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Impact of Synchronous Condensers on Power System Static Voltage Stability Considering Line Contingencies in the Presence of Renewable Generation

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***Abstract*—Ever-growing electrical loads are having a massive impact on the operation and stability of the power system. Moreover, the integration of renewable generation poses various challenges to the future power system, especially regarding stability. Thus, this paper presents the impact of synchronous condensers on static voltage stability analysis for a test transmission network, considering line contingencies, in the presence of renewable generation. The main purpose of this study was to identify critical buses in the power system when line contingencies occur. Uncertainty in the form of (N-1) and (N-2) contingencies was considered in this study. The impact of renewable generation was also assessed. To analyse the static voltage stability, the conventional power-voltage curve method, using continuation power flow, was applied on the IEEE 14-bus test system. DIgSILENT PowerFactory software simulations were used to obtain the results. The P-V analysis accurately quantified the critical buses for both cases, considering (N-1) and (N-2) line contingencies.**

Keywords—contingency, critical bus, power system, renewable generation, static voltage stability

I. INTRODUCTION

Since the early 20th century, power system stability has been documented as a significant issue for secure system operation [1-2]. Most blackouts caused by power system instability have demonstrated the significance of this phenomenon [3-4]. Historically, transient stability has been the leading stability issue in most power networks. However, with the introduction of novel technologies and increasing load demands, several kinds of instability have come into the picture. For instance, voltage stability, frequency stability and interarea oscillations have gained importance. This has necessitated an understanding of the concept of power system stability. A lucid concept of various kinds of instability is vital for the acceptable operation of power systems. Reference [5] has classified power system stability into three types: rotor angle, frequency, and voltage. An account of these types of stability follows.

Rotor angle stability is the ability of synchronous machines in the power system to maintain synchronism when a disturbance is applied. Instability can result when the angular swing of generators leads to loss of their synchronism. Small-signal, rotor-angle stability deals with stability under small disturbances, such as minor load variations. Large-angle stability focuses on large disturbances, such as three-phase short circuit.

Frequency stability is the ability of a power system to maintain steady frequency after severe system stress causes a substantial disparity between generation and load. It relies on the ability to preserve equilibrium between system supply and demand, with a minimum inadvertent loss of load. Instability can manifest itself in the shape of sustained frequency swings, which subsequently cause generating units and loads to trip. An example of this phenomenon is the forming of an under generated island with inadequate under-frequency load shedding such that frequency declines swiftly, resulting in a blackout of the island within a short span of time. Longer-term phenomena include situations in which steam turbine overspeed controls cause frequency instability.

Voltage stability is the ability of a power system to maintain steady voltages at all buses in the system after being subjected to a disturbance from a given initial operating condition. It depends on the ability to maintain equilibrium between system demand and system generation. Instability may manifest itself in the shape of a continuing decrease or increase of voltages at some or all buses. The culprit for voltage instability is typically the loads: in response to a disturbance, power expended by the loads is apt to be reinstated, mostly due to motor slip alteration and tap-changing transformers. Reinstated loads upsurge the strain on the high voltage network by snowballing the reactive power consumption, thereby producing additional voltage drop. A deteriorating state results in voltage instability when load dynamics try to reinstate power consumption outside the transmission system capability. A term which is frequently used in this regard is voltage collapse. It is defined as the procedure by which the order of events complementing voltage instability causes a total blackout or unusually low voltages in a larger portion of the power network. Large-disturbance voltage stability is the ability of a power system to maintain steady voltages after the occurrence of large disturbances, such as three-phase faults. The inherent features of system and load determine this ability. It is essential to investigate the nonlinear response of a power system over a period of time to compute large-disturbance voltage stability. The evaluation period typically ranges from a few seconds to tens of minutes. Small-disturbance voltage stability is the system's ability to maintain steady voltages when small disturbances occur, such as gradual changes in system load. In modern power networks, factors such as congested transmission lines and increasing load demands have caused a highly stressed system. Presently, imminent voltage instability poses a grave risk to the security of these networks. There are two main techniques that are used to analyse voltage stability: static and dynamic. The former approach deals with traditional power flow solutions that are suitable for cases where precontingency and post-contingency situations are recognized for voltage stability limits. The dynamic method, however, uses highly non-linear differential equations to incorporate the dynamics of generators [6-7]. The main reason for voltage instability is the lack of reactive power. With large loading, a voltage stability issue may arise as voltages on some or all buses reach a critical point and are unable to regain their original values. Voltage instability is usually a localized process. Nevertheless, it may grow into a network-wide issue if Transmission System Operators (TSOs) do not take appropriate timely measures [8]. Annually, voltage instability is the reason for huge revenue losses. Voltage instability was a major cause of the 2003 Northeast U.S. blackout. Voltage instability also caused the 1987 Tokyo blackout [9].

