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Analyzing Voltage Stability in IEEE 57-Bus System Using Voltage Collapse Proximity Index (VCPI)

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Abstract

The comprehensive study highlights how power systems have evolved over the decades to meet the growing demand for electricity. Increasing energy consumption has made maintaining voltage stability a significant challenge. As a result, voltage stability has become a critical parameter that requires in-depth analysis in modern power systems. This research aims to improve voltage stability analysis in the IEEE 57-bus system using VCPI analysis to identify the weakest buses, enhancing the accuracy of stability assessments and reducing the risk of voltage instability. The proposed methodology utilizes MATLAB software to conduct the power flow analysis, followed by the Voltage Collapse Proximity Index (VCPI) analysis to pinpoint the weakest bus in the 57-bus network. Bus 18 was observed to have the highest VCPI value of 1.0359 pu, signifying it as the weakest bus in the network. It is recommended to apply voltage stability techniques like VCPI for a more comprehensive analysis. Instead of relying on initial values such as voltage magnitude, VCPI provides a reliable measure for assessing the risk of voltage instability, offering valuable insights for future research.

1. Introduction

The study of power systems was conducted for many decades, evolving alongside technological advancement and societal needs. Initially, power system operations focused on generation, transmission, and distribution to meet the basic demand for electricity. However, recent advancements have led to a significant increase in electricity consumption to meet the rising energy demand. With this growing demand, maintaining voltage stability has become a considerable challenge. Hence, voltage stability has become a critical parameter requiring detailed analysis in power systems.

Voltage stability refers to a system's capacity to maintain voltage levels within acceptable limits at all buses, not only under normal conditions but also when subjected to disturbances [1]. This indicates that, during normal operations, the voltage remains stable within acceptable ranges. However, when disturbances occur in the system, the voltage becomes unstable which can result in an uncontrollable decline in voltage levels. Therefore, voltage stability analysis has become crucial in this research area to ensure that power systems can effectively adapt to growing demands.

The IEEE 57-bus system has become recognized as a standard test system for studying voltage stability and power flow analysis, as it represents a medium-sized power grid that is larger than basic test systems such as the IEEE 6-bus and 14-bus systems. The size and the complexity of the IEEE 57-bus system make it ideal for conducting power flow analysis, as it reflects real-world applications even though the system is not as large or complex as actual power grids.

One of the key applications of this test system is identifying the weakest buses in the IEEE 57-bus system. The weakest bus is typically a load bus that is more likely to experience voltage instability. This bus may not be able to operate effectively under high incremental load values [2]. Voltage stability analysis can be conducted using the Voltage Collapse Proximity Index (VCPI), which is one of the key indicators for pinpointing the weakest bus. This bus should be closely monitored in research studies to prevent negative impacts, as failing to address it early could disrupt the stability of the entire system.

The literature highlights the study to demonstrate the effectiveness of VCPI, highlighting it as one of the simplest and fastest methods for predicting these indices [3]. Chaithra et al. (2018) analyzed voltage stability through power flow simulations on the IEEE-14 bus system to assess the effectiveness of the VCPI technique. The analysis identified Bus 6 as the most critical bus, with the highest recorded VCPI value of 0.02987. In contrast, Bus 9 showed the lowest VCPI value at 0.00397, indicating it as the most stable bus, with a value close to zero. The VCPI value varies from 0 to 1. Analysis of the VCPI results shows that values near zero correspond to stable system conditions, whereas values approaching one indicate a critical situation, suggesting the system is close to voltage collapse [4].

This research aims to enhance voltage stability in the IEEE 57-bus system by using VCPI analysis to identify the weakest buses. The goal is to improve the accuracy of voltage stability assessments and reduce the risk of voltage instability in power systems.

2. Methodology

This methodology demonstrates quantitative analysis by applying the IEEE 57-bus test system as a model to perform power flow analysis using MATLAB simulations. The power flow analysis aims to determine the voltage magnitude values at all buses in the system. Subsequently, the VCPI is calculated using a specific equation that utilizes the voltage magnitude results from the power flow analysis to pinpoint the weakest bus in the electric power network. Figure 1 illustrates the detailed research plan, providing a structured workflow for effectively executing the study. The plan outlines the progression from the initial stages to completion, ensuring the achievement of the study's objectives and goals within the intended scope.

