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Reviewing Voltage Stability: A Comprehensive Classification and Evolution of Improvement Methods

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Abstract

Voltage stability has become a foremost concern for researchers in recent years. Nowadays, the system always operates at its maximum limits due to the continuous increase in its load. Therefore, any disturbance or overloading can create instability or voltage collapse. Voltage stability can be classified based on disturbances and sustaining time. This paper explains the different classifications of voltage stability and presents a review analysis and benefits of numerous methodologies such as FACT devices, distribution generation (DG), and load shedding to enhance the voltage profile of the system.

Keywords: Voltage stability, Voltage collapse, FACT, Distribution generation, load shedding

1. Introduction

In recent years, power systems have become more complex and less secure due to the high penetration of renewable energy sources and extended interconnected networks. Improper planning and operation increase the uncertainty and insecurity of the system. Voltage stability is a critical factor for power systems to operate reliably and efficiently. also, electric utilities are obligated under Cataclysm to utilize their power networks' available transmission capacity effectively. As a result, power transfers have increased, transmission margins have decreased, and voltage-security margins have dimmed. In certain situations, when combined with constant interruptions, this might lead to issues with voltage stability, perhaps leading to a catastrophic voltage collapse.

According to CIGRE and IEEE Task Forces, voltage stability can be defined as the "ability of a power system to conserve acceptable voltages at all buses under normal circumstances and after being subjected to an interruption"[1]. The loads, generator outputs, and other critical operational characteristics of the power system are all continuously changing, making it a highly nonlinear system. The system's stability in the context of a disturbance is contingent upon the system's pre-disturbance operating condition and the sort of disturbance. Voltage stability issues may arise due to contingences like high power demand, lack of reactive power sources etc. and If these issues are not dealt with correctly, they can lead to voltage sags, surges, voltage collapse, or blackouts. Voltage collapse occurs when a sequence of events linked to voltage instability results in a significant portion of the power system having an insufficient voltage profile [2]. Voltage stability is essential in ensuring the reliable and safe operation of power systems. The following factors can lead to voltage instability:

- An increase in load demand can lead to a voltage drop, which can cause a system to become unstable.

- Generators, SVC or synchronous condensers play a crucial role in maintaining the voltage level within the system. If they reach their reactive power limits, it can cause voltage instability.
- The action of tap-changing transformers can cause voltage instability, particularly if there are delays in switching to a new tap position.
- If a large load is disconnected, the system's voltage may rise, and this can cause instability when the load is reconnected.
- If a transmission line is tripped, it can cause changes in the system's power flow, leading to voltage instability.
- A generator outage can cause an imbalance in the system's power supply and demand, leading to voltage instability.

In the past few decades, numerous blackouts have occurred in homes and various countries [3]. Some of the examples are as follows:

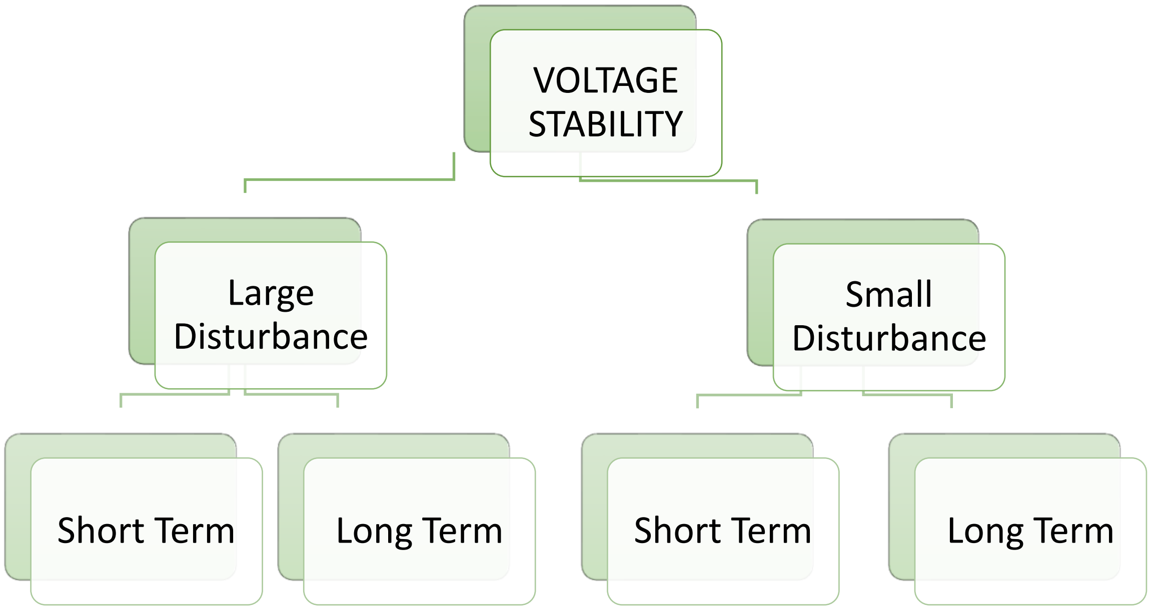
- In Egypt, on April 24th, 1990, a voltage collapse caused a blackout.
- In Brazil, on March 11th, 1999, a lightning strike caused 440 kV circuits to trip, resulting in a blackout.
- In India, on January 2nd, 2001, a transmission line fault led to a blackout.
- In Canada and the Northeast United States, on August 14th, 2003, a lack of maintenance, human error, and equipment failure caused a blackout.
- In Italy, on September 28th, 2003, a tripping of power lines resulted in a blackout.
- In Indonesia, on August 18th, 2005, a transmission line failure caused a blackout.
- In India, on July 31st, 2012, a voltage collapse caused by the overloading of the transmission line resulted in a blackout.

In 2012, India experienced the biggest power on July 31st. The blackout was caused by transmission lines being overloaded, leading to a voltage collapse. This left 22 Indian states without power, affecting approximately 670 million people, hundreds of trains, and hundreds of thousands of households. Similarly, in 2005, Indonesia experienced a severe blackout that lasted for seven hours and affected 100 million people.

Researchers have been concerned about voltage stability following such blackouts and voltage collapse incidents. Improving the system voltage profile is also an important aspect of the study. This paper presents a classification of the system voltage stability and a review of the methods and techniques used to improve voltage stability.

2. Prepare Your Paper Before Styling

Voltage stability can be categorized in different ways based on the kind of disturbances or the research time, as shown in Fig.



Regarding their period and time length, voltage stability can be divided into two types: long-term voltage stability and short-term voltage stability. Long-term voltage stability generally lasts from several minutes to dozens of minutes and is mainly related to the study of generator excitation current limiters, transformer tap adjustments, etc. On the other hand, short-term voltage stability lasts only a few seconds and focuses mainly on the study of HVDC converters and induction motors [4].

2.1 Short-term Voltage Stability

Small voltage stability refers to the ability of the system to maintain acceptable voltage levels at all the buses after experiencing small disturbances, such as a small amount of load changes, etc.; in this case, a voltage near the load does not change or is close to the pre-disturbance value. The properties of loads, constant controls, and distinct controls at a specific moment in time all have an impact on this type of stability. By understanding this concept, it is possible to anticipate how changes in the system will affect voltage levels. This type of instability can be effectively analyzed by study-state approaches that use linearized system dynamic equations at the given functioning point [4]. The dynamics of fast-acting load components, such as inverter-based generators, electronically controlled loads, HVDC links, and induction motors, affect short-term voltage stability. It's also the cause of delays in fault clearing [5].

