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Effect of grid-connected photovoltaic systems on static and dynamic voltage stability with analysis techniques – a review

Abstract. *This paper presents an overview on the effect of grid-connected photovoltaic (PV) system on static and dynamic voltage stability and discusses the analysis techniques used to quantify the effect. A review on the published works showed that the PV system design, PV parameters and the distinct design of power system network affect system voltage stability. Furthermore, a discussion is also made on the optimization techniques used for determining optimum PV placement and sizing for the purpose of improving voltage stability.*

Streszczenie. W artykule dokonano przeglądu metod analizy wpływu dołączenia systemu fotowoltaicznego na właściwości statyczne i dynamiczne sieci. Odpowiedni projekt wpływa na stabilność napięciową. Analizowano też metody optymalizacji położenia systemu. ***Przegląd metod analizy wpływu podłączenia systemu fotowoltaicznego na właściwości statyczne i dynamiczne sieci***

Keywords. Grid-connected solar PV system; static voltage stability; dynamic voltage stability; Optimum PV placement and sizing
Słowa kluczowe: system fotowoltaiczny, system fotowoltaiczny dołac\ony do sieci

1. Introduction

Renewable energy sources, such as photovoltaic (PV) systems, wind turbines, and fuel cells, are integrated into conventional power systems to address fossil fuel deficiency, intensifying energy demand, and environmental pollution. Among all types of renewable energy resources, solar PV receives major attention for its promising energy resources and low-cost installation. The fundamental operation system of solar PV differs from other generating systems. Solar PV converts sunlight into DC power using semiconductor solar cells. The DC power is then converted into AC power through a DC-to-AC converter. Given this electronic conversion system, solar PV does not have inertia, and its dynamic behavior depends on the characteristics and controls of inverters. PV systems are categorized into small-scale and large-scale PV systems; the former is rated at 20 MW or less and usually connected at distribution or sub-transmission system, and the latter is rated up to 1000 MW and normally connected at transmission level [1]–[3]. PV systems can be constructed through two ways. First, stand-alone PV systems are installed roof-mounted or ground-mounted close to the loads. Second, grid-connected PV systems are installed at remote locations with wide land area. The solar energy market, especially on grid-connected PV systems, is growing rapidly during the past few years, and this growth rate is expected to continue. During the last decades, global solar PV production sustained an annual growth rate of more than 40% [4]. The power supplied by PV system could be comparable to that supplied by conventional generator. For example, California has integrated PV systems of more than 500 MW at high-voltage transmission systems [5].

The integration of PV into a power system causes certain technical effects because the network design initially does not consider the integration of distributed generation (DG). Examples of technical issues are power system operation and control, power quality, and power system stability. This study evaluates PV system effect on power system voltage stability. Modern power systems operate close to their voltage stability limits because of economic factors. Therefore, detailed design is crucial to assess grid-connected PV system effect on system voltage stability. Small-scale PV is usually considered negative loads and thus may not affect power system operation. The effect on voltage stability is also neglected. However, the integration of high penetration level of PV system significantly influences the overall dynamics of the power system.

Power system stability has been a major concern in the last few decades. System stability is defined as the ability of an electric power system to remain in equilibrium after being subjected to a physical disturbance, with most system variables bounded. Thus, practically the entire system remains intact [6]. Stability issue in a power system with integrated PV system is categorized into rotor angle stability, frequency stability, and voltage stability, as shown in Figure 1. Rotor angle stability refers to the ability of synchronous machines of an interconnected power system to remain thus after being subjected to a disturbance [6]. Disturbance increases angular swings of a few generators and thus leads to the loss of synchronism with other generators. Rotor angle stability can be divided into small-signal rotor angle stability and transient stability. Frequency stability refers to the ability of a power system to maintain steady frequency following a disturbance that results in imbalance between generation and load [6]. Frequency stability issues are normally associated with inadequacies in equipment responses, poor coordination of control and protection equipment, or insufficient generation reserve. Voltage stability is defined as the ability of a power system to maintain steady voltages at all buses in the system after being subjected to some form of disturbances. Voltage instability leads to tripping loads, transmission line faults and/or synchronism loss in certain generators and voltage collapse [6].