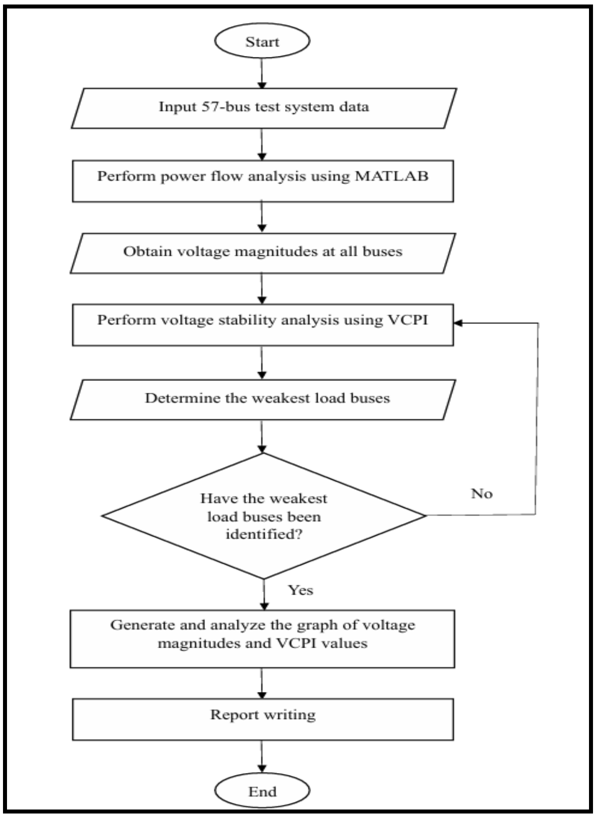

Fig. 1 *Flowchart of the research study*

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2.1 IEEE 57-Bus Test System

The single-line diagram of the IEEE 57-bus standard test system is shown in Figure 2. The test system model was constructed based on this diagram, which outlines the details of the buses, generators, transformers, and transmission lines [5]. Bus 1 is defined as the slack bus in the dataset, while Buses 2, 3, 6, 8, 9, and 12 are marked as generator buses. The other 42 buses are categorized as load buses, responsible for distributing electrical demand throughout the system. The system comprises 17 transformers and 63 transmission lines linked to the buses. Furthermore, as illustrated in the figure, Bus 18 and Bus 25 are interconnected by two transmission lines, designated as Line A and Line B for clarity in the following sections.

