Voltage Stability Analysis in Renewable Energy Dominated Power Systems: A Review

Brighton Ombuki, Roy Orenge and Ariel Mutegi

***Abstract*—**In the past decade, power systems across the world have witnessed a trend of increased penetration in renewable energy systems. This proliferation has been caused by the significant global commitment to achieve a net-zero electricity sector and the need to adopt sustainable energy systems. Due the distinct generation characteristics of renewable energy systems, their proliferation has brought about new technical challenges in the stability and operation of power systems. One of the major challenges that gained prominence is voltage instability. Voltage instability stems from the inability of a power system to maintain its reactive power balance; either through inadequate reactive power generation or transmission lines failing to transmit the necessary amount of reactive power. In this paper a review of voltage stability analysis techniques that can be employed in renewable energy dominated power systems is provided with their strengths and weakness. This paper aims to present a guide for voltage stability studies which should find application among power system practitioners and those interested in the voltage stability phenomenon.

***Keywords*—**Renewable Energy, Voltage Stability, Voltage Stability Indices, Power System Stability

I. Introduction

Power systems are complex and non-linear 'machines' whose purpose is to facilitate an adequate and reliable supply of electricity to end-use sectors. This secure operation is only achieved through efficient planning and operation in all key aspects at the generation, transmission and distribution stages. In the past few decades, renewable energy technologies have become one of the major generation components in electrical networks. According to the International Energy Agency (IEA), the installed renewable energy capacity globally is forecast to reach more than 4800GW by 2026, representing an approximated 60% increase from installed capacity at the end of 2020. Renewables will represent over 80% of the new power capacity installed globally from now until then, and the figure is expected to increase further [1]. Presently, variable renewable energy sources (VREs) are the fastest growing and account for more than 50% of the total installed renewables capacity in the world annually [2], [3] . Variable renewable energy generation refers to the generation resources whose output is not completely controllable by transmission system operators. Wind and solar power generation are the predominant variable renewable energy sources currently in the world. These VREs differ in various aspects from conventional generation sources; the key aspects being their generation output and their asynchronous nature [4]. These aspects have brought, and are expected to bring about new technical challenges in the secure operation of power systems.

According to the Institution of Electrical and Electronics Engineers (IEEE) and the international council of Large Electric Systems (CIGRE), voltage stability is the ability of a power system to maintain recommended voltages in some or all the buses under normal operating conditions and after being subjected to disturbances [5]. It is a problem driven by the loading dynamics in stressed systems that usually arises when a power system is unable to generate the required reactive power, and/or transmission lines fail to transmit the same [6]. Voltage instability has been responsible for some of the major network collapses in the world since 1965 [7], [8]. These incidents resulted in significant economic losses and adverse social effects [7]. In light of the above, there has been a growing interest among power system practitioners to understand the voltage stability phenomenon.

II. Variable Renewable Energy Generation and Voltage Stability

A power network is said to be stable if it can regain its equilibrium after having been subjected to disturbances [5]. In the event of disturbances such as faults in lines, or loss of generation, a disruption in the flow of active and reactive power in the network can occur. This can cause the voltages to vary beyond recommended limits leading to brownouts and possibly subsequent blackouts. In the context of voltage stability, most grid-tied wind turbine and solar PV technologies are connected directly to the grid via stators and power electronic converters. As a result, they are sensitive to grid disturbances. Without correct settings in their fault ride-through (FRT) capabilities, protection mechanisms can disconnect them from the grid. In networks where there is significant penetration of centralized variable renewable generation, these disconnections can lead to imbalances in the generation and demand of active and reactive power. If such networks have deficiencies in fast response spinning reserves, they can experience large frequency and voltage drops resulting in blackouts. An example of such a scenario was the 2016 South Australian blackout [9]. In such

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events, literature has shown dispersed large-scale VREs can help power systems avoid such scenarios and improve system voltage stability [10], [11]. Similarly, the unpredictability and variability of the variable renewable energy sources over different time frames to electricity demand can cause unprecedented drops in the amount of power generated. This can also result in significant voltage stability problems.