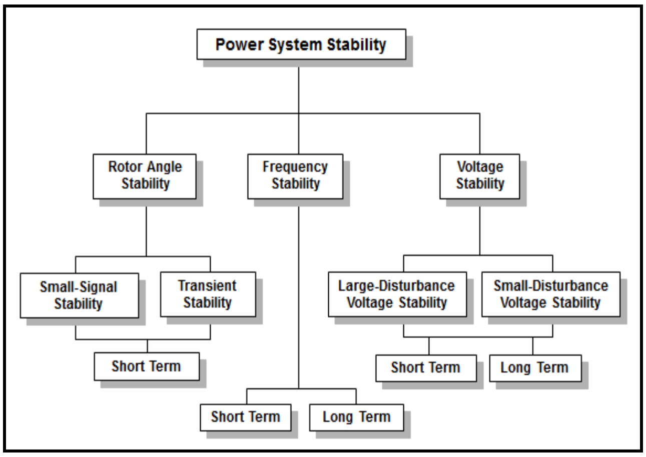

Fig. 1. Classification of Power System Stability

Numerous works have been conducted to study PV effect on power system stability by considering various analysis techniques. Solar PV generations are mostly designed along with existing power system configurations to address the effect of high-penetration solar PV on power system stability. Transient stability normally occurs because of a large disturbance, such as three-phase fault. The occurrence of such a fault results in either sudden disconnection of PV system or shut down of PV inverters. Disconnecting a large number of PV causes a negative effect on power system transient stability. PV generator penetration level and dispatch generator location affect power system transient stability [7]. Voltage sags and damping of the inter-area mode of synchronous generators that are not dispatched by PV generation may increase. High-penetration PV on transient stability with low-voltage ride through capability may also negatively affect transient stability [8]–[10]. The penetration level of PV generation on power system may alter bus frequency. Studies have shown that 20% of solar PV penetration levels degrade bus frequency below the acceptable operation limit [11]. Another study shows that a high penetration level of PV system in one area of a grid does not affect the frequency stability of the entire power system [12]. However, under large disturbances, the frequency oscillations are damped faster than normal, with less magnitude. Among the three types of power system stability, voltage stability has become a major subject of research because of the increasing energy demand from utilities and the fact that modern power systems operate close to their loadability limits. Therefore, this paper discusses PV effect on power system voltage stability and reviews assessment techniques used to quantify the effect.

2. Voltage Stability Analysis Techniques

Various methods have been proposed by researchers to analyze voltage stability problems. Static voltage stability analysis is applied in real-time operation, and the calculation consumes a short time. Conversely, dynamic analysis is more accurate than static analysis, but requires considerable data information for modeling and relates to the coordination of protection, controls, and short-term voltage stability analysis.

2.1 Static Voltage Stability Analysis Techniques

Established methods for static voltage stability analysis are the methods based on P–V and Q–V curves, continuation power flow (CPF), and singularity of power flow Jacobian matrix at the voltage collapse point. P–V curve method is widely used to analyze voltage stability by determining the available amount of active power margin before voltage collapse point. Q–V curve method is used to investigate the amount of reactive power at the load end for obtaining desired voltage. Modal analysis of Jacobian matrix is also widely used in power system stability analysis. CPF is a technique by which power flow solutions can be obtained near or at the voltage collapse point. Multiple power flow (MPF) technique can be used to determine voltage collapse point by increasing loading factor. The accuracy of this technique depends on the step size of the loading factor. MPF and CPF techniques are commonly used for their accuracy. However, using these techniques for voltage stability analysis of large power systems is time consuming. All the above-mentioned analysis techniques are used to determine the voltage collapse point, which is a point where the voltage decreases at the maximum loading a system can tolerate. Voltage collapse point occurs in a faulted power system and/or in a power system with lack of reactive power, as well as heavily loaded power systems [13]. The drawback of such techniques is that they do not provide adequate information on the appropriate placement of PV systems. PV systems are usually placed at the weakest bus of a power system. Different analysis techniques have been applied to determine the weakest bus based on static voltage stability. The techniques are based on eigenvalue analysis [14], sensitivity analysis, Jacobian matrix singular analysis, ΔP, ΔQ, and ΔV margin indices, and voltage stability index (VSI) based on line and bus stability factors [15]. Voltage stability line and bus indices are commonly used based on the ratio of Thevenin's impedance to load impedance with values between 0 and 1. A power system is considered to reach its voltage collapse point when the index value approaches 1.

