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VOLTAGE STABILITY ANALYSIS AND DETECTION IN LARGE SCALE RENEWABLE INTEGRATED GRID: A REVIEW

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Abstract
Voltage stability assessment and detection in renewable integrated grid is paramount important these days. Huge penetration of renewable energy into the grid is happening in an unprecedented way. This situation can be realized as replacement of synchronous generators with non-synchronous generators. The non-synchronous generators are generally coupled to the grid through voltage source converters and line commutated converters. Therefore, the characteristics of non-synchronous generators are understandably different from synchronous generators. Besides, the large scale penetration of the renewable energy sources into the grid leads to several operational problems, specifically voltage stability problem. Several voltage stability assessment methods and indices are proposed in the literature, based on conventional grid assuming dominant power generation through synchronous generators. These methods may not be sufficient to analyze in large scale renewable integrated grid. This paper endeavor to provide a comprehensive review of voltage stability assessment, and detection in large scale renewable environment. The impact of voltage source converters, line commutated converters and load characteristic are the main considerations in this review. The extent at which these converters output can be stretched is analyzed by considering different load models. The interaction among line commutated converters and voltage source converters, and their behavior with weak system and strong system is analyzed. The methods to improve the voltage stability with large scale solar into the grid are studied.

Keywords:
Stability, Grid, Non-Synchronous Generators.

I. Introduction

A large-scale renewable integrated grid, also known as a renewable energy grid or a smart grid, refers to a power system that is designed to incorporate a significant amount of renewable energy sources and effectively manage their integration into the overall electricity grid. It involves the deployment of various technologies, strategies, and infrastructure to enable the efficient and reliable integration of renewable energy generation, such as solar, wind, hydro, and geothermal power, into the existing power grid [1]. Here are some key aspects and components of a large-scale renewable integrated grid: As the name suggests the grid relies heavily on renewable energy sources for electricity generation. These sources typically include solar photovoltaic (PV) panels, wind turbines. The renewable energy sources are intermittent and therefor large-scale energy storage technologies are very crucial to obtain balance. The excess energy produced during favorable period is stored and is utilized during higher demand.

The real time energy consumption and two way flow of electricity may be recorded using the advanced metering techniques. Smart meters are the major building blocks of advanced metering. These meters not only allow for accurate billing but also useful for load monitoring and load control. The load control typically achieved by sending price signals to the consumers. The present state of the grid may also be notified [2].

The integrated grid is connected to substations of load centers through transmission lines. The transmission line expansions are another challenge. This often involves building new transmission infrastructure and upgrading existing grid infrastructure to accommodate the increased capacity.
The integrated grid is aimed to improve the reliability of the power system, as the system is always prone to several disturbances. It has been realized that incorporating distributed generation, the grid becomes less dependent on centralized power plants. Additionally, the large scale integration of renewable energy sources into the grid may improve grid resiliency to climate change impacts and reduce greenhouse gas emissions.

II. Large Scale Integration

Large-scale renewable integrated grids have the potential to reduce reliance on fossil fuels, and mitigate climate change. A sustainable environment may be created. However, their successful implementation requires careful planning, collaboration among stakeholders, supportive policies and regulations, and significant investments in infrastructure and technology.

When integrating a large-scale renewable energy generation into the grid, several stability issues can arise due to the inherent characteristics of renewable energy sources. Here are some common stability issues that can occur:

Voltage stability refers to the ability of the power system to maintain steady voltage levels within an acceptable range before and after the occurrence of disturbance [2]. The intermittent nature of renewable energy sources can cause voltage fluctuations. These voltage variations are high especially during periods of high renewable energy generation. This can result in voltage sags or swells. Sag or swell beyond a limit can cause damage to sensitive equipment [3].

Frequency stability is also crucial for the reliable operation of an electricity grid. Traditional power systems with conventional generation have inherent inertia that helps maintain stable frequencies. However, renewable energy sources doesn't have inertia, and sudden changes in their output can cause frequency deviations. The inertia is provided by a controller.

Power quality issues are another major focus area in renewable integrated grid. Variations in power output, voltage and frequency may lead to harmonic distortions, and other power quality problems. These issues can affect the performance of sensitive electronic devices and may require additional filtering or power conditioning measures to maintain a high-quality power supply.

Integrating large-scale renewable energy into the grid requires proper synchronization between the renewable energy sources and the existing grid infrastructure. Achieving accurate synchronization is essential to maintain a stable and reliable power supply. Lack of synchronization or improper synchronization can lead to grid disturbances, equipment damage, and even blackouts [4].

Fault Ride-Through Capability: Faults or disturbances in the power system, such as short circuits or line failures, can occur. Power plants, including renewable energy sources, need to have the capability to ride through and recover from these faults. However, certain renewable energy technologies, such as solar PV systems, may have limited fault ride-through capabilities. Grid codes and technical standards often define requirements for fault ride-through capability to ensure the stability and resilience of the grid.

