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Development and Analysis of Voltage Stability Indices for Power System Assessment

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Abstract

In power system transmission, voltage stabilization is critical to maintaining supply quality and developing the reliability of PEs as expected by ever-increasing customers. Voltage failure causes unwelcome concerns for domestic customers, as well as a large cost for owners for the abrupt cessation of operations. To prevent such a calamity, proper forecasting of voltage stability is critical. In this paper, stability indices were improved with a focus on specific applications of voltage collapse proximity with time. The comparison of several index formulation alternatives based on their significance is explicitly described, which will help power system engineers and scholars apply them. The use of measurements to operate, monitor, and manage PES is of the utmost importance in this assessment. There is also an increasing interest in offering measurement-based indices that capture the dynamic properties of the system. Although some efforts have been made to produce an index that considers Thevenin's network impedance at a bus, the assumptions made are incorrect. Finally, the State of the Art offered in this study allows for a glimpse of the most relevant index suggestions, beneficial for assessing stability in electrical power system research

Keywords- Voltage Stability, Newton Rapson Method, Jacobian Matrix.

Introduction

The current electric power system is under a lot of stress because the need for electricity is growing so quickly and there aren't any plans to upgrade or add to the grid's infrastructure, like generating units and transmission lines. This is because of problems with "operations, finances, and planning. The quickly fluctuating demand for electric power raises the possibility of voltage collapse in an EPSN, which results in the cutoff of some loads or lines by the protective mechanisms. There are occasions when the protective mechanisms in the system incorrectly classify the voltage collapse as a short circuit, which results in the system experiencing large-scale outages with the generation units, lines, and loads. Additionally, the prevalence of renewable energy sources is growing, which makes the power-flow changes much worse. In this case, the system might go through big changes, especially if the line in the network is too sensitive or if a big source is cut off from the service. To give it an example, a sensitive line interruption, like one that ties a big generator to the system, can cause an imbalance between the load and the generation. As a result of a line outage, the power flow redistributes the power to other lines, which causes other lines to become overloaded and may result in cascaded outages". In a chain reaction, the sudden power outages lead to cascading power outages throughout the system, which ultimately results in the grid going completely dark. The rapid appearance of a voltage collapse might result in the fragmentation of a portion of the In order to comprehend the reasons behind these failures, it is essential to take into consideration the fact that modern power systems are required to function at a higher level of intensity than in the past. There is a demand for power that is constantly growing, and in the not-too-distant future, we can anticipate an even greater increase in this demand due to the proliferation of electric vehicles. At the same time, transmission networks are not expanded due to economic and environmental issues, and only a small number of lines are installed. In addition, the increasing utilization of renewable energy sources has a tendency to increase the stress levels of the networks. This is because these sources exhibit a higher degree of dynamic and unpredictable behavior.

Voltage Stability and Factors

One of the most common and widely accepted definitions of voltage stability is a power system's capacity to maintain a constant acceptable voltage at all buses in the system under normal operating conditions and after being subjected to a disturbance. Voltage stability is described as the system's voltage being stable. When a disturbance, an increase in load demand, or a change in system conditions causes a progressive and unpredictable decrease in voltage, the system is said to be in a state of voltage instability [2]. Maintaining or reestablishing equilibrium between load demand and load supply delivered by the power system is crucial for voltage stability.

1. Factors Affecting Voltage Stability

Load characteristics are the primary and highly influential variables that have a strong impact. If the load increases at a rate that exceeds the maximum power capacity of the system, the voltage may become unstable. For instance, the primary asynchronous motor has a substantial influence on the voltage stability of loads, irrespective of their magnitude. The reactive power consumed by an asynchronous motor will diminish in direct proportion to the reduction in the system's voltage. The drop in voltage will exacerbate the severity of the reactive power absorbed by an asynchronous motor, hence intensifying the voltage instability. Dynamic characteristics consider a greater number of parameters compared to static characteristics since the load static characteristic ZIP model has a different impact on voltage stability.