Since most VREs are asynchronous, without appropriate control techniques, they can also cause voltage instability. Consider the case of fixed-speed wind turbines with squirrel cage induction generators (type 1 wind turbines), unlike conventional synchronous generators, only active power can be controlled. They heavily rely on the grid to control the output voltage. The more active power they produce, the more reactive power they absorb from the grid. In stressed grids with minimum reactive power support, increased penetration of type 1 wind turbines without adequate compensation can result in voltage sags at the generator output terminals and even voltage sags in the grid. The authors in [12] have shown that the increased penetration of squirrel cage induction generator-based wind systems without reactive power compensation diminishes the loadability limits of a power system. The advanced doubly-fed induction generator (DFIG) wind system offers the advantage of separate active and reactive power control courtesy of power electronic converters [13]. Because of this characteristic, when controlled properly and at appropriate levels of penetration, DFIGs can improve the voltage stability of power systems as in [14]. Some DFIGs can also be used to provide ancillary services by providing reactive power even when no real power is generated [13]. Solar PV systems on the other hand are connected to the grid through inverters. These inverters cannot provide a large amount of inertia to the grid, secondly, even though they are capable of providing reactive power support to a network, this ability is quite limited by the inverter-rated current and the voltage at the point of common coupling. This limited reactive power capability can have a significant impact on the voltage stability of a power network. This limitation can be overcome by the use of large-capacity inverters and reactive power sources at extra costs or real power curtailment at the expense of reactive power [10], [15]. Similar to wind generation technologies, studies on solar photovoltaic integration have indicated that at appropriate penetration levels small-scale PV integration improves power transfer in a system and can positively impact voltage stability [16]. In [17], the impact of high penetration of photovoltaic systems on large interconnected systems was investigated using a portion of the Western U.S interconnection. It was observed that as the level of PV penetration increased beyond 20%, the steady state voltages of the buses increased, causing overvoltages in some buses within the study area. It was also observed that as PV penetration levels increased, disturbances or sudden loss in PV generation in the network resulted in greater voltage dips and sustained rotor angle oscillations of neighbouring synchronous generators. In general, most research has shown that large-scale VREs integration can have both beneficial and detrimental effects depending on their size and where they are located.

III. Voltage Stability Analysis in Renewable Energy Dominated Power Systems – Recent Trends

The deployment of renewable energy sources including VREs is one of the major levers in the quest to achieve a net-zero electricity sector. It is also clear that power system voltage stability is one of the major issues affected by the deployment of renewable energy technologies. Consequently, several studies have been conducted in the recent past focused on renewable energy technologies and power system voltage stability, all aimed at enriching the current knowledge base in the field of renewable energy and power system stability.

In [18] the authors proposed a global sensitivity analysis (GSA) method for power system voltage stability evaluation. The proposed GSA method was developed to perform a priority ranking of renewable energy variabilities that can affect loading margins and was tested on the IEEE 9 and 118 bus systems. The GSA method was shown to offer improved accuracy compared to the local sensitivity analysis method. In [19], an analysis of the voltage stability of power grids with high penetration of solar photovoltaic whilst considering its intermittency and the uncertainties associated with load demand was conducted on the IEEE 14 and 30 bus test systems. In this work, a methodology for voltage stability analysis using Monte Carlo simulation and QV-based modal analysis was employed. The results provided insights as to how the critical eigenvalues of a network vary over daytime hours with respect to changes in the level of PV penetration and solar irradiance. The impact of stochastic load and renewable generation uncertainty on the dynamic voltage stability margin of power systems was studied in [20]. The authors incorporated the stochastic trajectories describing the uncertainty of load, wind and solar generation in an IEEE 39 bus system and used Monte Carlo simulations to compute its stochastic loading margins. It was observed that the volatile nature of both demand and renewable energy generation can lead to a decrease in the size of the dynamic loading margin.