2.2. Dynamic Voltage Stability Analysis Techniques

Voltage stability is a dynamic event, but static approaches for voltage stability analysis have been widely used. Dynamic voltage stability is studied by time-domain analysis considering fault at specific location and time. Voltage magnitude and voltage sag, if present with time varying, are considered in assessing the voltage stability of grid-connected PV systems. Various PV parameters, such as solar insolation (i.e., solar radiation and temperature) and the dynamic modeling of PV system (i.e., power electronic converter and reactive power compensator), are important in dynamic voltage stability analysis of grid-connected PV systems [16, 17].

2.3. Optimization Techniques for Determining Optimum PV Placement and Sizing for Voltage Stability Improvement

The integration of DG, including PV system, into a distribution system changes the system into an active network that affects system operation, with high system loss and low voltage profile [18]. PV system installation at non-optimal places with non-optimal sizing may create other opposite effect to system technical parameters, thus leading to voltage instability. To address the limitations required for a grid-connected PV system installation, considering system voltage stability is therefore crucial. PV system provides active power support to the network. Thus, high PV penetration needs optimal placement of PV system to maintain system voltage stability and prevent system voltage collapse. Optimization technique that considers power flow equations, bus voltages, active and reactive power limits of generators, and other operating limits, is applied by maximizing loading factor. To size a PV generator, optimal selection of PV panel number, battery storage size, and power controller size, is considered. PV module parameter and other components from manufacturers are usually used [19]. Optimization techniques applied to determine optimum sizing and placement of various configurations of PV systems are artificial neural networks, fuzzy logic, genetic algorithm, hybrid systems, and wavelet [20]–[32]. However, none of these proposed techniques considers voltage stability or voltage collapse as the objective function. Table 1 shows a summary of optimization techniques applied to determine optimum location and sizing of PV systems using different objective functions considering voltage stability analysis.

Table 1: Summary of optimization techniques of DG and PV system incorporating voltage stability

No.	Authors	Year	Reference	Optimization Technique	Objective Function
1	Aman, M.M. et al.	2012	[33]	Golden section search algorithm	Optimum DG location and sizing that considers a new power stability index (PSI)
		2013	[34]	Particle swarm optimization	Optimum DG placement and sizing by maximizing bus voltage using SI-index and line voltage stability using L_{mn} index
2	Ishak, R. et al.	2014	[35]	Particle swarm optimization	Optimum DG location that considers critical buses using maximum PSI
3	Kayal, P. et al.	2013	[36]	Particle swarm optimization	Optimum DG (based on wind turbine generation unit and PV array) placement that considers voltage collapse using a voltage stability factor
4	Nasiraghdam, H. et al.	2012	[37]	Multi-objective artificial bee colony	Optimum hybrid PV/wind turbine/fuel cell system sizing by maximizing the minimum value of VSI; VSI = 0 is measured as voltage collapse point
5	Hung, D.Q. et al.	2013	[38]	Self-correction algorithm	Sizing multiple PV and battery storage units with an optimum power factor that considers voltage stability margin
6	Hernandez, J.C. et al.	2007	[39]	Multi-objective function that evaluates technical and economic benefits.	Optimum location and sizing of grid-connected PV system that considers voltage collapse point

3. Effect of Integrating PV Generation on Voltage Stability

The effect of PV generation on power system voltage stability requires comprehensive static and dynamic analyses. Injecting active power as a PV source to the weakest bus in a test system alters the static voltage stability limit. PV system parameters, such as temperature, cloud shedding effects, and rapid fluctuation in solar radiation, play a role in dynamic voltage instability. Voltage instability may occur at load centers of heavily loaded network when existing generators are dispatched with PV generation. Cloud transient affects power system stability at a high penetration level [40]. Cloud sweep that happens in a few seconds contributes to PV power drop and leads to voltage fluctuation and voltage drop in case of large load increase. Voltage may drop below the acceptable limit that voltage stability cannot sustain. PV system effect on dynamic voltage stability is studied by considering various PV parameters, such as temperature, irradiance, and load [41]. PV system is connected at a three-bus network with total injected power equal to total load, and PV parameters are varied one at a time [41]. Reduced Jacobian matrix analysis shows that the system is stable despite changes in PV parameters. However, eigenvalue sensitivity analysis shows that voltage stability is initially affected by temperature and then by irradiance and load.

