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Review Paper

The Review on Voltage Stability Analysis of Power Systems with Solar Distributed Generation using VCPI

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Abstract:- *This comprehensive review paper investigates the challenges and strategies of maintaining voltage stability in power systems integrated with solar distributed generation, focusing on the application of the Voltage Collapse Proximity Index (VCPI). As renewable energy, particularly solar power, becomes increasingly prevalent in power grids, understanding its impact on voltage stability is crucial. VCPI emerges as a vital tool in this context, offering a reliable measure for assessing the risk of voltage instability. This paper synthesizes various research findings and methodologies related to VCPI, highlighting its role in enhancing grid resilience against voltage instability in solar-integrated systems. The results indicate that VCPI is effective in predicting voltage collapse, especially in scenarios with high solar power penetration. This review not only collates data from diverse studies to present a coherent view of the current state of voltage stability in solar-integrated power systems but also identifies gaps and suggests directions for future research. It aims to provide a foundation for enhancing voltage stability mechanisms and strategies in power systems with a growing reliance on solar energy. This work is particularly relevant for researchers and practitioners seeking to optimize the integration of renewable energy sources into existing power grids while maintaining grid stability and reliability.*

Keywords: *Voltage Stability, Solar Distributed Generation, VCPI (Voltage Collapse Proximity Index)*

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1. Introduction

Electricity plays a vital role in our daily lives. People use electricity for various purposes, such as lighting homes, running electronic devices, transportation, and industrial processes. Energy demand has increased over the years due to population increase, economic development, and the increased use of technology. It is predicted that total energy consumption is 20% today and will increase by 50% in 2050 (1). Due to its continuous increase, energy demand poses challenges related to the availability and affordability of energy (2). Non-renewable sources such as fossil fuel (gas, oil, and coal) and nuclear energy will be depleted since they cannot be replaced because we currently depend on them to supply our energy needs. As a result, renewable energy like solar photovoltaic (PV), wind, and hydropower are introduced to address the availability of energy issues.

Solar photovoltaic (PV) is one of the fastest-growing renewable energy sources worldwide. Malaysia receives an average of 4500kWh/m^2 of solar radiation daily, with approximately 12h/day\ of abundant sunshine (3). Due to the abundance of sunlight and limited rain, the weather conditions in Malaysia are favorable for the utilization of PV systems. Solar PV generates electricity from sunlight and converts it directly into electrical energy (4). Its adoption has increased in recent years to reduce greenhouse gas emissions and minimize energy costs (5). As technology advances, the cost of solar panels is expected to decrease, potentially leading to the widespread use of solar panels in the future.

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However, with the increasing use of solar PV, there are reliability concerns for power grids with high penetration, such as voltage stability.

In addition, voltage stability has been defined as the ability of a power system to maintain the voltage value at all buses after the power system is exposed to any disturbances (6). Voltage stability has become a concern in modern power distribution networks due to the rising demand for electricity and increasing penetration of distributed generation (7). Voltage is one of the important parameters that will be measured to maintain bus voltage after the load demand changes. It will lead to voltage collapse when the system receives extra loads and reactive power cannot be supplied to maintain the bus voltage.

This paper presents a detailed review of the current state and challenges in voltage stability analysis within power systems that incorporate solar distributed generation, particularly emphasizing the application of the Voltage Collapse Proximity Index (VCPI). It aims to shed light on the critical aspects of integrating solar energy into the grid, highlighting the key methodologies and findings in this area of study.

2. Voltage Stability

The study of the power system was conducted many years ago. The development of power systems has led to an increased demand for electrical energy (8). Voltage stability has become a critical parameter for analysis, as it plays a significant role in power systems to meet the required demand (9). Voltage stability is defined as the power system's ability to maintain steady-state voltages at all buses under normal operating conditions and after being subjected to a disturbance (10). Therefore, voltage stability can be assessed by analysing the power system's behavior under various scenarios to ensure a reliable and uninterrupted electricity supply.

The concept of voltage stability is categorized into two categories: small disturbance voltage stability and large disturbance voltage stability (11). Small disturbance analysis focuses on how the system voltage responds to small changes in load. This is influenced by load characteristics, continuous controls, and discrete controls at a specific time. On the other hand, large disturbance analysis assesses the system's ability to regulate voltages during system faults and generation loss. It is influenced by the characteristics of system loads and the interaction between continuous and discrete controls and protections. In the short term, the small disturbances analysis uses the continuous power flow method while the large disturbance analysis uses the time-domain analysis (12).

The major issue in voltage stability is that the increasing load demand in the distribution network can lead to lower voltage values, potentially causing the entire system to voltage collapse. This is because the reactive power has reached the stability limits and may not be sufficient to meet the increased demand (13). Consequently, the major problem that could occur during this time was a blackout in the distribution area and this phenomenon remains a critical challenge worldwide (14). Therefore, to address the issue of voltage stability, there are several approaches that can be taken, including reactive power compensation, network load ability improvement, network re-configuration and optimally distributed generation (15).

3. Solar Distributed Generation

Solar Distributed Generation (DG) is one of the renewable energy sources being widely used worldwide due to its clean and emission-free properties. It can be proven when past research says that the percentage of global power from renewable energy gradually increased to 26% in 2019. DG refers to the use of solar photovoltaic (PV) systems to generate electricity for residential, commercial and industrial buildings. DG can generally be defined as electric power generation within distribution networks or on the customer side of the network (16). It is expected to become more important in future generations as it produces electricity closer to the point of electricity consumption. This decentralized offers advantages over traditional power generation, including lower transmission losses, increased energy resiliency and meeting energy needs (17).