Beyond quantifying the effects of the uncertainties associated with renewable generation on the voltage stability of power systems, other works have focused on the impacts of variable renewable energy technologies on the short-term and long-term voltage stability of power systems. For instance, in [21] and [22], the long-term and short-term voltage stability of power systems with increased PV penetration was investigated. In the former, time domain simulations and dynamic QV curves were used to determine the performance of solar PV systems when compared to synchronous generators in mitigating long-term voltage stability. The results showed that oversized inverters with improved reactive power gain performed better than stressed synchronous generators. In the latter, it was observed that installation of photovoltaic power plants has significant impacts on the short-term voltage stability of power systems if they are disconnected from a system after a voltage sag and their fault-ride through capabilities to return to specified power outputs is low.

The use of renewable energy technologies as a means of improving the voltage stability of electrical networks has also been studied in the recent past. An index, – the critical voltage reactive power ratio (CVQR) index was developed in [11] and was used in tandem with bus loading margins to assess the viability of utility-scale solar PV plants in enhancing the voltage stability of weak national grids, taking a case study of the Nigerian transmission network. The results showed that when the reactive power capability of the solar PV systems was considered, they offered better performance in mitigating the overvoltages in the network as compared to shunt reactors. A smart inverter – PV STATCOM was proposed in [23] where a photovoltaic inverter could be controlled as a dynamic reactive power compensator during critical system needs on a 24/7 basis. The proposed smart inverter was found to successfully regulate the voltage at the point of common coupling to within utility acceptable ranges during the low voltage ride-through period. The authors in [24] investigated the stability improvement of power systems connected with DFIG and SCIG wind energy conversion systems (WECS) using the voltage stability index. The results showed that; (i) a static synchronous series compensator (SSSC) enhanced the performance of the SCIG and DFIGs, and (ii) the combined use of both types of wind conversion technologies coupled with the SSSC controller offered the best performance. In [25], the voltage stability of the IEEE 14 bus test system with grid-connected wind farms was conducted using PV curves and QV modal analysis. The performance of a static VAR compensator (SVC) and a static synchronous compensator was also evaluated during normal and disturbance conditions. The results showed that both devices improved the loadability limits of the system, with the STATCOM offering better voltage stability improvement.

Recent literature shows there is an increasing interest in the area of voltage stability and renewable energy technologies predominantly focusing on three key areas i.e., the impacts of the intermittencies associated with variable renewable energy generation, the performance of the variable renewable energy technologies in maintaining grid voltage stability during and after disturbances and the application of these renewable energy technologies in improving the voltage stability of transmission networks. At the same time, a lot of work has delved into the development of voltage stability indices. As a result, over 50 VSIs are available in open literature [26], [27] whose general classification and guide for use is yet to be clearly defined [28]. Therefore, to effectively contribute to this growing body of literature and innovate solutions to existing voltage stability challenges, it is becoming imperative for power system practitioners to understand the indices used in voltage stability analysis, and how to best approach voltage stability studies.

VOLTAGE STABLITY INDICES

There are two main approaches for voltage stability analysis in electric power systems with either conventional or renewable energy generation. These are the static and dynamic approaches. Static voltage stability analysis is used to determine the elements contributing to voltage instability in a network and the proximity of the network or these elements to voltage instability whereas dynamic voltage instability is the approach used by researchers when trying to understand the sequence of events leading to voltage instability [29]. All voltage stability analysis methods are developed by analysing the characteristics of the voltage collapse point [30]. There are different stability indices employed in dynamic and static voltage stability analysis.

A. Dynamic Voltage Stability Indices

Voltage stability analysis of electrical power systems is essentially a dynamic problem. The dynamic mechanism of voltage instability is studied by considering the dynamic effect of generators and their regulating systems, the effect of tap-changing transformers, load types, and other dynamics in the system. The analysis of the dynamic effect of these components helps researchers understand and explain the events that occur in a network before the voltage critical point of a network is reached. The primary indices that have been developed for these studies are time domain simulations, bifurcation analysis and the energy function method.