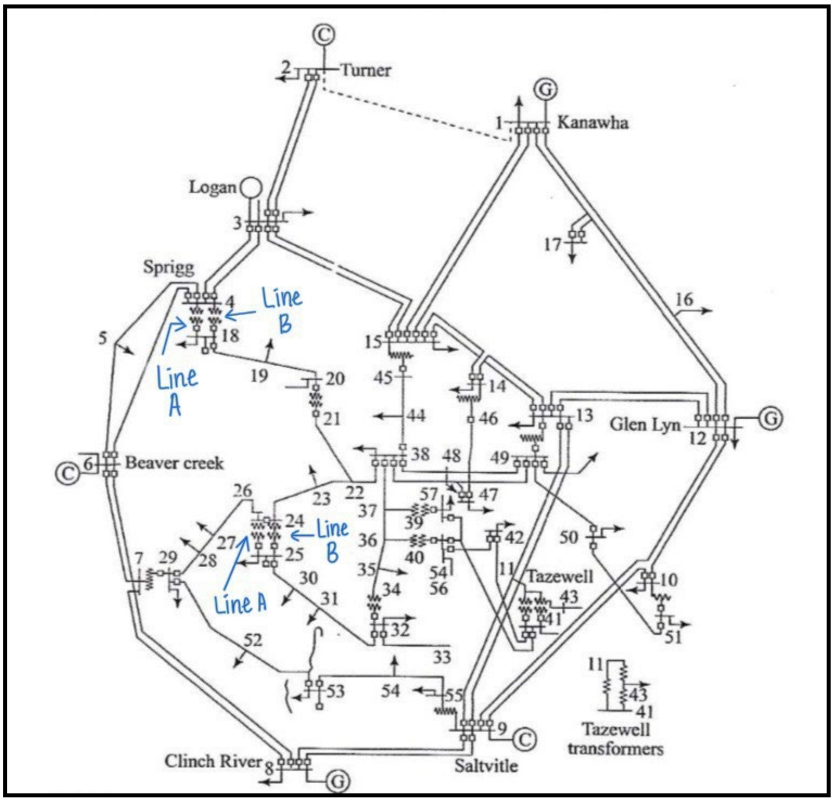

Fig. 2 *Standard IEEE 57-bus test system [6]*

2.2 Power Flow Using the Newton-Raphson Method

The Newton-Raphson method is known for its effectiveness in solving power flow problems efficiently [7]. This technique uses an iterative numerical process to improve approximations of real-valued functions, providing accurate results in power flow analysis. Its fast convergence and high accuracy make it superior to other methods such as Gauss-Seidel and Quasi-Newton, especially when applied to larger or more complex power systems like the 57-bus networks [8].

The process starts with the initialization of system variables, including voltage magnitudes and phase angles for all buses. Power flow equations are then formulated, outlining the initial load condition at each bus by considering both real and reactive power. This specialized method uses the Jacobian matrix, which includes the partial derivatives of the power flow equations. The formula for this matrix is provided in Equation 1 [9]. The partial derivatives indicate how minor voltage changes affect the power at each bus. Once the power mismatches at any bus are determined, the Jacobian matrix modifies the voltages until the power mismatches are reduced to an acceptable level. Finally, the voltage magnitudes and power angles are updated using Equations 2 and 3 [9].

$$\begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} = \begin{bmatrix} J_1 & J_2 \\ J_3 & J_4 \end{bmatrix} \begin{bmatrix} \Delta \delta \\ \Delta V \end{bmatrix} \tag{1}$$

$$V_i^r = V_i^{r+1} \tag{2}$$

$$\delta_i^r = \delta_i^{r+1} \tag{3}$$

Where,
ΔP is defined as the changes in real power at each bus during the iterative process
ΔQ is defined as the changes in reactive power at each bus during the iterative process
$\Delta \delta$ is defined as a power mismatch in the power angle changes
ΔV is defined as a power mismatch in the voltage changes
J_1 - J_4 is defined as the elements of the Jacobian matrix
V_i^r is defined as the updated voltage values
δ_i^r is defined as the updated power angles

2.3 Voltage Collapse Proximity Index (VCPI)

The Voltage Collapse Proximity Index (VCPI) serves as a stability indicator to estimate how close a system is to experiencing voltage collapse [10]. This study demonstrates that, despite voltage levels being within permissible limits, the VCPI indicates potential risks of voltage instability in the network. This indicator was selected for the analysis as it evaluates the stability of each line in the IEEE 57-bus network. The VCPI is computed using the formulas provided in Equations 4 and 5 [10].

$$VCPI\ (Power) = \frac{P_r}{P_{r(max)}} \tag{4}$$

$$VCPI\ (Power) = \frac{Q_r}{Q_{r(max)}} \tag{5}$$

The numerator represents the real or reactive power delivered to the receiving end, while the denominator indicates the maximum real or reactive power transferable through the line. These values can be calculated using Equations 6 and 7 [10], as shown below.

$$P_{r(max)} = \frac{V_s^{\ 2}}{Z_s}\frac{cos\emptyset}{4cos^2((\theta-\emptyset)/2)} \tag{6}$$

$$Q_{r(max)} = \frac{V_s^{\ 2}}{Z_s}\frac{sin\emptyset}{4cos^2((\theta-\emptyset)/2)} \tag{7}$$

Phase angle in Equation 8 [10],

$$\emptyset = tan^{-1}\left(\frac{Q_r}{P_r}\right) \tag{8}$$

Where,
V_s refers to the sending end voltages
Z_s refers to the line impedances
P_r refers to the active power at the receiving end
Q_r refers to reactive power at the receiving end
$\emptyset$ represents the phase angle
θ represents the angle of the line impedance

Figure 3 illustrates the step-by-step process used to perform the VCPI analysis in this study. It outlines how the VCPI is calculated based on system parameters and how the calculated values are used to assess the voltage stability of each line.