Cloud shading can cause PV power fluctuations related to voltage and frequency fluctuations. Solar radiation ramp rate can be 705 Wm^{-2}/s, as recorded in [42, 43], with a few-second changes from clear sky to heavy cloud shading. Given the short period of cloud shading, voltage drop of some remote buses is at intolerable low level that voltage stability cannot be sustained [40]. Considering the fact that PV systems only generate active power, cloud shading will only affect system frequency at transmission level. However, voltage fluctuation at distribution level is considered because distribution systems have special characteristics, such as dynamic loads and high X/R ratio [44, 45]. PV power output intermittency leads to unwanted voltage rise in network. A voltage unbalance of 1% relates to 6 times to 10 times of unbalance current [46]. Voltage unbalance can cause damage to household equipment, whereas current unbalance creates unnecessary temperature rise in motor windings that degrades the performance and decreases the lifespan of induction motors.

The effect of various PV penetration level integrated into transmission systems of 34.5 and 69 kV to 345 and 500 kV is studied in [47]. PV penetration level is defined as the ratio of total PV generation to total system generation, as expressed in the following equation:

(1)

$$PV\ penetration\ (\%)\ for\ generation\ based = \frac{Total\ PV\ generation\ (MW)}{Total\ generation\ (MW)}$$

PV system modeling based on residential rooftop PV system has been considered for static and dynamic analyses [47]. For steady state analysis, additional percentage of PV generation in the system shows a reduction on voltage magnitude, except at 20% of PV generation, where an overvoltage of +10% occurs in certain buses. Results also show an increase in reactive power from synchronous generator as a support to the active power generated by PV system. Dynamic analysis presents voltage sags with 5% differences at high-penetration PV. Static PV generator modeled as current source is connected to a 16-bus distribution system [48] and the P–V curve is used to analyze the effect of PV penetration level on voltage stability. PV penetration level in this study is defined as the percentage of total power of DG over total load demand, and it is given by,

(2)

$$PV\ penetration\ (\%)\ for\ load\ based = \frac{Total\ PV\ generation\ (MW)}{Total\ load\ demand\ (MW)}$$

Results show that a high PV penetration improves loading margin with a minimum grid loss observed at 30% PV penetration level.

A control model of a static PV generator integrated at distribution system is comparatively studied in [49]. The PV generator is designed based on a current source converter with PV and PQ control models, where PQ control model is based on power factor control, and PV control model is based on voltage control. P–V curve is applied to analyze the effect of different PV models on static voltage stability. PV control model provides higher loading margin than PQ control model. The effect of solar irradiance on voltage stability is studied in [50]. Analysis shows that the amount of PV power is proportional to solar irradiance. In case of sudden drop in irradiance, PV power will drop, thus leading to bus voltage drop. This voltage fluctuation must be kept within statutory limits to avoid voltage collapse.

Eigenvalue method and non-linear model simulation has been proposed to analyze the stability of a grid-connected PV system [51]–[53]. The PV system is equipped with a DC-to-DC boost converter and a DC-to-AC single-phase inverter to transfer the low DC voltage energy of the PV system to the grid. Insolation variation caused by cloudy weather reduces V_g (output DC voltage of PV system) and E_d (DC voltage across DC line capacitance) but increases γ_i (extinction angle of the DC-to-AC inverter). Power quality issues, including transient voltages, are studied in [54]. The point of common coupling line voltage RMS value drops during three-phase to ground fault and consumes more than 0.2 s for the system to recover. The voltage at steady-state condition shows a slightly low value during fault. STATCOM is installed to maintain the system voltage in steady-state condition and utilize a short recovery time of the system voltage to avoid voltage collapse.

4. Conclusion

In this paper, various analysis techniques and effects of grid-connected PV systems on voltage stability have been reviewed. These analysis techniques comprise different methodology to address voltage stability problems. Effects of PV generation on power system voltage stability are thoroughly examined based on various factors that influence system static and dynamic voltage stabilities. The efficiency of voltage stability analysis depends on the system design, application, and scenarios. The number of studies presented in this paper is neither complete nor extensive but an impartial sample of the effect of a grid-connected PV system on voltage stability with various analysis techniques.

From the review, it can be concluded that the effect of PV system on transmission/distribution system stability depends on a few factors such as meteorological factors, PV installation latitude, shading effect, and solar PV plant type integrated at various PV penetration level. Researchers have focused on addressing voltage instability caused by various PV penetration level and solar radiation in view of cloud sweep. However, no studies have considered other meteorological factors such as cell temperature, humidity level, and wind level, which may cause intermittent power output and thus lead to voltage instability. Climate changes, such as rainy and winter seasons, must be considered because they may lead to PV power output fluctuation. Therefore, extensive research on the effect of grid-connected PV systems on voltage stability that considers the aforementioned factors must be conducted.

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