Although some research has been conducted on static voltage stability of transmission networks, these studies do not consider the line contingencies, which this study considered while assessing static voltage stability. Moreover, the impact of renewable generation on voltage stability is also of great significance and hence, this needs to be investigated, as well. The remainder of this paper is organized as follows. Section II discusses various methods for assessing static voltage stability. Section III discusses the computation procedure. Section IV describes the relevant case studies for the static voltage stability assessment of the IEEE 14-bus system. Section V discusses the results obtained. Finally, Section VI concludes the paper with suggested future research directions.

II. Static Voltage Stability Methods

There are several techniques that can be used to assess static voltage stability: modal analysis, singular value decomposition, sensitivity analysis, and the power-voltage (P-V) curve method [10-11]. A brief discussion on these methods follows [12].

A. Modal Analysis

The technique of modal analysis is used to assess voltage stability in [13–18]. The power flow Jacobian matrix is the basis for this analysis. It has been used for classifying the critical system bus, which causes system instability. A well-defined origin can be used to study both the steady-state stability and the voltage collapse point [19]. The authors in [13] used the eigenvalue and related eigenvectors of the reduced Jacobian matrix to conduct a modal analysis. In their work, the voltage variation with the reactive power was incorporated with reference to the rank of eigenvalues. Work in [14] focused on the system security augmentation with reference to the voltage stability. In addition, this study determined the voltage collapse point by sensitivity and eigenvalue analysis that was applied on the Italian Electric Power Company (ENEL) transmission system. Reference [15] used the Jacobian matrix to research the geometry of the reactive power load flow. The approach was founded on the maximum power transfer point. Consequently, the margin distance to the collapse point was computed.

B. Singular Value Decomposition

This technique is used for estimating the reactive power compensation required to optimally distribute the resources throughout the system for attaining voltage stability. The minimum singular value of the power flow Jacobian matrix is used as a measure to compute the distance between the static voltage limit and the system operating point. Reference [20] focused on the relation between singularity of load flow in the Jacobian matrix and the singularity of dynamics of the system. The work determined that maximum loadability is determined by the singularity of load flow Jacobian. Reference [21] deals with comprehensive research of the singular value decomposition technique. The method can approximate the point of system collapse and can identify the critical buses. Reference [22] used a weighted least square algorithm to suggest a novel static state estimation algorithm. The proposed method is based on the singular value decomposition method.

C. Sensitivity Analysis

Weak buses are the buses which have the most tendency to become unstable with respect to voltage [23]. These buses are usually identified by conducting a bus sensitivity analysis. The sensitivity analysis is used to enhance the loadability of weak buses and hence, improve the global stability of the power system. The sensitivity index for bus voltage is considered as the bus voltage changes with reference to $\frac{\Delta V_i}{\Delta Q_i}$ and $\frac{\Delta V_i}{\Delta P_i}$ changes [24-25]. Nevertheless, the sensitivity index is not adequate to classify weak buses, particularly, in an interconnected network [26-27]. Compared to other approaches, sensitivity analysis is of greater significance in the identification of critical buses in the network. It is, however, imperative to examine how altering network situations impacts the critical point. Moreover, sensitivity analysis can be used for computing the reactive power margin (MVAr distance to the voltage collapse point) of the weak buses [28-29].

D. P-V Curve

Power system voltage stability focuses on the relationship between transmitted power (P) and receiving end voltage (V). A conventional way to display this relationship is through a P-V curve, which is attained using a steady-state analysis. For this analysis, P (system active power) is increased in steps and the voltage (V) is observed at system buses. This technique uses Continuation Power Flow (CPF). The CPF starts with a base load, and consequently, computes the maximum transfer power by increasing the load in discrete steps. Therefore, the loadability margin can be computed which represents the maximum active load at the critical buses in the power network. Consequently, curves for these buses are plotted to attain the voltage stability of a system. The relationship between bus voltage and MW transfer is nonlinear, which necessitates the full power flow solutions [30]. According to the philosophy of this method, the system bus is stable if the operating point is above the nose point. However, the system bus is unstable if the operating point lies in the lower portion of the P-V curve. After the nose point, the load flow no longer converges. The distance between the operating point and the nose point is known as the stability margin at that bus. The nose point is also known as the knee point or critical point.