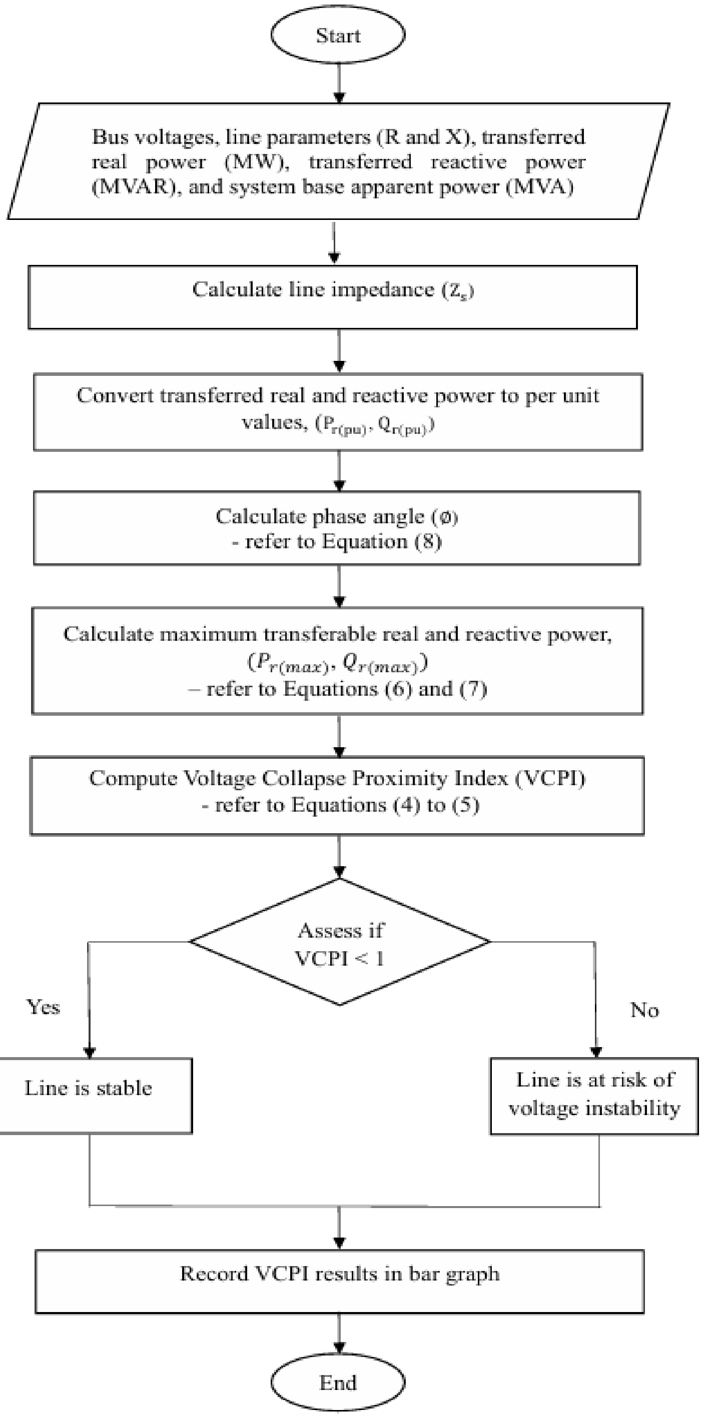

Fig. 3 *Flowchart of the vcpi analysis*

2.4 MATLAB Code

MATLAB is a high-level computational software widely employed in numerous fields for performing matrix-based operations, developing algorithms, and interfacing with other programming languages [11]. The power flow analysis conducted in this study utilized scripts developed based on the Newton-Raphson method [12]. Key parameters, including bus data, line data, impedance values, real and reactive loads, and reactive power limits, were modified to match the standard IEEE 57-bus test system, ensuring the precision of the results. Lastly, the voltage magnitude values at each bus were recorded and will be analyzed.