1. The power grid's capacity to transfer power, including infrastructure, features, and operational methods, among other aspects.
2. Voltage stability devices include control, reactive power compensation, generators, safety equipment, transformer tap adjustment, and onload tap changers. When these interactions occur at the right time, they have a major impact on voltage stability.

3. Other factors can impact voltage stability, and the following situations can exacerbate the problem.

4. The distance between the load centre and energy foundation is too far. This leads in the transmission of electrical power over large distances. Furthermore, the transmission power of the transmission lines, combined with the increasing reactance, will cause a segment of the lines to become overloaded, progressively causing the line to trip and, in severe situations, resulting in voltage collapse.

5. In recent years, smaller power plants have been replaced with larger ones with higher capacity. This has increased the unit's synchronous responsiveness while decreasing its inertial time constant. The rise in generator synchronous reactance reduces the power limit of the transmission lines, which leads to stability difficulties.

6. Transmission lines gradually expand in capacity due to increased loads and long distances between power generation and load. In this situation, if lines are destroyed as a result of an accident, there will be considerable power vacancies at both the transmitting and receiving ends, posing a significant risk to the system's power stability.

7. Increasing the number of transmission lines increases the risk of recurring failures. Voltage instability and voltage collapse issues are also prevalent in household use, however they are not as problematic.

Problem Formulation for Voltage Stability Index

It simplifies the Newton-Raphson method by decoupling the active and reactive power calculations, leveraging the weak coupling between voltage magnitudes and angles in most practical power systems.

$$\Delta Pi = Pdi - Pgi - \sum_{j=1}^{n} V_i, V_j\,(G_{IJ}\cos(\theta i - \theta j) + B_{IJ}\sin(\theta i - \theta j) \quad \textbf{(1)}$$

$$\Delta Qi = Qdi - Qgi - \sum_{j=1}^{n} V_i, V_j\,(G_{IJ}\sin(\theta i - \theta j) + B_{IJ}\cos(\theta i - \theta j)) \quad \textbf{(2)}$$

Where:

- **P_i and Q_i are the active and reactive power injections at bus i_i.**
- **V_i and V_j are the voltage magnitudes at buses i and j.**
- **$\theta_{ij}=\theta_i-\theta_j$ is the voltage angle difference between buses i_i and j_j.**
- **G_{ij} and B_{ij} are the conductance and susceptance between buses i_i and j_j.**

Jacobian Matrix

In the Newton-Raphson method, the power flow equations are linearized using the Jacobian matrix J which relates the changes in power **injections (ΔP, ΔQ) to changes** in voltage magnitudes (ΔV) and angles ($\Delta\theta$)

$$\begin{bmatrix}\Delta P\\ \Delta Q\end{bmatrix} = J\begin{bmatrix}\Delta\theta\\ \Delta V\end{bmatrix} \quad (3)$$

2. Newton Rapson Method

The Newton-Raphson load flow analysis is a numerical technique used to solve the power flow equations that describe the balance of real and reactive power in an electrical power system. The Newton-Raphson method is an “iterative approach that starts with an initial guess of the voltage magnitudes and phase angles at each bus in the system and then iteratively refines these values until the power flow equations are satisfied.

The power flow equations are a set of nonlinear equations that relate the voltage magnitudes and phase angles at each bus in the system to the real and reactive power injections and consumptions at each bus. The power flow equations are typically expressed in polar coordinates, with the voltage magnitude and phase angle at each bus represented as a complex number.

The Newton-Raphson algorithm operates through the linearization of power flow equations by means of the Jacobian matrix. This matrix comprises partial derivatives of the power flow equations concerning voltage levels and phase angles at every bus. Subsequently, the linearized calculations are solved through matrix algebra to derive a revision for the voltage magnitudes and phase angles at every bus.[48]

The Newton-Raphson method is a numerical iterative technique used to solve non-linear equations. It is widely used for load flow analysis in power systems". The basic formula for the Newton-Raphson method is as follows:

Step 1: Initialize the bus voltage magnitudes and angles
Step 2: Compute the admittance matrix Y_{bus}
Step 3: Set the iteration counter k = 0
Step 4: Compute the power mismatch vector ΔP and ΔQ
Step 5: Compute the Jacobian matrix J
Step 6: Solve for the correction vector ΔV using the equation JΔV = -[ΔP; ΔQ]
Step 7: Update the bus voltage magnitude and angle using the correction vector ΔV
Step 8: Check for convergence using the maximum power mismatch and tolerance value
Step 9: If convergence is achieved, terminate the algorithm. Otherwise, increment k and go back to step 4.
The Jacobian matrix J is given by:

$$J = [\partial \Delta P/\partial |V| \ \partial \Delta P/\partial \theta \ ; \ \partial \Delta Q/\partial |V| \ \partial \Delta Q/\partial \theta] \quad (4)$$

Where,

- $\partial\Delta P/\partial|V|$ is the partial derivative of active power mismatch with respect to voltage magnitude,
- $\partial\Delta P/\partial\theta$ is the partial derivative of active power mismatch with respect to voltage angle,
- $\partial\Delta Q/\partial|V|$ is the partial derivative of reactive power mismatch with respect to voltage magnitude, and
- $\partial\Delta Q/\partial\theta$ is the partial derivative of reactive power mismatch with respect to voltage angle.

The correction vector ΔV is given by:

$\Delta V = [\Delta|V|; \Delta\theta]$…………………………………………………………………………..(5)

where,

$\Delta|V|$ is the correction in voltage magnitude, and

$\Delta\theta$ is the correction in voltage angle.

Simulation Result

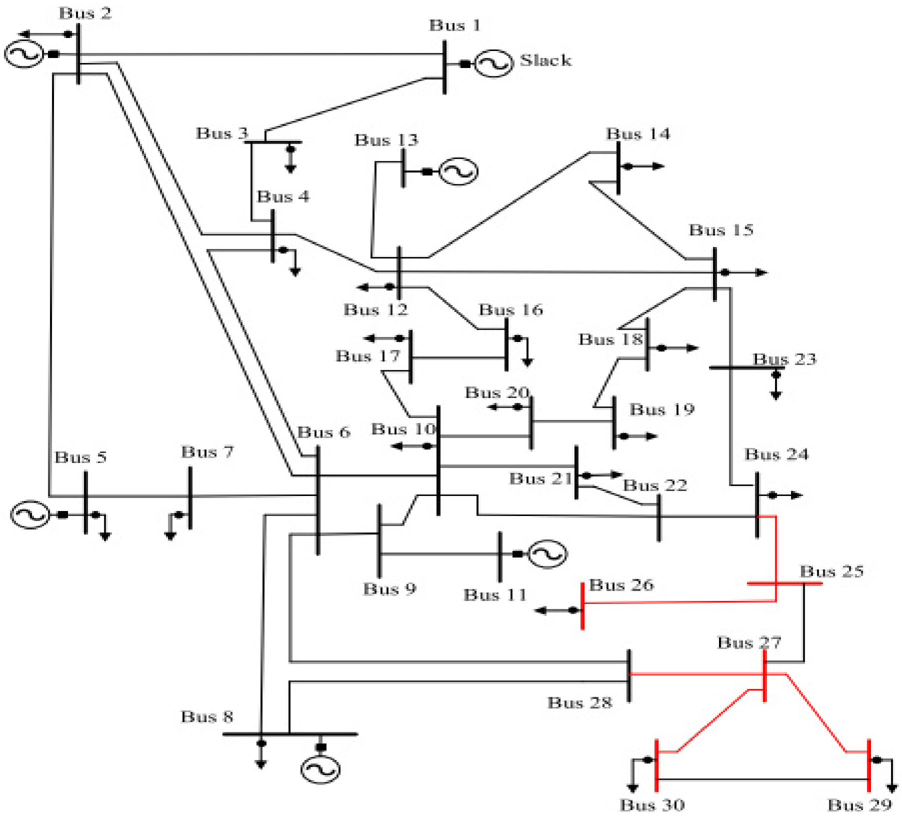

Fig. 1: Bus Test System Single Line Diagram of IEEE 30 [6]