This paper describes a P-V analysis to identify critical buses for a test transmission network in the presence of (N-1) and (N-2) line contingencies. The novelty of the work is the consideration of both (N-1) and (N-2) line contingencies, in identifying critical buses, using static voltage stability assessment, considering the effect of synchronous condensers (SCs). The impact of integrating renewable energy generation is also studied.

III. Computation Procedure

The IEEE 14-bus test system was used to conduct the required studies. Two cases were considered. In Case 1, SCs were disconnected from the system, whereas in Case 2, they were connected. The computation procedure for identifying critical system buses for both cases is shown in Fig. 1. In the first step, all (N-1) and (N-2) transmission line contingencies were defined for the network. A P-V analysis was conducted for each (N-1) and (N-2) line contingency using DIgSILENT PowerFactory software. After conducting the analysis, P-V curves were plotted for each bus. From the resulting plots, critical buses were identified. The next step was to integrate renewable generation sources, such as wind generation in the form of squirrel cage induction generator (SCIG) and doubly fed induction generator (DFIG), and photovoltaic (PV) generator.

IV. Case Studies and Simulations

As mentioned previously, IEEE-14 bus test transmission system was used to conduct the required analysis. The system consists of 14 buses (of which 11 are load buses), 2 synchronous generators, 3 SCs (connected at Buses 3, 6 and 8) and a total of 16 transmission lines. The total load was 259 MW, and the installed capacity of the generators was 272 MW [31]. For P-V curve analysis, the system active power was subjected to an augmentation of 1 MW at each step; and corresponding voltages at system buses were observed. This was first done for the system without any contingency so that the critical bus could be identified. Then, the procedure was conducted for both (N-1) and (N-2) transmission line contingencies.

V. Results and Discussion

This section discusses the results of the P-V analysis, first without SCs and then including them. The SCs were connected to Buses 3, 6 and 8 in the latter analysis. For each analysis, three subcases were considered: base case, (N-1) line contingencies, and (N-2) line contingencies. An SC is essentially a DC-excited synchronous motor, whose shaft is unconnected, but it can rotate freely. It is used to regulate conditions on the power system grid rather than to convert electric energy to mechanical energy, or vice versa. Its field is controlled using a voltage regulator to either generate or absorb reactive power, as required, to adjust the voltage of the grid [32].

Case 1: P-V analysis without considering SCs. First, P-V curves were plotted for the base case (no contingencies). The plot for P-V curves for all of the system buses is shown in Fig. 2. It should be noted that the software stops plotting the curve as soon as the knee point is achieved; however, it is not hard to trace the curve back intuitively. A likely reason for not plotting further is that only the knee point is of interest, and there is no use in conducting further analysis once this instability point is reached. As evident, the voltage magnitude for Bus 14 at the nose point is the lowest. Therefore, Bus 14 is the critical bus.

In the next step, (N-1) line contingencies were considered. The P-V curves for each (N-1) line contingency were plotted against the voltage magnitude of system buses. For instance, P-V curves for Line 1-5 contingency are shown in Fig. 3. From the curves, it is evident that Bus 14 is the critical bus. Similarly, all critical buses were identified for the remaining (N-1) line contingencies. The results are provided in Table I. The graphical results are shown in Fig. 4. As is evident, Bus 14 is the critical bus as it had the highest frequency for being the critical bus when (N-1) line contingencies were considered. Here "frequency" is defined as the number of times a bus becomes critical. A similar analysis was conducted for (N-2) line contingencies (amounting to 120 contingencies). The graphical results are shown in Fig. 5. Again, Bus 14 is the critical bus.

