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Assessment of reactive power contribution of photovoltaic energy systems on voltage profile and stability of distribution systems

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ABSTRACT

This paper studies the impact of large-scale photovoltaic (PV) generation, up to 50% penetration level, on distribution system voltage regulation and voltage stability. The system voltage profiles are computed using power-flow calculations with load variation of a 24-h time scale. The steady-state voltage stability is examined at different times of the day using a developed continuation power-flow method with demand as continuation parameter and up to the maximum loading conditions. The load-flow analysis, implemented for both voltage regulation and voltage stability analysis, is performed by using the forward/backward sweep method. The secant predictor technique is developed for predicting the node voltages which are then corrected using the load flow solver. Three models of the PV interface inverter are implemented in this study with full set of data representing environmental conditions. The voltage profiles are regulated using the PV interface inverters, where the available inverter capacity is utilized for regulating the system node voltages. The most possible scenarios of system voltage collapse are investigated at different times of the study period. The developed methods and models are used to assess the performance of a 33-bus radial distribution feeder which operates with a high level of PV penetration. The results show that the PV interface inverters operate for reactive power support in distribution system resulting in improved voltage profile, secure power systems operation, and increasing the lifetime of the online tap changing transformers due to minimizing the total number of switching operations.

Introduction

Nowadays, renewable energy sources become a more significant source of energy in the new millennium. Among these renewable energy sources, PV energy resources are attracting a growing amount of interest due to the gradual development of technology and the reduction of PV system cost. Besides assisting in the reduction of the emission of greenhouse gases, they add the much-needed flexibility to the energy resource mix by decreasing the dependence on fossil fuels. Therefore, the installed capacity of grid-connected PV power system installations has grown dramatically over the last five years [1]. The PV directly converts sunlight into electricity using the photoelectric effect. The production of electricity from solar sources depends on the amount of light energy in a given location. Solar output varies throughout the day and through the seasons. Grid-connected PV systems are designed to inject all of the real power produced by PV modules [2]. They are represented as negative power loads. The size of the negative PV load is dependent on the environment conditions, i.e., radiation and temperature. Large-scale PV generation has been considered as an important new alternative energy in the 21st century's energy structure [3].

Furthermore, most of the new PV capacity has been installed in the distribution grid as distributed generation. As PV penetration levels increase, its integration impact on electric networks draws researchers' concern around the world [4,5]. The size of the PV system, its location on the circuit, the impedance of the system, and the way the PV inverter operates, will determine its impact on the system voltage [6]. One of the important issues is to understand the impact of large-scale grid-connected solar PV generations on system voltage [7,8]. As the penetration level of PV generation increases, it will have impact on the voltage stability and regulation of distribution systems. Because its operation depends on environmental conditions, the characteristics of PV systems may be different from those of typical synchronous generators [9].

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Voltages at the customer service entrance are maintained by utilities within an acceptable range to ensure adequate operation and lifetime of customer equipment. This is achieved by on-load tap changing transformers (OLTC) and reactive power support [10]. Reactive power supply is also essential for reliable operation of the electric power systems. The shortage of reactive power supply can contribute to voltage collapse, as reported in several recent major power outages [11]. It has been proved that inadequate reactive power compensation during stressed operating condition can lead to voltage instability [12]. Capacitor banks are widely used in power systems for voltage regulation. However, capacitor banks are switched on or off, which are not a continuous variable real-time source of reactive power. Moreover, the reactive power from capacitor banks decreases as the system voltage decreases (by voltage squared) when reactive power is most needed [13].

Without or with small penetration of PV generation, fluctuations in loads and voltage levels in most distribution systems are relatively small and predictable and so the relatively slow operation of OLTCs and VAR devices is acceptable [14]. However, the fluctuations are not predictable when distribution systems are subject to large scale PV generation. In this situation, OLTCs and VAR devices will not be sufficient to ensure adequate voltage regulation because the variability of PV generation can occur on a timescale much shorter than the present equipment can deal with. The output of a PV module can be reduced dramatically when even a small portion of it is shaded by cloud. For instance, cloud transients can cause ramps in PV generation on the order of 15% per second at a particular location slowing to perhaps 15% per minute for an entire distribution circuit due to its spatial diversity [1]. Therefore, for PV generation resources to maintain the voltages within the acceptable limit, they should have the capability of producing reactive power in addition to the active power for voltage support.