1) Time Domain Simulations

Voltage instability in power systems can range from a few seconds to several minutes, therefore time-domain simulations are considered to be the most powerful methods currently in literature for investigating the dynamic process of voltage instability. Effective time domain simulations should take into account the impact of time-varying components and discrete and continuous controls in a power system. For instance, in [31] the authors have employed the use of time domain simulations to investigate the dynamic voltage stability of an upgraded Nordic32 test system and the modified IEEE reliability voltage stability (RVS) test system. In the simulations, the effects of automatic load tap-changer transformers, generator over excitation limiters, and discrete controls that are usually triggered during voltage decline in a system such as the automatic switching of shunt compensation are considered to illustrate their response to a large disturbance, impacts on the secure operating points and the maximum loadability limits of the test systems. The effects of corrective control of system integrity protection schemes are also investigated. The main difficulties in time domain simulations arise in the choice of load models. Different load models can yield different results and conclusions during studies.

2) Bifurcation Analysis

The bifurcation method for voltage stability analysis is based on bifurcation theory which states that dynamical systems experience sudden changes in ‘qualitative’ or topological changes in their behaviours due to slow smooth changes in their parameter values. In dynamic voltage stability analysis, the dynamic properties of components and controls are varied to predict how a power system becomes voltage unstable. At the bifurcation point, any system parameter changes lead to instability [29], [32] and [33]. There are many types of bifurcation, and they are correlated with power flow solutions failing to converge. Bifurcation analysis in voltage stability can also be related to static voltage stability to a certain extent. Consider the bifurcation theory diagram in Fig. 1; since it is similar to PV and QV curves, the voltage collapse point of a bus can be predicted by identifying parameter values (load) that lead to the bifurcation point [32]. The authors in [34] investigated the influence of grid connected front-end wind-controlled wind turbines (FSCWT) on power system voltage stability. In particular, they used bifurcation theory and time domain simulations to determine the influence of reactive power variations and wind speed fluctuations on the grid's voltage stability. The major findings were that with a gradual increase in wind speed, the reactive power capacity of the grid connected FSCWTs decreased. In [35] saddle-node bifurcation theory was applied to PV curves to determine the effect of FACTS devices – STATCOM and UPFC controllers on power system voltage stability.

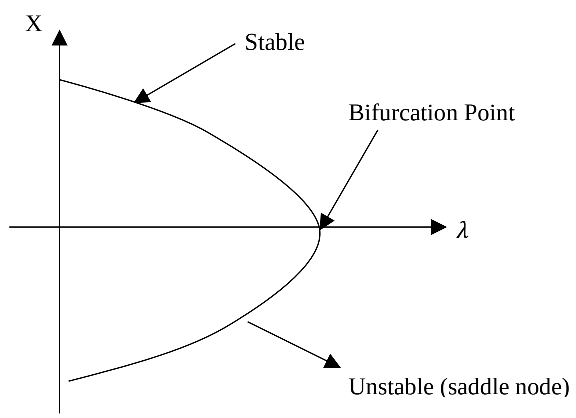

Fig 1: Bifurcation Theory Diagram

3) Energy Function Method

The energy function method provides a quantitative measure of the current operating point of a power system and the point of voltage collapse in a power system using an energy function. In this method, the non-linear differential equations that describe a power system are evaluated by the Lyapunov direct method [29]. Due to the many factors that affect voltage stability in a power system, constructing a proper energy function is difficult [36]. In [37], an energy function and an auxiliary function derived from the former were used to assess the voltage stability of an islanded microgrid. The results indicated that a properly formulated energy could be well adapted to monitor the stability condition of a system's operating points.

B. Static Voltage Stability Analysis

Static voltage stability analysis is described as taking 'snapshots' of probable operating conditions at various time frames to validly point out the mechanism of, and proximity to voltage instability. When applied correctly, this approach can provide the necessary information in a system for proper planning, operation, monitoring and control. The indices used in static voltage stability analysis are categorized into PV and QV curves, Jacobian matrix methods, and the system parameter-based indices.