2.2 Long-term Voltage Stability

Equipment such as tap-changing transformers, thermostatically controlled loads, and generator current limiters operate at a slower pace and play a crucial role in ensuring long-term voltage stability. This type of stability is characterized by a gradual decrease in voltage levels at specific points in the network. Long-term instability can occur when the equilibrium is lost due to load dynamics that attempt to restore power consumption beyond the maximum power transfer limit. The ability to maintain stable voltage during large disturbances is influenced by the specifics of the power system and its load, as well as continuous monitoring and protection. To assess this voltage stability, it's necessary to review the non-linear response of the power system for an appropriate amount of time. This includes observing the interactions and performance of various components, such as motors, underload transformer tap-changers, and generator field-current limiters. Furthermore, instability may result if remedial action is taken too late to restore a stable equilibrium state, leading to a failure to attain the equilibrium condition [5], [6].

3. IMPROVEMENT METHODS OF VOLTAGE SATBILITY

Voltage stability is an eminent aspect of power system security and control. A stable system's voltage profile makes the overall system reliable and secure. In literature, many techniques and methods are employed to improve voltage stability and build the system healthy. This paper presents the review analysis and advantages of different methods for a system's reliable operation.

3.1 FACTs Controllers

A Thyristor-controlled series capacitor (TCSC) is employed to boost the system FACT controllers are power electronic devices that help improve the stability and controllability of power systems. They are particularly effective in enhancing voltage stability, power transfer capability, and reducing system losses. There are four types of FACT devices: series-connected controller, shunt-connected controller, series-series connected controller, and series-shunt connected controller.

voltage levels. TCSCs are series capacitors connected in parallel with thyristor-controlled inductors, which allows for variable capacitive reactance. This paper presents two algorithms, PSO and PSO-TVAC, used to determine the appropriate rating and location of TCSC. The study shows that the PSO-TVAC algorithm is more efficient than simple PSO and is reliable for large systems. furthermore, by placing the TCSC in an identified location, the system stability and power transfer capability are ameliorated [7].

Telang et al., [8] used the STATCOM (static synchronous compensator) to enhance the voltage level of the weak bus of the system to improve overall stability and loss reduction. This method used the tangent vector method for stability analysis and also showed the comparison in voltage profile with or without STATCOM.

Sundar et al., [9] introduces a Distribution Static synchronous Compensator (D-STATCOM), a shunt-connected device that comprises a two-level Voltage Source Converter (VSC). It effectively controls the active and reactive power between DTATCOM and AC system by appropriately adjusting the phase and magnitude of the output voltage of D-STATCOM. The index, equivalent to the electrical distance index (Zth), is proposed for the placement of the D-STATCOM, to enrich the voltage stability of the radial distribution system and reduce system losses.

3.2 Distribution Generation (DG)

Local generation support is the appropriate solution for improving the bus voltage profile. The bus node that has the lowest voltage collapse margin can be chosen for DG installation.

Kumar et al., [10] have chosen Dg to intensify the voltage stability margin with a multi-objective performance index using a Genetic Algorithm (GA) to identify the size of DG. Also, the voltage collapse index is used to find the location for placement, a node with a minimum voltage collapse index is considered a suitable location. This method achieved enhanced voltage collapse margin and load ability without violating any operating constraints.

Ekonomou et al., have presented a detailed analysis of different types of distribution generations (wind turbines, desal generators, and PV cells) and decried the different sizes and locations of DG to remediate the system's voltage profile and reduce energy losses. The extended N-R method has been used for load flow analysis. This method concludes that when three DG's are placed at different, specific locations, it reduces the loss and improves the voltage profile without violating the minimum voltage limit of any node compared to a single DG [11].

3.3 Load Shedding

The load shedding method is proposed by Affonso et al., [12] using re-scheduling programming to upgrade system security and voltage stability margin. The model analysis technique is used to identify the area prone to instability. This method provides the results are; (i) reactive power re-scheduling provides a gain of 6% and is not flexible (ii)active power re-scheduling provides a gain of 32% but generation cost will increase (iii) active and reactive power re-scheduling gives the best results and power loss and generation cost all reduces.