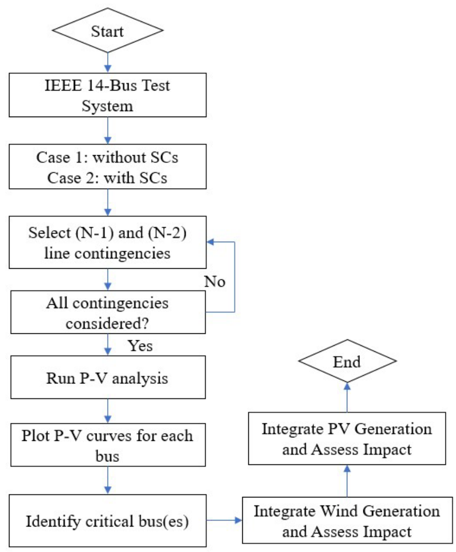

Fig. 1. Computation procedure.

Case 2: P-V analysis considering SCs. Now, SCs were connected to the network at Buses 3, 6 and 8. The P-V curves were plotted for the base case (no contingencies). The plot for P-V curves for all system buses is shown in Fig. 6. As evident, the voltage magnitude for Bus 5 at the nose point is the lowest. Therefore, Bus 5 is the critical bus. In the second case, (N-1) line contingencies were considered. The P-V curves for each (N-1) line contingency were plotted against the voltage magnitude of system buses. For instance, P-V curves for Line 1-5 contingency are shown in Fig. 7. From the curves, it is evident that Bus 5 is the critical bus. Similarly, all critical buses were identified for the remaining (N-1) line contingencies. The results are provided in Table II. The graphical results are shown in Fig. 8. As is evident, Bus 5 is the critical bus, as it has the highest frequency for being the critical bus, when (N-1) line contingencies are considered. A similar analysis was conducted for (N-2) line contingencies (amounting to 120 contingencies). The results are shown graphically in Fig. 9. Again, Bus 5 is the critical bus. In conclusion, it can be said that Bus 14 is the critical bus for the IEEE 14-bus test system (without SCs) when the system operates normally (no contingency). In the presence of (N-1) and (N-2) line contingencies, the same bus is the critical bus. With the inclusion of SCs, Bus 5 is the critical bus when the system operates normally (no contingency). In the presence of (N-1) and (N-2) line contingencies, the same bus is the critical bus. Research work in [33] also validates the results which were obtained for the base case. The overall summary of a P-V analysis of the IEEE 14-bus test system regarding critical buses is shown in Table III. Similarly, results were obtained with renewable generation (SCIG, DFIG, PV) integration and are shown in Tables IV-VI.

Recent research [34-36] strongly indicates that voltage stability in power systems is a growing area and in-depth research is required to further expand its horizon, especially with the rising uncertainties in power systems [37-45].

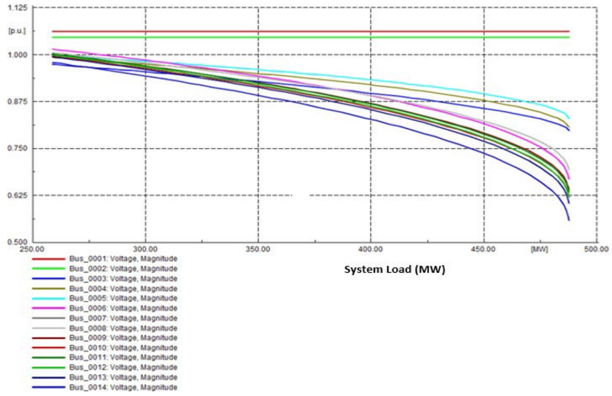

Fig. 2. P-V curves for base case (bus 14 is the critical bus).

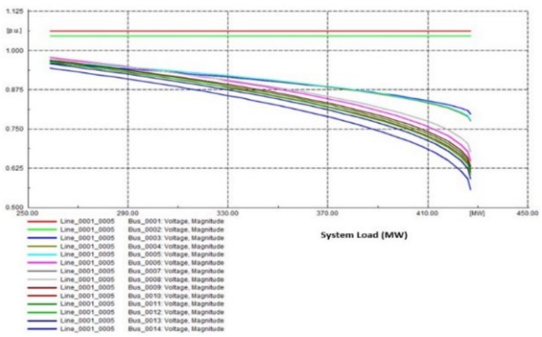

Fig. 3. P-V curves for Line 1-5 contingency (bus 14 is the critical bus).

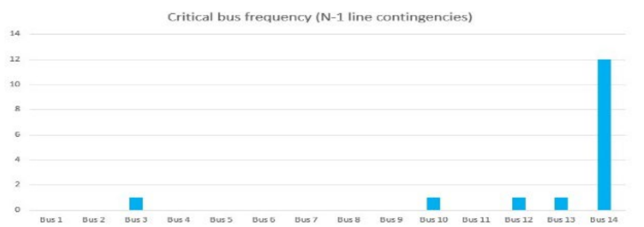

Fig. 4. Bar graph showing that Bus 14 is the critical bus for (N-1) line contingencies.