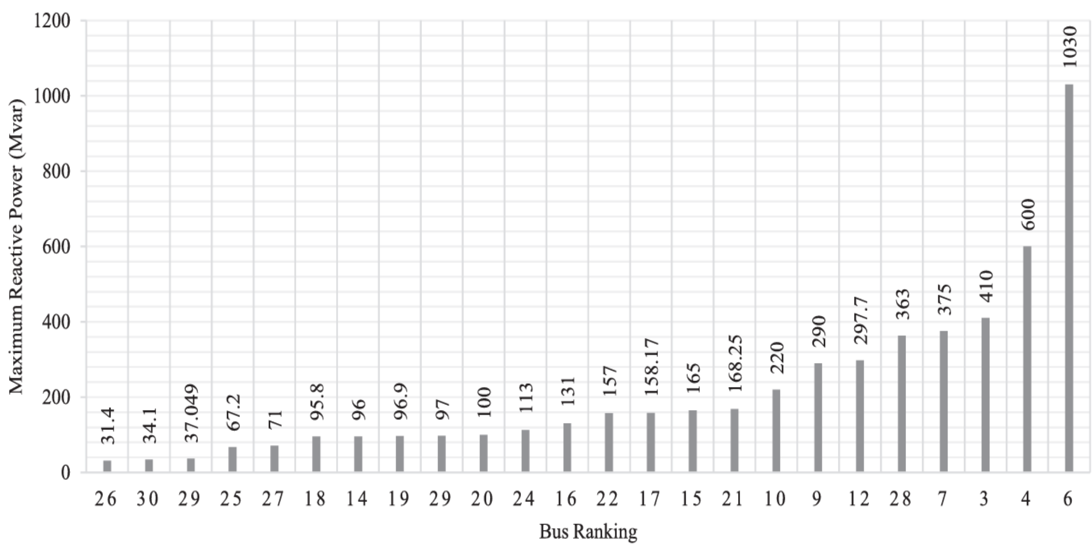

Fig. 2: IEEE-30-Bus System with Maximum Permissible Reactive Load

The Fig. 2 shows "the maximum permissible reactive power load at each load bus in the IEEE 30-bus system.