Kisengeu et al., suggest a UVLS (under-voltage load shedding) technique to amend the voltage profile of the system. This method considers the ABC-PSO algorithm to shed an optimal amount of load also it can compute multi-object functions as compared to other GA, PSO-ANN and ABC-ANN techniques. The benefit of the ABC-PSO algorithm is that it provides 89.56% of post-contingency load and 99.32% of recovery of voltage profile with different relay settings [13].

Author Echavarren et al., [14] have presented an LP-based algorithm to shed minimum load to enhance load margin to voltage collapse. Load margin is an indicator to determine the distance to voltage collapse. The optimization algorithm identifies the optimal location and amount to minimum load shedding. The objective function of this method is minimizing the total load demand decreases. As a result, the method achieves the target improvement of load margin, generation and demand limits.

3.4 Other techniques

Dynamic Voltage Restorer (DVR) is a compensating device that maintains the variation in load voltage even when the source voltage has distorted. It is a cost-effective solution to mitigate sag and swell of load voltage. The author proposed DVR to improve the power quality and alleviate variation in load voltage of the distribution system [15].

In a paper [16], Furukakoi et al., have utilized a battery storage system to enhance the stability of the system's voltage. In this method, a controlled battery storage system is installed at the load substation, and the system's stability can improve by regulating the active and reactive power of the energy system. The paper's findings suggest that stability improvement is more effective when both active and reactive power are compensated, compared to compensating the reactive power.

Nassaj et al., have focused on the load term voltage instability caused by interference of OLTC transformer performance and maximum reactive power limitation of the generator and transmission line. To mitigate this, safe and effective tap changing of OLTC in an adaptive and predictive manner is presented in this paper, based on sensitivity analysis and shows the effectiveness of This method in preventing voltage instability [17].

Obumba et al., [18] have presented the under-voltage load shedding mechanism to avoid voltage instability and also introduces parallel lines to decrease the overall impedance that increases voltage stability. This method also reduces the loss of the system and improves power transfer capability. This paper exhibits that after implementing this method, the voltage level has increased by 6.2% and the power transfer capability has upgraded by 42.09% as well.

The author Mohlwini et al., have used capacitor banks (CBs) to improve the voltage stability of the radial network. Using CBs, the impedance of the line is reduced, thereby reducing losses and improving the system voltage stability limit. It also improves the power factor. The paper proposed the voltage stability index, calculated using load flow analysis, to select the location and size of capacitor banks[19].

4. Challenges and Future Work

Power systems are undergoing and will continue to experience significant structural modifications. The emergence of smart-grid technologies, the use of FACTS devices and HVDC lines more frequently, changes in load types and demand profiles, changes in energy storage technology, new entities (like microgrids and energy communities), and changes in characteristics of electricity generation are the main drivers of these transformations. Future power systems are likely to be dominated by energy storage, production from renewable energy sources, and power electronics converter-interfaced loads. These structural changes affect all manifestations of power systems' stability: angle, voltage, and frequency [20]

In Future, it is essential to closely monitor the research and development in engineering fields such as power electronics, machine learning, and artificial intelligence as they may significantly impact voltage stability in power systems. In addition, it is essential to examine the role of emerging technologies such as advanced energy storage systems, smart-grid solutions, and renewable distribution generation in enhancing voltage stability and overall system resilience.

5. CONCLUSION

In conclusion, this paper provides an in-depth understanding of the various disturbances that are encountered during power system operation, leading to different types of voltage instability. The cause of this instability is an overloaded system and insufficient reactive power reserves. The paper reviews different methodologies used in past research to address this issue and presents solutions to enhance system stability, making it robust and reliable. The synthesis of knowledge presented in this paper not only consolidates existing information but also serves as a valuable resource for researchers and practitioners, seeking to advance the state-of-the-art in voltage stability analysis and control.

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