Generally, solar DG systems usually have a capacity between 5 and 25 kW for small PV systems. It generates electricity for on-site consumption and establishes an interconnection with low-voltage transformers within the electric utility system. Solar DG systems can be classified into two groups: stand-alone and grid-tied (18). A stand-alone solar system can operate independently from the grid, potentially continuing power production and storing energy for future use. It produces energy through the inverter to the power bank or solar battery storage for load consumption (19). In contrast, a grid-tied solar system offers good performance as it is directly connected to the power grid and is immediately disconnected during a power outage (20). Currently, the majority of solar DG systems in use today are not connected to batteries or additional power sources to provide a continuous power supply to a load.

Distributed generation has the potential to meet consumer needs by reducing the necessity for traditional utility investments in distribution, transmission, and generation systems (21). Furthermore, integrating DG can result in several benefits, including reduced environmental impact, decreased transmission losses, and lower electricity costs (22). One factor of this integration is maintaining grid stability by supplying electricity during peak times and expanding to meet energy needs. DG is based on solar PV that is connected to the utility grid using inverters to regulate both active and reactive loads as outputs (23). Therefore, the increased deployment of DG raises concerns and challenges for power systems, such as bi-directional power flow and increased fault levels (24).

4. The Impact of Solar Distributed Generation on Voltage Stability

In power systems, voltage stability has been a widespread concern to ensure all buses in the network can maintain the desired voltage when facing load disturbances (25). The voltage value at each bus must be kept within permissible limits of 0.90 – 1.00 per unit and should not exceed 1.10 per unit (26). Maintaining the voltage value by connecting solar DG in power systems is crucial. This is because the connection of a solar DG to a distribution network has proven to be an effective solution for the network's power flow. Generally, connecting DG systems in a demands-dominated area is essential, as it needs to import power to meet the electricity needs of consumers. Therefore, the placement of DG has the potential to enhance voltage stability in the distribution system, as it can reach the maximum demands (27).

The effects on voltage stability can be accessed through generator bus models and slack bus models of DG. Generator bus models represent active generators with parameters related to voltage. If the number of DG with the generator bus model is not appropriately managed, it can lead to a decrease in voltage stability due to an excess of electricity production and challenges in integrating DG with the grid. On the other hand, the slack bus as the reference bus where the voltage magnitude and phase angle are specified (28). It has the potential to increase voltage stability because the slack bus allows DG to be connected at various locations and capacities, providing more flexibility in the system. In summary, the slack bus is preferred over the generator bus, potentially leading to an enhancement in voltage stability (29).

In previous research, the proposed method was examined on the IEEE 14-bus system. The standard test configuration includes five synchronous generators with three synchronous compensators (30). This system comprises 14 buses, considering 11 loads with a total demand of 362 MW and 108 MVAR. It considers solar DG with a capacity of 15 MW and incrementally increases it by 10 MW. The solar DG is installed at the identified weakest bus to prevent the power system from collapsing, particularly as the reactive loads approach their maximum values. The stability of the system also increases when connected with a larger solar DG. Overall, the integration of solar DG has both positive and negative impacts on voltage stability based on its characteristics and the power system. Therefore, introducing the voltage collapse proximity index (VCPI) serves as a solution for voltage stability analysis (31).

5. Voltage Stability Analysis with VCPI

Voltage stability analysis is a critical aspect of monitoring the stability of power systems. Various methods exist for assessing the voltage stability indices, such as line stability index, voltage stability margin, and voltage collapse index (32). The literature introduces the voltage collapse proximity index (VCPI) as a tool for evaluating the voltage stability of all buses connected to a complex power system (33). This is because the voltage collapse proximity index is calculated based on the maximum power transferred through a line in the power network (34). The effectiveness of VCPI has been tested in various studies, establishing it as one of the simplest and fastest methods for predicting these indices (35).

The main idea of VCPI is connected to the concept of maximum power transfer in the line. Only active and reactive amounts of calculation are required at the associated bus. Moreover, it takes less time to calculate because it does not require matrix inversion and only measures the voltage value at the bus. The VCPI value varies from 0 to 1. The VCPI value starting from 0.1 to closer to zero is considered a stable condition, while the VCPI value closer to unity is considered critical to collapse (36). In previous research, the IEEE-14 bus system was chosen to carry out the test of the effectiveness of VCPI. The results indicate that bus 6 is identified as the weakest bus, with the highest value among all the buses which is 0.02987. While bus 9 is the healthiest bus, with a value of 0.00397, the smallest compared to other buses and almost close to zero (37). This method has been proven to determine the steady-state stability of the system.

In summary, VCPI offers a range of advantages that collectively contribute to the efficient, reliable, and resilient operation of power systems. Their proactive approach to identifying the weakest bus makes them useful tools to ensure the continuous delivery of electrical power. VCPI acts as an early warning when the system operates closer to its stability and results in lower voltage values. Early detection enables the mitigation of voltage collapse to prevent the system from becoming unstable and reduce the risk of large-scale blackouts (38). Besides that, VCPI can be applied to modern grids, including smart grids (39). It is because VCPI is designed to operate in real-time where the data is crucial for efficient operation and control. Therefore, VCPI is useful for predicting the collapse point in the power system (40).

6. Conclusion and Future Scope

Based on the review that has been made, the research process focuses on voltage stability analysis in electric power systems with photovoltaic integration. The objective is to identify the weakest load buses based on the highest VCPI values, indicating voltage collapse. Subsequently, the weakest load buses are connected with solar DG in various increments. As a result, voltage stability increased as the maximum limits of active and reactive loads expand to larger solar DG installations. Future research is directed towards integrating VCPI into the broader smart grid to enhance power system monitoring and control capabilities. This integration empowers the grid to proactively tackle voltage stability challenges, contributing to the establishment of a power system to become more reliable, efficient, and resilient.

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