizing of PVDG units.

Before installing PVDG units in a distribution system, a feasibility analysis has to be performed. PVDG owners are requested to present the type, size, and location of their PVDG [27]. The power system is usually affected by the installation of PVDG. Therefore, the allowable PVDG penetration level must comply with the harmonic limits. Thus, optimal placement and sizing of DG is important because installation of DG units at optimal places and with optimal sizes can provide economic, environmental, and technical advantages such as power losses reduction, power quality enhancement, system stability, and lower operational cost [11].

Several methods have been applied to determine the optimal location and size of PVDG in a distribution system. The analytical method used for optimal PVDG placement and sizing is only accurate for the model developed, and it can be very complicated for solving complex systems. The power flow algorithm [10] has been used to find the optimum PVDG size at each load bus by assuming that each load bus can have a PVDG unit. However, this method is ineffective because it requires a large number of load flow computations. Analytical methods can also be used to place the PVDG in radial or meshed systems [38]. In this method, separate expressions for radial and meshed systems are required, and complex procedures based on the phasor current are applied to solve the PVDG placement problem. However, this method only determines the optimum PVDG placement and not the optimum PVDG size as it considers a fixed PVDG size.

The metaheuristic method is also used in optimal placement and sizing of DG in distribution systems. This method applies an iterative generation process which can act as a lead for its subordinate heuristics to find the optimal or near-optimal solutions of the optimization problem [39]. It combines different concepts derived from artificial intelligence to improve performance. Some of the techniques that adopt metaheuristics concepts include genetic algorithm (GA), Tabu search, particle swarm optimization (PSO), ant colony optimization (ACO), and gravitational search algorithm (GSA).

The implementation of the general optimization technique for solving the optimal placement and sizing of PVDG problem is depicted in Figure 2. A multiobjective function is formulated to minimize the total losses, average total voltage harmonic distortion, (THD_v) and voltage deviation in a distribution system. The procedures for implementing the general optimization algorithm for determining optimal placement and sizing of PVDG are described as follows.

(i) Obtain the input network information such as bus, line, and generator data.

(ii) Randomly generate initial positions within feasible solution combination, such as the PVDG location, PVDG size in the range of 40% to 50% of the total connected loads, and PVDG controllable bus voltage in the range of 0.98 p.u to 1.02 p.u.

(iii) Improvise the optimization algorithm using the optimal parameters such as population size, number of dimension, and maximum iteration.

(iv) Run loadflow and harmonic loadflow to obtain the total power loss, average THD_v and voltage deviation.

(v) Calculate the fitness function.

(vi) Check the bus voltage magnitude and THD_v constraints. If both exceed their limits, repeat step (iv).

(vii) Update the optimization parameters.

(viii) Repeat the process until the stopping criteria are achieved and the best solution is obtained.

5. Conclusion

This paper describes an overview of the relevant aspects related to PVDG and the impacts it might have on the distribution system. This paper evolves the background of PVDG and its impacts on power quality and the maximum allowable penetration level of PVDG connected to a distribution system. The implementation of the general optimization technique for solving the optimal placement and sizing of PVDG problem with multiobjective functions

