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Review Article

Voltage Stability Assessment and Control Using Indices and FACTS: A Comparative Review

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The problem of voltage stability is becoming a more acute and indispensable topic given the major and sensitive role it plays in the electrical system. It can be considered a major factor in the initiation of blackouts around the world. Hence, the need for reliable and fast tools to detect and control the approach of instability points throughout the network, namely, voltage stability indices and flexible alternating current transmission systems (FACTS) devices for the control and management of the electrical network. In this paper, an update on the existing blackouts in the world has been presented. Based on the brief overview of the most significant definitions of voltage stability presented in this work, a new definition of voltage stability has been proposed. A detailed comparative study on voltage stability analysis methods has been conducted. Furthermore, an exhaustive discussion on the various voltage stability indices and FACTS devices existing in the literature with their contribution to voltage stability prediction and improvement has been proposed.

1. Introduction

Over the last decade, the world is facing rapid growth in energy demand driven by increasing population and economic activities. Consequently, electrical networks are found in a situation close to the capacity limits and are becoming more fragile. At that condition, any contingency could quickly accelerate the voltage collapse which may lead to a blackout [1]. In this century, remarkable cases of blackouts worldwide have been recorded. In Bangladesh 4 October 2022, more than 130 million people were left without electricity after a grid failure [2]. Pakistan also reported last year (January 9, 2021) a blackout caused by the tripping of the Guddu thermal power plant [3]. Another one occurred in March 2019 in Venezuela [4, 5], plunged almost the entire country into darkness due to the existence of obsolete transformers feeding the network. The limitation of electrical substations also aggravated the situation. In addition, major blackouts recorded from 2011 to the present are presented [6–8] in Figure 1 together with their impacts and the nature of their causes. Several causes of these blackouts are provided in the literature [9, 10]. In addition, a classification of blackout causes into technical, managerial, and climatic causes was mentioned in [11, 12] as shown in Table 1.

Several works have indicated that the reactive power deficit problem and, consequently, voltage instability are the initiating factors of major blackouts [13–15]. For this reason, managers pay particular attention to the evaluation and control of voltage stability to maintain the stability of electrical networks and avoid major blackouts as they occur in some countries. Thus, it becomes imperative for the grid operator to have reliable and fast tools to detect and analyze the approach of instability points anywhere in the grid. For this purpose, the estimation of the distance of the power system to the voltage collapse can be very convenient. With the static or dynamic approaches developed for voltage

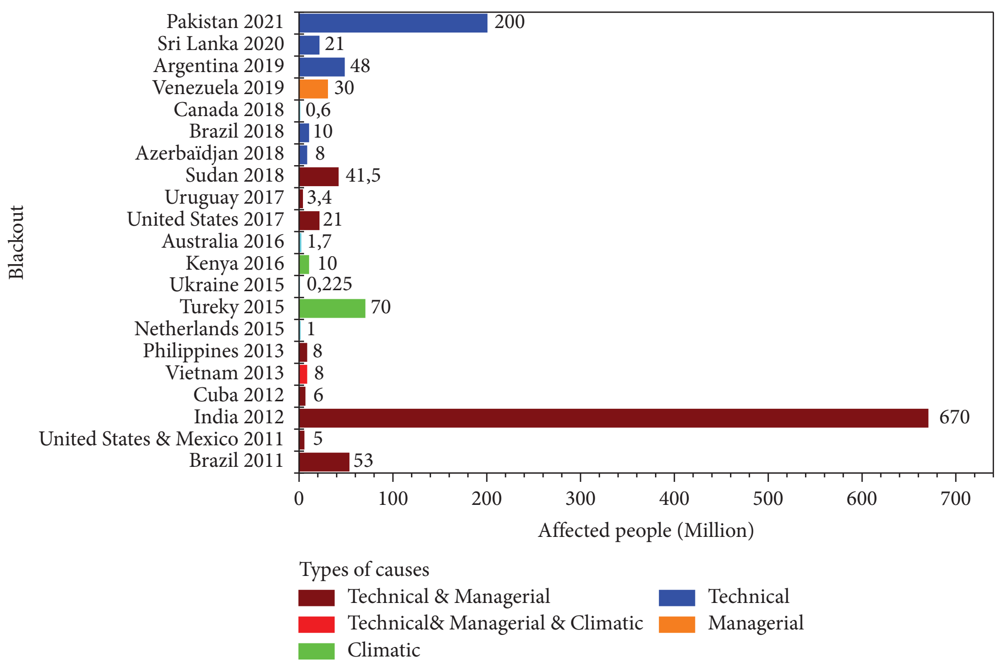

Figure 1: A recap of major blackouts recorded since 2011: causes and impacts [10-12].