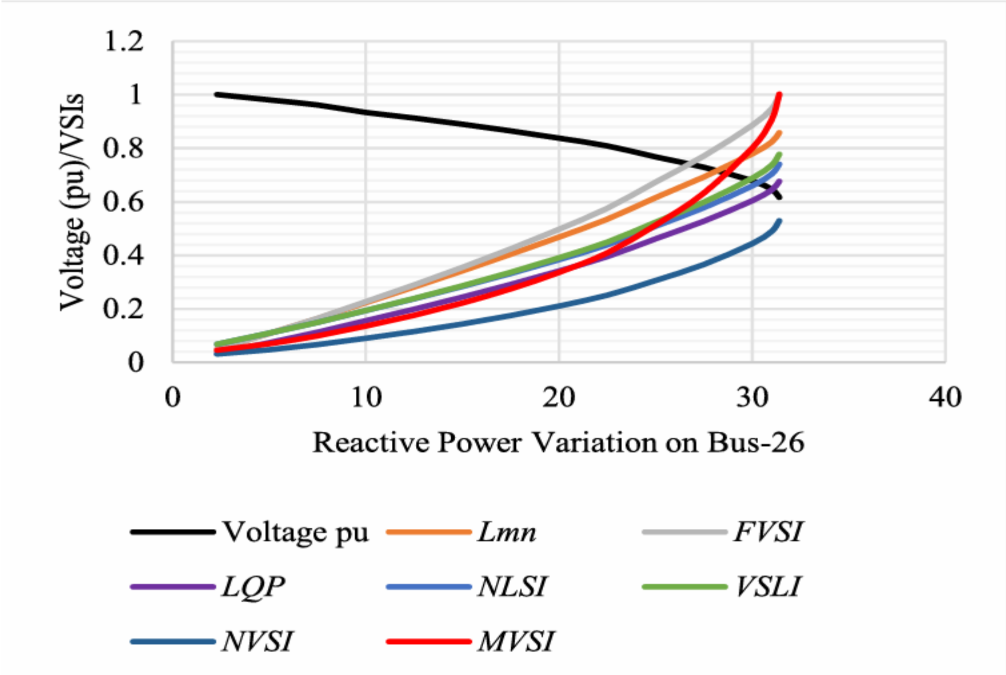

Fig. 3: Reactive Power variation on Bus-26

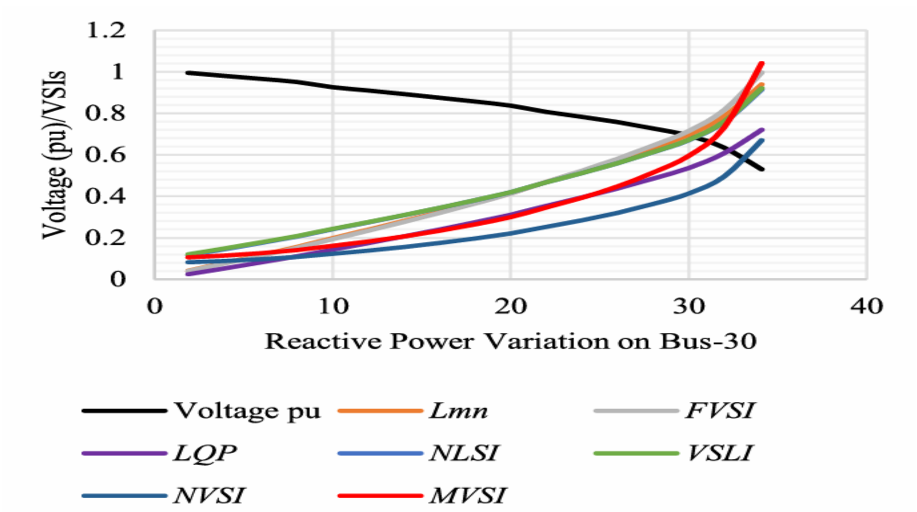

Fig. 4: Reactive Power Variation on Bus-30

Figures 3 and 4 depict the “voltage magnitude and voltage stability indicators (Lmn, FVSI, LQP, VSLI, NLSI, NVSI, and MVSI) in relation to the changes in reactive power for buses 26 and 30. It demonstrates that the proposed index exhibits significantly greater responsiveness compared to other indices when the reactive power variation surpasses 70% of the maximum load-ability.

The NLSI (Normalised Load Sensitivity Index) and VSLI (Voltage Sensitivity Load Index) have values much below 1 due to the substantial amount of reactive power being injected at bus-26. The values are close to one because of the significant reactive power being supplied at bus-30. Any additional rise in load on these buses leads to the divergence of power-flow solutions, suggesting that the load has hit the threshold level and is nearing the critical voltage point.

The comparative results of the newly proposed index (MVSI) and the existing VSIs (Lmn, FVSI, LQP, NLSI, and NVSI) under base case loading conditionsas a bar chart. The system's stability is evidenced by the bar chart, which indicates that all indicator values are in close proximity to zero”. A system is considered to be in a stable condition (unity) when there is no stability indicator value approaching the stability limit.

The figure 5 shows how the stability index (NVSI) and the new planned index (MVSI) differ significantly. When the line resistance value is zero, the MVSI and NVSI measurements are equivalent. Conversely, the following subsection illustrates the case of heavy loads, when the error rate between the indices is relatively high.