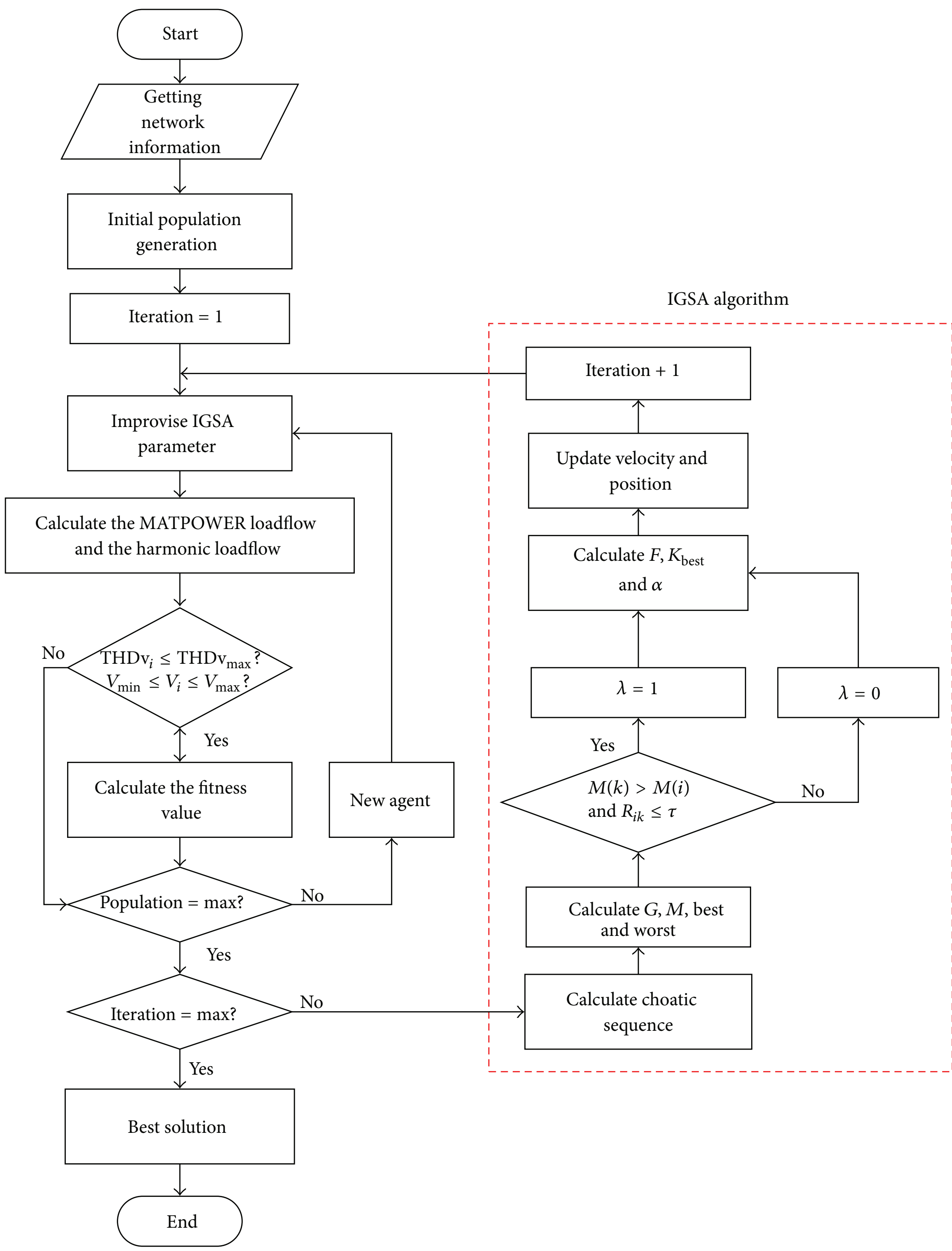

Figure 2: Flowchart of the general optimization technique for determining optimal placement and sizing of PVDG in a distribution system.

such as minimization of losses, THDv, and voltage deviation is explained. The multiobjective functions are considered as the technical benefits factors for optimal planning PVDG in the distribution system. It is concluded that there are great opportunities and benefits such as technical, economical, and environmental benefits are offered when installing PVDG in a distribution system. However, there are some technical issues and challenges come up when incorporating PVDG in a distribution system. These issues and challenges concluded by several researchers need to be assessed for proper PVDG planning and operation in the distribution network. These issues are as follows.

(i) Reliability: the amount of power produced by renewable energy source based PVDG is not consistent like wind and solar source. Thus, the high penetration of PVDG into grid can decrease the reliability of the power system network.

(ii) Power quality: the high penetration of PVDGs can lead to more harmonic propagation into the power system network, increase the losses, and possibly decrease the equipment life time.

(iii) Voltage fluctuation: it is a significant issue for high penetration level of PVDG. This issue desires to be critically considered in integrate inconsistent sources. For example, the fluctuation of solar source in supplying power to the load will caused overvoltage or undervoltage. The voltage fluctuation is very bad impact on the sensitive equipment.

(iv) Reverse powerflow: incorporating PVDG in the system causes malfunctions of protection systems as they are configured by the unidirectional form.

(v) System frequency: the unbalances between supply and demand will result to the deviations from the system nominal frequency. The high penetration of PVDG affects system frequency and makes the process of control more complicated.

(vi) Protection schemes: the common distribution networks are configured in the radial form. Thus, the protections system is designed accordingly to the unidirectional flow patterns. However, the integrating of PVDG changes the flow into bidirectional and needs additional safety equipment and resizing of the network such as grounding, short-circuit, breaking capacity, and supervisory control and data acquisition (SCADA) systems.

(vii) Islanding protection: anti-islanding protection schemes presently implement the PVDGs to remove immediately for grid faults through loss of grid (LOG) protection system. This significantly decreases the advantages of PVDG deployment. For avoiding disconnection of PVDGs during LOG, several islanding protection schemes are being developed. The biggest challenge for the islanding protection schemes is the protection coordination of distribution systems with bidirectional fault current flows.

Conflict of Interests

The authors hereby confirm that there is no conflict of interests in the paper with any third party.

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