3. Results and Discussion

The section presents the results of the power flow analysis and VCPI, concentrating on identifying the weakest bus in the 57-bus system.

3.1 Power Flow Analysis

Figure 4 shows the results obtained from the power flow analysis after all the data for the 57-bus system were entered into the MATLAB code, with the output displaying the voltage magnitude values. According to the figure, Bus 31 shows the lowest voltage magnitude of 0.834 pu, along with real and reactive loads of 5.8 MW and 2.9 MVAR. In comparison, Bus 1 reflects the highest voltage magnitude of 1.040 pu, with corresponding loads of 55 MW and 17 MVAR for real and reactive power.

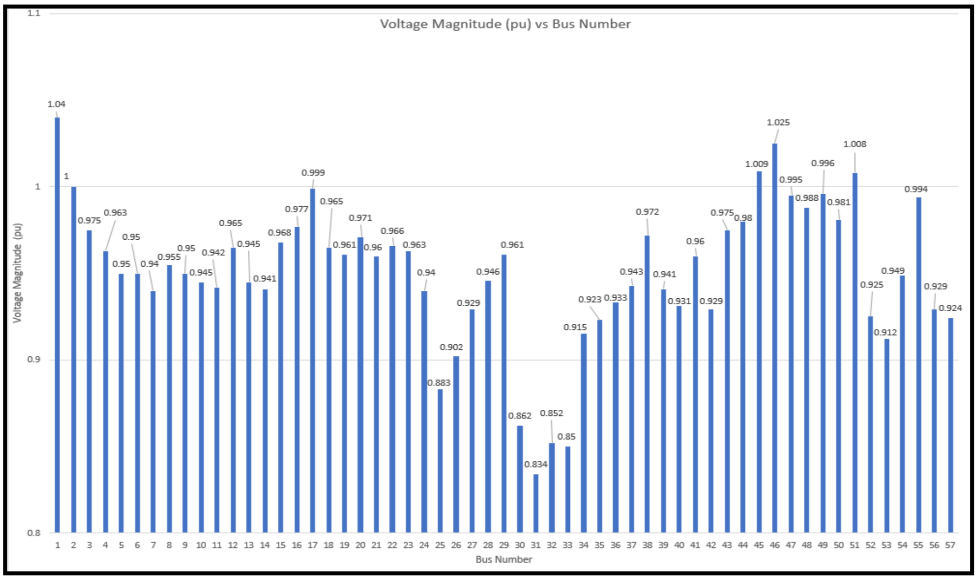

Fig. 4 *Voltage levels across the IEEE 57-bus test system*

For voltage stability in power systems, voltage magnitudes at each bus should be maintained within the range of 0.95 to 1.05 per unit [13][14]. Voltage magnitudes at several buses, including Bus 7, 10, 11, 13, 14, 24, 26, 27, 28, 34, 35, 36, 37, 39, 40, 42, 52, 53, 54, 56, and 57, fall below 0.95 per unit. Conversely, Bus 1, 2, 45, and 51 maintain voltage levels close to unity, indicating that these buses are operating efficiently and maintaining stable conditions within the power system.

However, five buses display voltage magnitudes outside the permissible voltage limits, as illustrated in Figure 5. These are Bus 25 with a voltage magnitude of 0.883 pu, Bus 30 with 0.862 pu, Bus 31 with 0.834 pu, Bus 32 with 0.852 pu, and Bus 33 with 0.850 pu.