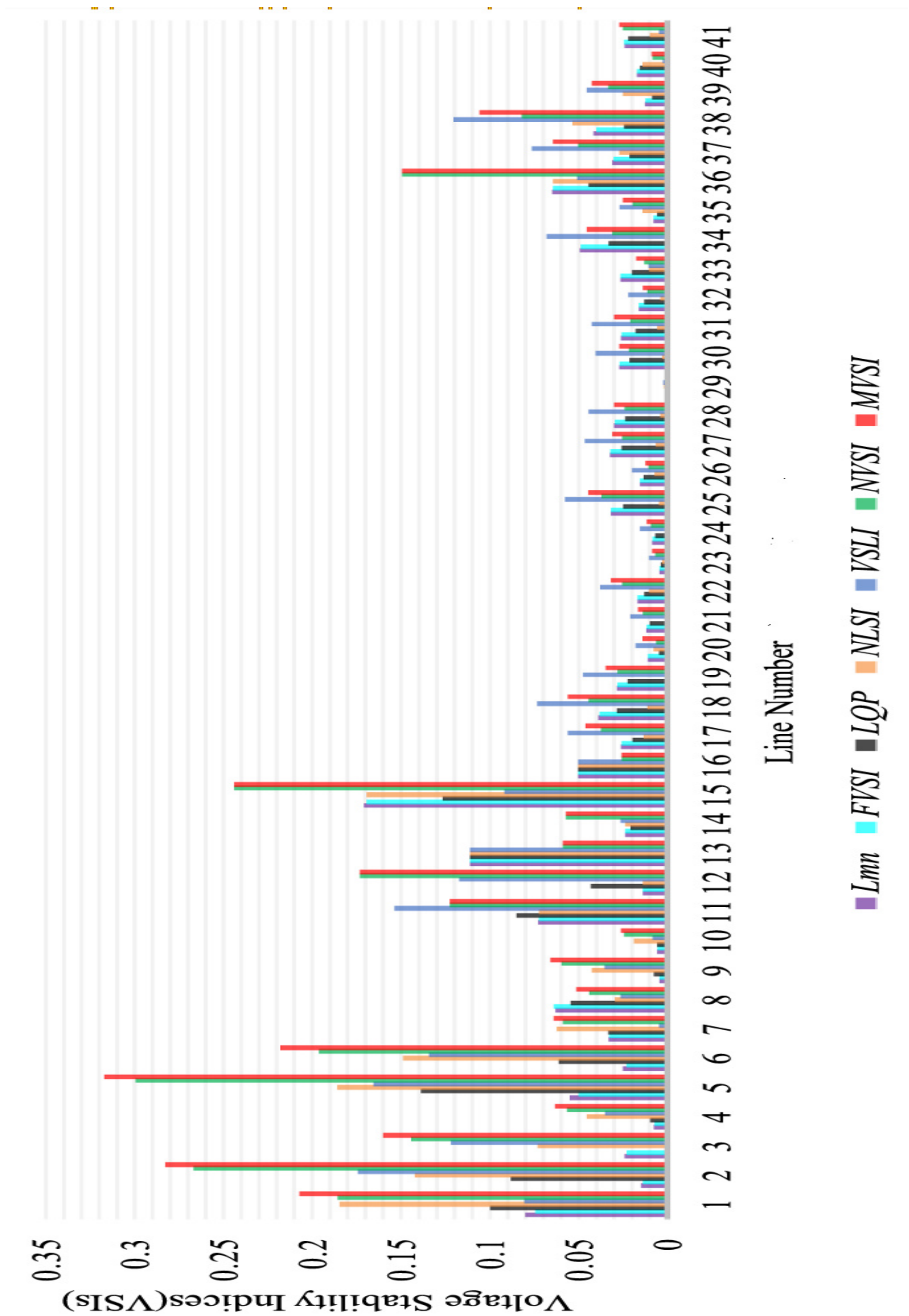

Fig. 5: Different VSIs of Lines at the Base Load Condition

Conclusion

The application of the modern voltage stability index (VSI), which incorporates massive active and reactive power inputs, provides a robust method for identifying and mitigating potential voltage instability in power systems. By calculating the VSI for each bus and line, this approach effectively ranks bus numbers based on their stability indices, pinpointing the weakest buses and the most critical lines susceptible to voltage collapse. The proactive identification of these critical components allows for targeted interventions, such as load shedding and reactive power compensation, to enhance the overall stability and reliability of the power grid. The methodology's application to the IEEE 30 bus test system highlights its accuracy and efficiency, making it an invaluable tool for optimizing load-ability and maintaining system stability in real-world scenarios. Through this approach, power system operators can ensure more resilient and reliable grid performance, capable of withstanding varying load conditions and preventing potential blackouts.

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