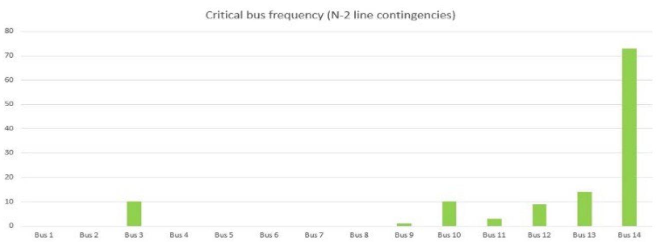

Fig. 5. Bar graph showing that Bus 14 is the critical bus for (N-2) line contingencies.

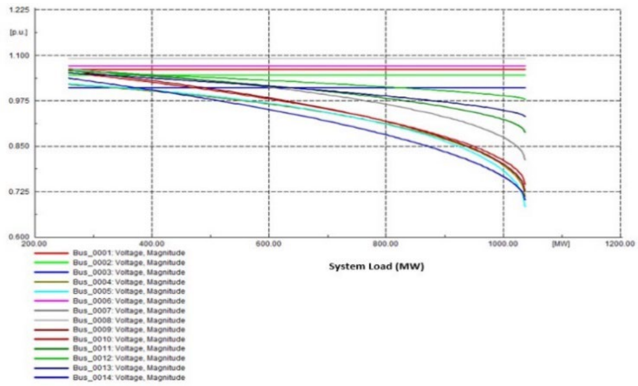

Fig. 6. P-V curves for base case (bus 5 is the critical bus).

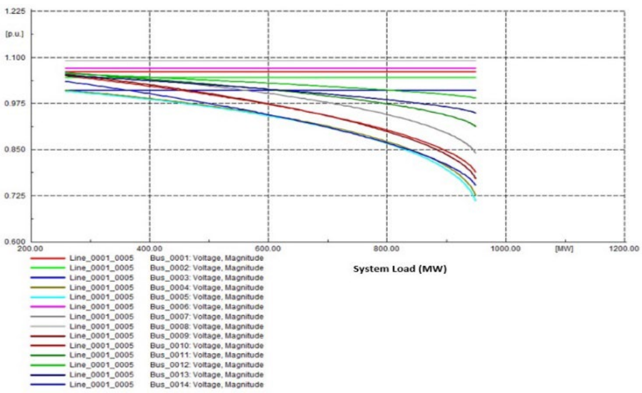

Fig. 7. P-V curves for Line 1-5 contingency (bus 5 is the critical bus).

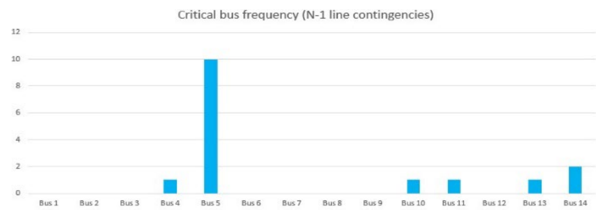

Fig. 8. Bar graph showing that Bus 5 is the critical bus for (N-1) line contingencies.

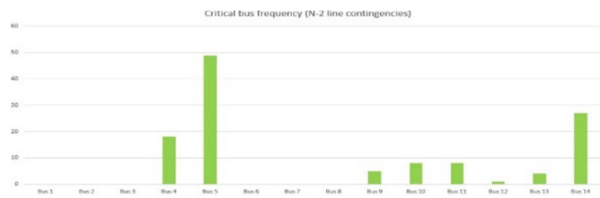

Fig. 9. Bar graph showing that Bus 5 is the critical bus for (N-2) line contingencies.