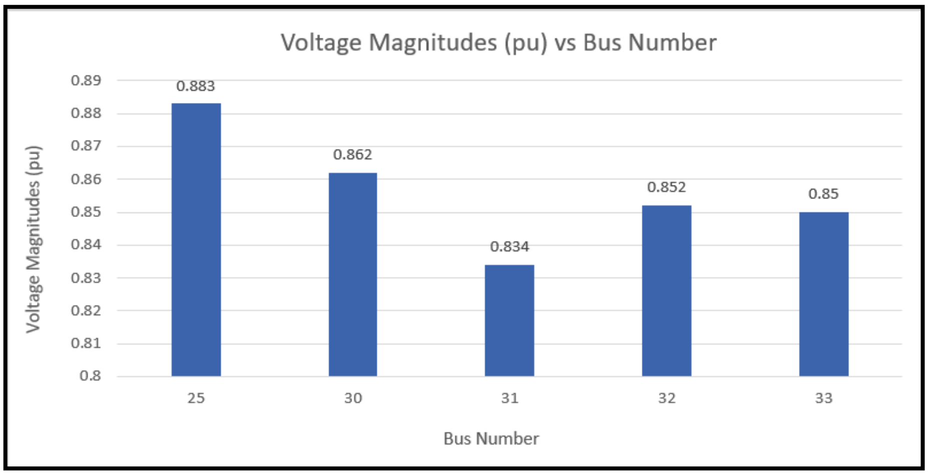

Fig. 5 *Five buses outside the voltage stability standard ranges*

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The reason is that these buses are located farther from the major generation sources and have higher impedance, including both resistance and reactance, as indicated in the IEEE dataset. The increased impedance due to the greater distance from generation sources causes higher voltage drops across the power network, resulting in lower voltage magnitudes at these buses. Moreover, these buses are interconnected with neighboring buses, which means that a bus with a lower voltage magnitude can influence the performance of nearby buses. This occurs because of their connection through transmission lines, where a voltage change in one bus affects the voltage levels of other connected buses through the network. Therefore, instead of concentrating on the voltage magnitude values, the Voltage Collapse Proximity Index (VCPI) will be calculated for all buses. This approach aims to identify the weakest load bus in the system.

3.2 VCPI Analysis

Figure 6 displays the VCPI values, which are computed using the formulas presented in Equations 4 through 8. All values are expressed in per unit. The VCPI analysis focused on the load buses, specifically buses 5, 10, 13, 14, 15, 16, 17, 18, 19, 20, 23, 25, 27, 28, 29, 30, 31, 32, 33, 35, 38, 41, 42, 43, 44, 47, 49, 50, 51, 52, 53, 54, 55, 56, and 57.

Figure 6 reveals that Bus 18, located on the line from Bus 4 to Bus 18 (Line A), has the highest VCPI value of 1.0359 pu among the load buses. Conversely, the lowest VCPI, 0.0077 pu, is observed at Bus 23 on the line between Bus 22 and Bus 23. Bus 18 and Bus 25 are interconnected by two transmission lines, designated as Line A and Line B, as illustrated in the one-line diagram in Section 2.1.