1) PV and QV Curves

PV and QV curves define the loadability limits of load buses in a network and their corresponding voltages. A PV curve shows the dependence of bus voltage magnitude on active power whereas QV curves show the reactive power injection or absorption for various scheduled voltages at a bus. In the use of PV curves, the real power at a bus is increased while maintaining the power factor constant. For each load increment, power flows are calculated and the process is repeated until the maximum active power that can be imported from that bus is reached. QV curves are generated through the application of a fictitious VAR source at the test bus. Typical PV and QV curves are shown in Fig. 2 and Fig. 3 respectively. When using the QV method, the slope of the curve gives the stability of the bus. If the slope is positive, the bus is stable; if it is negative, it is unstable.

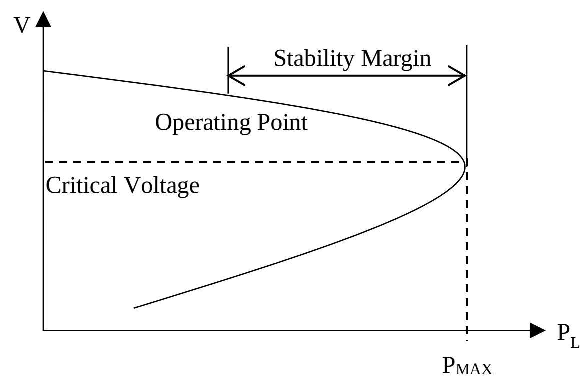

Fig 2: PV Curve

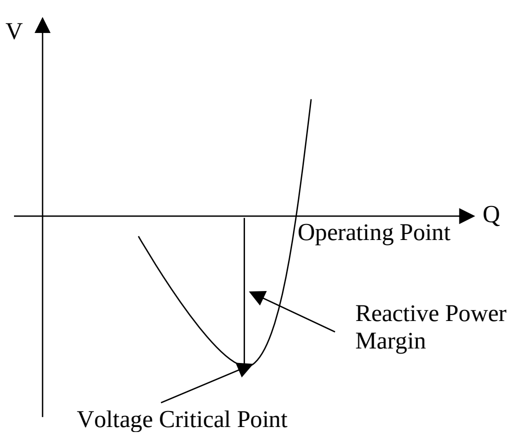

Fig 3: QV Curve

Analysis of PV and QV curves provides the active and reactive power stability margins. Several researchers have used these curves to develop voltage stability indices. In [38], two reactive-power-based voltage sensitivity indices were developed and used to assess the voltage stability of the IEEE 14 and 39 bus test systems. The critical voltage sensitivity index (CVSI) was developed to measure the rise or fall of critical voltages buses in the test networks, while the critical reactive power sensitivity index (CQSI) was formulated to evaluate the reactive power loss intolerance of each bus as renewable energy penetration (DFIG-WECS + PV) increased. The results showed that the test network buses, became increasingly intolerant to loss of reactive power as the renewable energy penetration increased.

Even though PV and QV curves are the only methods that can provide a measure of the proximity of a network's buses to voltage collapse in terms of actual physical quantities, they are bus-specific methods that require a lot of time and computational effort because at any given instant only one bus is considered for load variation. In large systems, repeated power flow studies have to be done for many buses. As a result, by themselves, PV and QV curves cannot be used to assess the voltage stability of a power system since they do not provide any information on the mechanism of voltage instability. They also suffer from convergence problems near the voltage critical point, to overcome these issues, continuation power flow (CPF) was formulated. It uses prediction and correction steps (a tangent vector) shown in Fig. 4 to predict the next stable operating point for a given load/generation scenario [29]. A boundary-derivative direct method for computing saddle-node bifurcation points was proposed in [39] for use in voltage stability analysis. The BDDM was compared with CPF method and was determined to offer better performance because it approached the saddle-node bifurcation quickly without multiple power flow calculations. It also offered good convergence.