System Planning and Grid Expansion: Integrating large-scale renewable energy sources may require significant changes in the system planning and grid expansion. The existing transmission and distribution infrastructure may need to be upgraded or expanded to accommodate the increased capacity and variability of renewable energy generation. Ensuring proper grid planning and timely investments are essential to maintain system stability during the integration process.
Addressing these stability issues requires advanced grid control and management techniques, improved grid infrastructure, and the development of grid codes and standards specific to renewable energy integration.

III. Voltage Stability in Renewable Integrated Grid

Ongoing research and development are focused on developing innovative solutions to mitigate stability issues and enable the seamless integration of renewable energy into the grid.

Voltage stability studies are important when considering large-scale integration of renewable energy sources for several reasons:

Voltage stability is crucial for the reliable operation of electrical equipment. Variations in voltage levels can impact the performance and lifespan of devices connected to the grid, such as motors, transformers, and sensitive electronic equipment. Voltage instability can lead to equipment malfunctions, increased maintenance costs, and even premature equipment failure.

Voltage stability is closely related to power quality. Fluctuations in voltage can result in voltage sags or swells, harmonic distortions, and voltage flicker, which can impact the quality of power supplied to consumers. Maintaining stable voltage levels within an acceptable range is essential for delivering high-quality power and avoiding disruptions to electrical systems [5].

Voltage variations can directly affect consumers' electrical appliances, particularly those sensitive to voltage changes. For example, variations in voltage can impact the performance of electronic devices, cause lights to flicker, or disrupt sensitive industrial processes. Voltage stability studies help identify potential voltage issues and enable appropriate mitigation measures to ensure a stable power supply to consumers.

Voltage instability can lead to cascading failures and system-wide blackouts. When voltage levels deviate significantly from the desired range, it can trigger protective relays and result in the disconnection of generators or transmission lines. These disconnections can further deteriorate system stability and potentially lead to a collapse of the power grid. Voltage stability studies help identify potential instability risks and allow grid operators to take preventive measures to maintain overall system reliability.

Voltage stability assessments play a crucial role in grid planning and operation. The suitable locations for reactive power compensation devices will be known. These devices with suitable capacities at strategic locations may improve the stability.

The integration of renewable energy sources can introduce additional challenges to voltage stability. Renewables, such as solar and wind, are often connected to the grid through power electronic converters, which can impact the voltage profile of the system. Understanding the voltage stability implications of integrating these variable generation sources is vital to ensure the reliable and stable operation of the grid.

IV. Main Review

While other stability studies, such as frequency stability and transient stability, are also significant for grid operation, voltage stability studies specifically address the impact of load models, generator excitation limiters, and overall system reliability. Voltage instability results in partial or complete blackout of power systems. By focusing on voltage stability, grid operators can ensure a stable and reliable power supply that meets the requirements of various electricity consumers while accommodating the integration of renewable energy sources.

Voltage stability is a critical aspect of a renewable integrated grid, as the intermittent nature of renewable energy sources can introduce voltage fluctuations and potential stability challenges. Voltage stability in renewable integrated grid can be understood as follows:

Renewable energy sources, such as solar and wind power, are inherently intermittent in their output due to factors like weather conditions. These fluctuations can result in voltage variations within the grid. For example, sudden changes in solar irradiation or wind speed can lead to rapid voltage change, affecting the load power intake. With reduced voltage if the system is operating with motor load severe effects like increased reactive current would occur.

Renewable energy sources typically interface with the grid through power electronic converters. These converters may not inherently provide reactive power support, which is essential for maintaining voltage levels within acceptable limits. Insufficient reactive power support can lead to voltage deviations and compromise grid stability [6].

In a renewable integrated grid, voltage control becomes more challenging due to the decentralized nature of renewable energy generation. Renewable energy sources are often distributed across the grid, and their power injection points may vary. Ensuring appropriate voltage control at different locations becomes crucial to maintain grid stability and prevent voltage instability issues.

Proper system planning is essential to address voltage stability in a renewable integrated grid. The placement and capacity of reactive power compensation devices, such as capacitors, voltage regulators, and STATCOMs (Static Synchronous Compensators), should be carefully considered to provide effective voltage support [2]. The voltage level at which it should be maintained is determined by the requirement of the reactive power. If the capacity of the reactive power devices supporting reactive power is less, in that case, due to insufficient reactive power voltage instability is initiated. It is therefore very crucial the placement of the device and the capacity of the device. Optimal placement of the device can ensure stability improvement.

In the renewable integrated grid, grid-codes and technical standards play a vital role in ensuring voltage stability. These codes often define requirements for voltage control, power factor control, and reactive power support from renewable energy sources. Compliance with grid codes helps maintain voltage stability and enables the seamless integration of renewable energy into the grid.

Voltage regulation and control strategies are employed to manage voltage fluctuations and maintain stability in a renewable integrated grid. These strategies may include voltage droop control, coordinated control of reactive power sources, and utilization of advanced control algorithms. Smart grid technologies, such as advanced monitoring systems and real-time control mechanisms, can also enhance voltage stability by providing accurate data and enabling proactive voltage control actions.