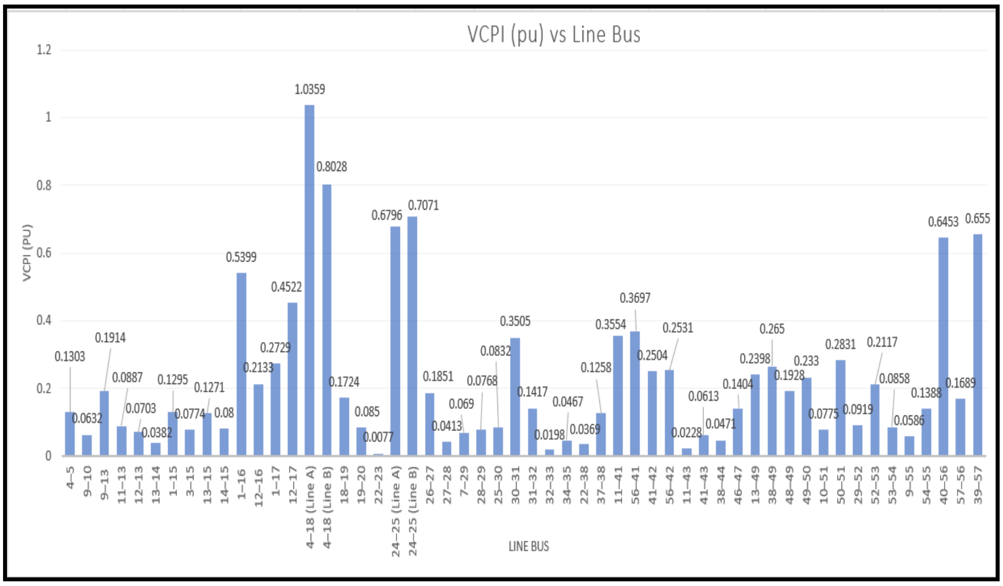

Fig. 6 *VCPI values for all load buses*

Due to its highest VCPI value, Bus 18 is recognized as the system's weakest bus. A higher VCPI value indicates that the system is operating closer to its stability limit, which could lead to voltage collapse as the real and reactive loads increase. Within this context, a VCPI value near zero signifies system stability, while a value close to one indicates a critical condition, suggesting the system is at risk of collapse.

It was observed that initially, five buses had voltage magnitudes outside the permissible limits, as discussed in Section 3.1. Following the VCPI analysis, it was discovered that Bus 18 is experiencing voltage instability, indicated by its higher VCPI value. Although the bus maintains a voltage magnitude of 0.965 pu within the allowable range, the VCPI suggests it is operating under unstable conditions. As observed, the five buses with voltage magnitudes outside the permissible limits do not align with the VCPI results, as voltage instability is not observed in those buses. This difference arises because the result is based on the IEEE 57-bus system data, where the VCPI method offers a different perspective on voltage stability. Therefore, it can be concluded that rather than depending on the voltage magnitude, it is recommended to use voltage stability techniques such as VCPI for a more comprehensive analysis.

4. Conclusion

This research presents a voltage stability analysis of the IEEE 57-bus system using the VCPI method. The study aims to identify the weakest bus in the 57-bus network for monitoring and addressing potential voltage collapse. Voltage collapse can occur rapidly when the load on the weakest bus increases, leading to the failure of the bus to maintain stable operation. The proposed method involves conducting a power flow analysis followed by the application of the VCPI to pinpoint the weakest bus. This approach helps to identify buses prone to voltage instability, enabling more focused attention on these buses. The simulation results show that some buses have voltage magnitudes outside the acceptable limits according to power system standards. However, the VCPI analysis indicates that voltage instability is not occurring in these buses. Instead, another bus, which has a voltage magnitude within the acceptable range is experiencing voltage instability. It can be concluded that Bus 18 is the weakest bus due to its higher VCPI value, and this bus needs to be analyzed and addressed to prevent the instability from spreading to the rest of the system.

As a suggestion for future work in this study, it is recommended to improve the voltage stability at Bus 18 by installing solar photovoltaic (PV) systems. This is because solar PV can help maintain the operation of Bus 18 even when load conditions increase. Furthermore, solar PV is not only capable of supporting the maximum carrying capacity of buses but also plays a crucial role in the transition from traditional energy sources to more environmentally friendly power alternatives. Instances such as reducing greenhouse gas emissions and minimizing energy costs offer additional benefits for future studies.

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Conflict of Interest

Authors declare that there is no conflict of interests regarding the publication of the paper.

Author Contribution

The authors confirm contribution to the paper as follows: ***study conception and design:*** *Nurfaraliyana Samburi, Ahmad Fateh Mohamad Nor*; ***data collection:*** *Nurfaraliyana Samburi*; ***analysis and interpretation of results:*** *Nurfaraliyana Samburi, Ahmad Fateh Mohamad Nor, Suriana Salimin, Nur Ellysa Mu'izz Mohd Zaini*; ***draft manuscript preparation:*** *Nurfaraliyana Samburi, Ahmad Fateh Mohamad Nor, Suriana Salimin, Nur Ellysa Mu'izz Mohd Zaini. All authors reviewed the results and approved the final version of the manuscript.*

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