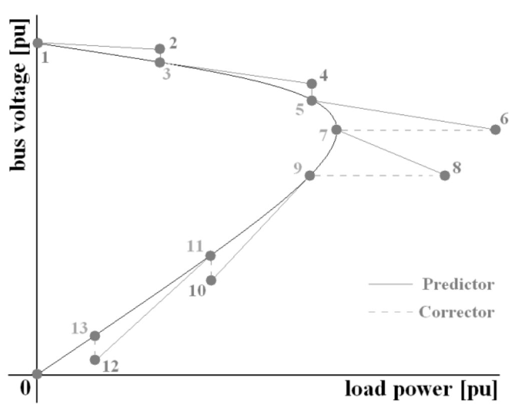

Fig 4: Continuation Power Flow Method for Tracing PV and QV Curves *[29]*

2) *Jacobian Matrix Based Methods*

Jacobian matrix-based methods assess the voltage stability of power systems by investigating the point at which the Jacobian matrix of the power flow equations becomes singular, this corresponds to the voltage collapse point of a network. The mature Jacobian based methods in literature are sensitivity analysis, modal based sensitivity analysis and singular value decomposition.

a) Sensitivity Analysis

Sensitivity analysis is obtained from the power flow equations and the Jacobian matrix, represented by equation 1.

$$\begin{bmatrix}\Delta P\\ \Delta Q\end{bmatrix} = [J]\begin{bmatrix}\Delta \delta\\ \Delta V\end{bmatrix} \quad (1)$$

Where,
ΔP and ΔQ are the mismatch active and reactive powers
Δδ and ΔV are the incremental changes in the bus voltage angle and magnitude respectively
$[J]$ is the power flow Jacobian matrix.

Since changes in reactive power cause a large variation in system voltages unlike active power changes, the active power mismatch can be assumed to be constant and the voltage response of a system evaluated by considering the relationship between Q and V. Equation 1 thus becomes;

$$\begin{bmatrix}0\\ \Delta Q\end{bmatrix} = [J]\begin{bmatrix}\Delta \delta\\ \Delta V\end{bmatrix} \quad (2)$$

Equation 2, can further be reduced to equation 3;

$$\Delta Q = J_R \Delta V \quad (3)$$

where J_R is the reduced Jacobian matrix given by equation 4;

$$J_R = \left[J_{QV} - J_{Q\delta} J_{P\delta}{}^{-1} J_{PV}\right] \quad (4)$$

Using equation 3, the relationship between incremental changes in voltage due to incremental changes in bus reactive power injection can be given by;

$$\Delta V = J_R^{-1} \Delta Q \quad (5)$$

A positive V-Q sensitivity indicates stable bus operation while a negative V-Q sensitivity indicates a bus is voltage unstable. The degree of stability can be perceived from the magnitude of its sensitivity. A smaller V-Q sensitivity magnitude indicates a stiffer bus while a larger sensitivity indicates a bus undergoes large voltage changes for reactive power imports hence it is voltage unstable. A small negative sensitivity represents a very unstable operation [29].

b) Modal Analysis

In modal analysis, mode shapes describing the inherent behaviour of a power system for a given configuration are obtained by representing the reduced Jacobian matrix in terms of eigenvector matrices and an eigenvalue matrix. These modes shapes depict the reactive-power voltage response of a power system for a given configuration. The reduced Jacobian power flow matrix represented in terms of eigenvector matrices is given in equation 5.

$$J_R = \left[J_{QV} - J_{Q\delta}{J_{P\delta}}^{-1}J_{PV}\right] = \xi\Lambda\eta \quad (5)$$

and

$$J_R^{-1} = \xi\eta\Lambda^{-1} \quad (6)$$

where,
ξ =right eigenvector matrix of J_R
η=left eigenvector matrix of J_R
Λ=diagonal eigenvalue matrix of J_R
$\xi\eta$=I, the identity matrix

Substituting equation 6 in equation 5, equation 5 becomes;

$$\eta\Delta V = \eta\Lambda^{-1}\Delta Q \quad (7)$$

where,
$\eta\Delta V$ is the vector of modal voltage variations
$\eta\Delta Q$ is the vector of modal reactive power variations

From equation 7, a corresponding i^{th} modal eigenvalue λ_i shows the stability of mode shape i with respect to reactive power changes. Mode shapes with large eigenvalues suggest small changes in the modal voltages for modal reactive power variations. This corresponds to a stable system, while small eigenvalues indicate a mode shape near instability. When the eigenvalue is 0, it is indicative of voltage collapse. This is because the modal voltage undergoes infinite changes for changes in the modal reactive power [29]. A system with any mode shape that has a negative modal eigenvalue is voltage unstable.