Energy storage systems, such as batteries, can contribute to voltage stability in a renewable integrated grid. These systems have the ability to absorb excess energy during periods of high renewable generation and release stored energy when generation levels drop. By balancing supply and demand, energy storage can help regulate voltage fluctuations and improve grid stability [7].

Addressing voltage stability in a renewable integrated grid requires a holistic approach that encompasses proper grid planning, effective control strategies, compliance with grid codes, and the utilization of energy storage systems. By ensuring voltage stability, the grid can accommodate the increasing penetration of renewable energy sources while maintaining a reliable and secure power supply.

The electric vehicle penetration into the distribution system grid also raising concerns for voltage stability problem. The degree of EV penetration largely affects the distribution system voltage stability. Many a times, the distribution system voltage stability is reflected to transmission system leading to the complete or partial blackout of power network. This paper studies and analyzes the impact of higher degree of EV penetration into distribution grid connected with renewable energy sources. The major advantage with the aggregated EVs at a parking lot is that, they can either support active or reactive power into the distribution system. However, electric vehicle behavior prediction is another challenge.

Large scale deployment of renewable energy sources is need of the hour globally not just for clean energy but also for reducing the fossil fuel dependency. Traditionally voltage stability problem is due to mismatch in load and system characteristic. However, the differences in dynamic characteristics of renewable enabled sources like solar PVPs, WECS etc., and conventional generators has brought the system utilities encounter with several non-traditional problems. Out of the available renewable energy

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sources, photovoltaic in GW scale is one of the choices in several countries. Such continual large scale PV into the grid may replace all the synchronous generators with PVs and battery energy storage systems. There are several control mechanisms in PVs. All these controllers and their impact on voltage stability should be studied. A scheme should be developed to mitigate voltage instability [8]. This paper proposes a corrective control scheme for large scale battery energy storage system to prevent long term voltage instability. An objective function is formulated to minimize investment cost and voltage drop by determining the suitable size of battery energy storage system and its optimal location. For this purpose, particle swarm optimization algorithm is applied.

Voltage stability assessment with huge wind energy penetration into grid is another study of interest. Wind energy is being fed into the grid using DFIG, whose dynamic characteristics determine the stability limit. Theoretically, it has been found that 100 % of wind energy penetration is possible. However, a detailed study is required before arriving to such conclusion. There is an evidence of literature showing that the huge wind energy penetration percentage increases by installing FACTS devices at weak nodes [9].

The automatic volt-watt and volt-var inverter response functions in solar PV generation also plays role in maintaining stability. With these two features a new set of equilibrium conditions are developed. The analytical criterion of stability is defined. The need for such new stability criteria and equilibrium conditions are due to the fact that when the inverter is operating close to maximum output power the operation of volt-watt causes sustained voltage oscillations at the distribution lines. These sustained oscillations are more dominant when the system is operating close to maximum stability limits. These oscillations have to be identified [10]. In this [11] a methodology is developed to identify such oscillations. This method is very effective especially if there exists only one inverter in the system. The practical system consists of several inverters and has their individual loop controls. The dynamic interactions of such multiple inverters are another research gap which should be addressed.

The non-synchronous generators from solar are influenced by some of the parameters like low voltage ride through and dynamic voltage support from converters. There are a few events of blackouts occurred in 2016 in California and in Australia. The blackout report shows that the California blackout is as a result of missing low voltage ride through capability, while the Australian blackout is due to insufficient dynamic voltage support [1, 2]. It is now understood that the impact of low voltage ride through and dynamic voltage support on power system has to be studied. Power system stability challenges with PV are given in [4].The impact of PV systems on transient stability [5-7]. This paper studies the impact of short term voltage stability and suggests a method to avoid the system from instability [11].

DFIG based wind generation in coordination with FACTS devices may be utilized to improve the voltage stability of the grid. A nonlinear control approach proposed in [12] improves the transient stability and voltage stability of the system. The DFIG rotor voltage and the STATCOM reference current computation is very crucial in this non-linear approach. The linearization error effects are reduced by using super twisting sliding mode control and zero dynamic multi input and multi output system. This methodology gone through rigorous faulty scenarios and found very effective in its operation. This methodology also effective in handling various possible disturbances leading to instabilities [13].

In summary, voltage stability issues arising from the integration of electric vehicles, renewable energy sources, and non-synchronous generators require comprehensive studies, control strategies, and mitigation approaches to ensure the stable and reliable operation of power grids.

V. Conclusion

The integration of electric vehicles (EVs) and large-scale renewable energy sources into the distribution system grid presents voltage stability challenges. The degree of EV penetration and the dynamic characteristics of renewable sources impact distribution system voltage stability, which can cascade to the transmission system and result in blackouts. Proper control schemes, such as battery energy storage systems and FACTS devices, are needed to mitigate voltage instability. The response functions of inverters in solar PV and the characteristics of DFIG-based wind generation also play crucial roles in maintaining stability. Addressing these challenges requires comprehensive studies, advanced control strategies, and coordination among various renewable energy components to ensure the reliable operation of the grid.

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