A number of publications [13,15,16] are available that address the benefits of using inverter-based distributed generation for voltage support. Several studies have been conducted to examine the possible impacts of high levels of utility penetration of this type of PV system. One of the first issues studied was the impact on power system operation of PV system output fluctuations caused by cloud transients [1]. Cloud transient effects on voltage profile were investigated in large scale transmission level [17]. Due to the special characteristics of distribution networks, performance achieved in a large-scale transmission system does not necessarily mean the same performance in distribution systems. The PV power support may lose most of its power within a short period in distribution systems due to cloud coverage. Cloud transient effects on voltage profile in small scale three-phase distribution system were investigated in [18].

Voltage stability steady-state analyses can be assessed by obtaining voltage profiles of critical buses as a function of their loading conditions. These voltage profiles, or shortly *P–V* curves, provide considerable insight into the systems behavior and operating conditions for different loading levels, and have been used by the electric power industry for assessing voltage stability margins and the areas prone to voltage collapse [19]. The gradual load increment will lead to a saddle-node bifurcation (SNB) point which corresponds to the maximum loading point (MLP), as shown in Fig. 1 [20,21]. Under these conditions, the Jacobian matrix becomes singular.

In this paper, the steady-state voltage profile and voltage stability of a large scale grid-connected PV power station is discussed under clear sky condition and cloudy sky condition at 50% PV penetration level. Moreover, effects of irradiance and temperature are studied. The PV power station applies a maximum power point tracking (MPPT) strategy where the generated real power of PV system depends mainly on weather conditions. The flow of reactive power in the feeder was investigated with different assumptions of inverter participation. The reactive power is also varying with the weather conditions whereas the constraint is satisfied at all time. Different models of PV inverter were studied together with different cases during the time of the day with clear sky and cloud incidents. These studies were performed on the IEEE 33-bus radial distribution system.

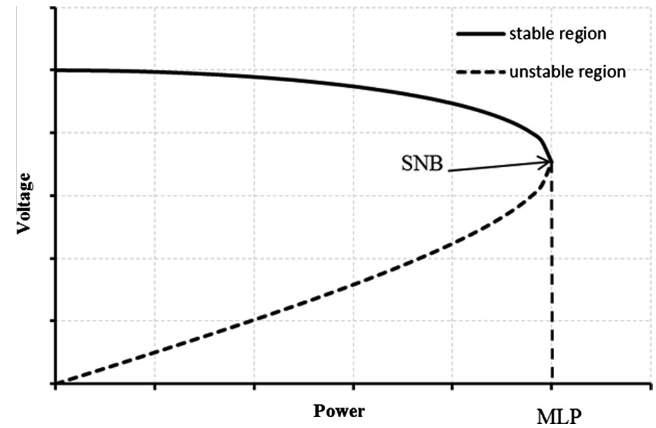

Fig. 1. A typical PV curve.

For voltage regulation analysis, the target is to hold all customers within the band of ±5% voltage during the 24 h of the day [22]. The voltage stability analyses are examined at different times of the day by continuation power-flow (CPF) as the load increment up to the MLP. The PV power station was divided between bus 18 and bus 33 as they are the weakest buses in the distribution system under study. Results for voltage regulation and voltage stability were plotted for bus 18 only to avoid repetition. The simulations were done by MATLAB M-file programming.

The organization of this paper is as follows: 'Reactive power support by PV conditioning unit' describes the reactive power support by PV inverter. 'Continuous Power-Flow Analysis' describes the continuous power-flow analysis. 'Modeling of PV array power' describes the modeling of PV array power. 'Results and discussion' analyzes the simulation results and discussions. Finally, 'Conclusion' provides conclusions regarding this work.

Reactive power support by PV conditioning unit

Currently, standards such as *IEEE*1547 [23] state that the PV inverter shall not actively regulate the voltage at the PCC. Therefore, PV systems are designed to operate at unity power factor (i.e., must not inject or consume reactive power or in any way attempt to regulate voltage). The inverter should be designed for this contribution in the first place in order not to cut into the real power capability of the PV because cutting into the real power capability has negative economic consequences for the owner [6].

To mitigate the above problem, it has been proposed that the interconnection standards for inverter based PV generation be changed in such a way to enable the inverters to assist with high speed voltage regulation [1,4,6]. In this case, the PV inverter will be required to have a maximum apparent power capability larger than the maximum power output of its PV array and the excess capability will be dispatched by the distribution utility for voltage regulation. Inverters with modern digital signal processor-based control systems have the potential to offer an economical, highly flexible means to control both real and reactive power flows under normal operating conditions. These inverters have quicker response and a larger reactive power adjustment range at rated real power than the excitation circuit of the synchronous machines [10].