Modal analysis is a powerful tool for static voltage stability analysis that can identify the voltage stability status of any system, give a relative measure of the system to voltage instability, and when the mode shapes are analysed correctly, they can yield insightful information on the components participating in mitigating or facilitating voltage instability. In [40], QV modal analysis was used to determine the impact of PV penetration on power system voltage stability. The results showed that depending on the size and location of PV integration, the voltage stability of a system is either enhanced or affected negatively.

c) Singular Value Decomposition (SVD)

The voltage critical point of a power system is the point where the maximum power transfer point of any system is reached; from a mathematical point of view, the voltage critical point of any power system is the singular point of its power flow Jacobian matrix. It is on this basis that singular value decomposition for voltage stability analysis was proposed in [41]. The singular value decomposition of the power flow Jacobian matrix is expressed as;

$$J = U\Sigma V^T = \sum_{i=1}^{n} \sigma_i u_i v_i^T \quad (8)$$

where
U and V are the $n \times n$ orthogonal matrices
u_i = left singular vector
v_i = right singular vector
$\Sigma =$ is a diagonal matrix with $\Sigma(A) = \text{diag}\{\sigma_i(A)\}$ for $i = 1,2,3,\ldots,n$ and all $\sigma_i \geq 0$ $for\ all\ i$

Substituting equation 8 in the power flow equation, equation 1 and evaluating it, it becomes;

$$\begin{bmatrix}\Delta\delta \\ \Delta V\end{bmatrix} = V\Sigma^{-1}U^T\begin{bmatrix}\Delta P \\ \Delta Q\end{bmatrix} \quad (9)$$

The smallest singular value σ_n is an indicator of the proximity of the steady-state stability limit, the right singular vector v_n corresponding to σ_n indicates sensitive voltages and angles and the left singular vector u_n corresponding to σ_n indicates the most sensitive direction for changes in the active and reactive power injection. Much like modal analysis which is derived from eigenvalue decomposition, singular value decomposition can be used to identify voltage weak facilities in a network, however, unlike modal analysis, it is a method that requires significant computational effort especially for large power systems, because of the complexities involved in the decomposition process.

d) System Parameter-Based Indices

These are indices developed for use in online and offline applications. They depend on a network's static operating parameters i.e., currents and voltages, and/or network impedances to determine the voltage stability of buses and the proximity of transmission lines to voltage instability.

(1) Line Stability Indices

Line voltage stability indices assess the voltage stability status of a system by referring to lines. They show the proximity of lines to a select voltage stability criterion usually from 0 to 1, where 1 is the voltage stability criterion. There are several line stability indices that have been formulated in literature [26], [27] and [30]. Line voltage stability indices are fast simple methods but offer limited accuracy compared to other classes of indices. They are formulated based on the two-bus representation of a power system. Consider the two-bus power system representation given in Fig. 6.

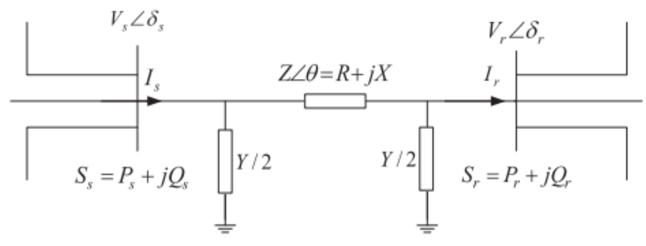

Fig. 5: Two-Bus Representation of a Power System *[30]*.