TABLE I. IDENTIFICATION OF CRITICAL BUSES FOR (N-1) LINE CONTINGENCIES (WITHOUT SCS)

Line Contingency Number	**Line Name**	**Critical Bus**
1	Line_0001_0002/1	14
2	Line_0001_0002/2	14
3	Line_0001_0005	14
4	Line_0002_0003	3
5	Line_0002_0004	14
6	Line_0002_0005	14

7	Line_0003_0004	14
8	Line_0004_0005	14
9	Line_0006_0011	14
10	Line_0006_0012	12
11	Line_0006_0013	13
12	Line_0009_0010	10
13	Line_0009_0014	14
14	Line_0010_0011	14
15	Line_0012_0013	14
16	Line_0013_0014	14

TABLE II. IDENTIFICATION OF CRITICAL BUSES FOR (N-1) LINE CONTINGENCIES (WITH SCs)

Line Contingency Number	Line Number	Critical Bus
1	Line_0001_0002/1	5
2	Line_0001_0002/2	5
3	Line_0001_0005	5
4	Line_0002_0003	4
5	Line_0002_0004	5
6	Line_0002_0005	5
7	Line_0003_0004	5
8	Line_0004_0005	5
9	Line_0006_0011	11
10	Line_0006_0012	5
11	Line_0006_0013	13
12	Line_0009_0010	5
13	Line_0009_0014	14
14	Line_0010_0011	10
15	Line_0012_0013	5
16	Line_0013_0014	14

TABLE III. SUMMARY OF THE P-V ANALYSIS FOR THE IEEE 14-BUS TEST SYSTEM

Case Type	Critical Bus (without SCs)	Critical Bus (with SCs)
Base Case	14	5
(N-1) line contingencies	14	5
(N-2) line contingencies	14	5

TABLE IV. SUMMARY OF THE P-V ANALYSIS FOR THE IEEE 14-BUS TEST SYSTEM (SCIG INTEGRATION)

Case Type	Critical Bus (without SCs)	Critical Bus (with SCs)
Base Case	3	2
(N-1) line contingencies	5	1
(N-2) line contingencies	3	7

TABLE V. SUMMARY OF THE P-V ANALYSIS FOR THE IEEE 14-BUS TEST SYSTEM (DFIG INTEGRATION)

Case Type	Critical Bus (without SCs)	Critical Bus (with SCs)
Base Case	4	11
(N-1) line contingencies	3	2
(N-2) line contingencies	2	6

TABLE VI. SUMMARY OF THE P-V ANALYSIS FOR THE IEEE 14-BUS TEST SYSTEM (PV INTEGRATION)

Case Type	Critical Bus (without SCs)	Critical Bus (with SCs)
Base Case	8	4
(N-1) line contingencies	2	3
(N-2) line contingencies	7	5

VI. CONCLUSION AND FUTURE WORK

Power systems are undergoing, and will continue to undergo, considerable structural transformations. These transformations are driven by changes in the mix and characteristics of electricity generation, changes in load types and demand profiles, emergence of smart grid technologies, new entities (such as microgrids, energy communities, etc.), energy storage technology, and increased use of Flexible AC Transmission System (FACTS) devices and High Voltage DC (HVDC) lines. Considering these transformations, it is critical to assess the voltage stability of the system. Therefore, this paper presented the impact of SCs on static voltage stability analysis for the IEEE 14-bus test system in the presence of both (N-1) and (N-2) line contingencies. The P-V analysis based on the CPF method was used. The critical buses were identified for both cases. In the absence of SCs, it was found that Bus 14 is the critical bus, irrespective of the number of line contingencies (N-1 or N-2). Similarly, it was found that Bus 5 is the critical bus in the presence of SCs, irrespective of the number of line contingencies (N-1 or N-2). Based on this particular test system, it can be deduced that without renewable generation, the number of line contingencies do not impact the location of critical bus; however, the presence of SCs can impact its location. However, inclusion of renewable generation (SCIG, DFIG, PV) can impact the location of critical bus depending on the size and location of renewable generation. The proposed approach to identify critical buses can aid power system planners in timely system maintenance to ensure correct, reliable, and efficient operation of power system.

To enhance the applicability and generalisability of this research, a suitable future direction would be to extend this study to a large-scale real transmission network, which includes generator and transformer contingencies in addition to line contingencies. A comparative analysis for other voltage stability enhancement technologies, such as static VAR compensator (SVC), static synchronous compensator (STATCOM), and unified power flow controller (UPFC), is also another potential area for future research. Artificial intelligence (AI) techniques, including deep learning and extreme learning, can be applied to produce a much faster solution. Uncertainties should accurately be incorporated in all aspects of voltage stability. Suitable probabilistic approaches are required to deal with uncertainties for voltage stability analysis and security assessment. Chance constrained optimization for voltage controls is another future research avenue.

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