Neglecting the line shunt admittances, the active and reactive power at the receiving end bus can be expressed by equations 9 and 10.

$$P_r = \frac{V_s V_r \cos\delta - V_r^2 - Q_r X}{R} \quad (9)$$

$$Q_r = \frac{P_r \mathrm{X} - V_s V_r \sin\delta}{R} \quad (10)$$

where,
$\delta = \delta_s - \delta_r$

V_s *and* V_r = voltage magnitude at the sending and receiving end buses respectively
P_s *and* Q_s = active and reactive power at the sending bus
P_r *and* Q_r = active and reactive power at the receiving bus
S_s *and* S_r = apparent power at the sending and receiving bus respectively
δ_s *and* δ_r = voltage angle at the sending and receiving bus respectively
R *and* X = line resistance and reactance

Equations 9 and 10 can be evaluated to form a 4th-degree equation, given by equation 11;

$$V_r^4 + (2P_rR + 2Q_rX - V_s^2)V_r^2 + (P_r^2 + Q_r^2)Z^2 = 0 \quad (11)$$

At the voltage collapse point, when the maximum power transfer limit is reached, equation 11 has two pairs of real identical roots. Increasing loading beyond this point results in the roots of the equation becoming complex. Voltage stability is only maintained when the discriminant of equation 11 is greater than or equal to zero [42]. This forms the theoretical basis for the formulation of line voltage stability indices.

The accuracies of line stability indices are dependent on the assumptions made during the formulation of the indices. They also offer different performance characteristics for different network operating conditions. More recently, transmission line $\frac{R}{X}$ ratios and system loadings have been shown to affect their performances [42], [43]. In [44], the authors used the Fast voltage stability index (FVSI) [45] and the line stability index (Lmn) [46] to research the effects of large-scale wind power (DFIG-WECS) integration on power system voltage stability, using the IEEE 30 bus test system. As the level of penetration increased, both indices showed the lines moved closer to the voltage stability criterion, indicating the system moved towards voltage instability. In [47], the performance of the Lmn and FVSI indices was compared using the IEEE 30 bus system under different loading conditions. The FVSI index offered better sensitivity, hence better accuracy compared to the Lmn index.

(2) Bus Voltage Stability Indices

Bus voltage stability indices are used to determine the voltage stability of buses in an electric power system. They do not provide any information on the voltage stability of transmission networks, as such, they can't be used in the determination of voltage weak facilities in a network [30]. However, unlike line stability indices, bus stability indices offer greater degrees of accuracy. There are many bus stability indices in literature given in [27] and the most common include the voltage collapse point indicator ($VCPI_{bus}$) [48] and the sensitivity factors [29]. Bus voltage stability indices have found application in optimization studies that employ heuristic and metaheuristic algorithms. In [49] for instance, the voltage stability factor (VSF) was used in the formulation of a multi-objective particle swarm optimization function whose purpose was to ensure optimal placement of a wind turbine generation unit and a PV array in radial distribution networks to minimize losses and enhance voltage stability. The authors in [50] used the voltage stability index formulated in [51] to formulate a hybrid evolution programming optimization function whose goal was to optimally place and size distributed generation and to improve voltage stability.

IV CONCLUSION

In this paper, a review of variable renewable generation has been presented. VREs can have both beneficial and detrimental impacts on the voltage stability of power networks. Voltage instability is one of the major hindrances in the quest to attain a decarbonized electricity sector. If a net-zero electricity sector is to be attained, emphasis must be placed on the phenomenon of voltage instability for proper planning, control and monitoring of power systems.

In the review of voltage stability indices, a classification-based approach has been used. The indices used in dynamic and static voltage analysis of power systems have been presented and the differences between the two approaches elaborated upon. Dynamic indices are employed to explain how the dynamic behaviour of components affects voltage instability. The main challenge identified in dynamic voltage stability analysis is the choice of load models since different load models yield different results.

In static voltage stability analysis, Jacobian matrix-based methods, though complex, offer the best accuracy compared to the power-voltage curves and system parameter-based VSIs. Using power-voltage curves and the bus and line indices is not enough to comprehensively assess the voltage stability of power networks especially those with increased renewable energy penetration. Employing a combination of the three index classifications and taking into account their respective strengths and weakness can provide better results in analysing the voltage stability of power systems.

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