Table 1: Classification of blackouts causes.

Technical causes	Managerial causes	Climatic causes
(i) Limited network capacity	(i) Lack of monitoring and control facilities;	(i) Storms;
(ii) Aging network infrastructure	(ii) Lack of control means (e.g., emergency); (iii) Poor maintenance management;	(ii) High winds;
(iii) Equipment reliability	(iv) Late decision-making;	(iii) Heavy snowfall;
(iv) Poorly adjusted protection and control equipment	(v) Neglected or untimely load shedding; (vi) Lack of consideration of alarm messages;	(iv) Incidents caused by animals;
(v) Faults. . .	(vii) Cyber-attacks. . .	(v) Extreme weather conditions. . .

stability analysis, details on the margin of voltage instability can be obtained. P-V, P-Q, and Q-V curves, modal analysis, sensitivity analysis, and voltage stability indices [16–18] are widely used methods for static analysis of voltage stability following load variations in the network. Otherwise, Dynamic voltage stability methods including small signal stability analysis, time domain simulations, bifurcation analysis, and energy function method [16, 19–23] are useful in studying voltage collapse scenarios and understanding the chronology of events that lead to voltage collapse. After evaluation and analysis of voltage collapse in an electrical network, the control of the identified unstable buses is required. The integration of FACTS devices is therefore a necessity. These devices act as electronic power controllers and compensators, providing a highly adaptable method for voltage regulation, line capacity management, and effective congestion control at remarkably fast rates. They are an effective solution to the voltage instability problems.

This article proposes a brief literature review of voltage stability. A clear classification of the different existing definitions of voltage stability has been elaborated in this work. In addition, a comparative study between prediction and analysis approaches of voltage stability has been comprehensively discussed to highlight the advantages and limitations of each method used. A particular interest was given to the different types of voltage stability indices, including line, bus, and global indices. Indeed, a thorough review was proposed wherein several voltage stability indices were examined in terms of their types, formulations, concepts, assumptions, critical values, advantages, and disadvantages. This comparative analysis was developed to provide a general basis for the appropriate selection of voltage stability index to identify weak lines and buses. FACTS devices used for voltage control and regulation are also examined in depth. A detailed classification of the different FACTS devices existing in the literature as well as a brief presentation of these devices according to the advantages they provide has been proposed. Moreover, a comparative table containing the different definitions, advantages, and limitations of each FACTS device has been developed. The results of this work are intended to provide a general guideline for other researchers to understand the voltage collapse phenomenon.

The rest of the document is organized as follows: Section 2 presents a brief literature review on voltage stability. Section 3 has been devoted to a recap of voltage stability indices. A detailed review of voltage stability control using FACTS controllers has been proposed in Section 4. The conclusion is presented in Section 5.

2. Brief Literature Review on Voltage Stability

2.1. Definitions and Classifications. The term "Voltage Stability" is largely defined in the literature based on several criteria, namely, delay, disturbance nature, and system states. Figure 2 presents the most significant definitions and classifications of voltage stability. Five definitions were presented in the literature according to Council on Large Electric Systems CIGRE [24], Institute of Electrical and Electronics Engineers IEEE [25], Kundur [17], Van Custen [26], and Hill and Hiskens [16, 20]. The classification depends on the nature of the disturbance and the time frame [24].

Given all the definitions and the nature of disturbances listed in Figure 2, voltage stability can be defined as the ability of the power system to continuously maintain an acceptable voltage for all buses in a system under normal operating conditions including after a small or large disturbance.

2.2. Factors Influencing Voltage Stability. The problem of voltage stability is strongly related to generation, transmission, and reactive power consumption. Indeed, when large generation units drop out of service due to abnormal operating conditions or disturbances, the supplied reactive power is reduced and some transmission lines are heavily loaded [27]. Thus, due to the additional reactive power demand, the load voltages decrease. The process eventually leads to voltage instability and voltage collapse. Figure 3 lists the various factors that affect voltage stability.

2.3. Voltage Stability Prediction. The prediction as well as the analysis of the voltage collapse phenomenon remains a critical challenge for operators and researchers. In this context, several studies and researchers have focused on presenting methodological approaches for the analysis [1, 22]. These can be divided into two broad categories, namely, dynamic and static voltage stability analyses. The dynamic analysis involves the dynamic elements associated with the generation, transmission, distribution, and load. It is characterized by its complexity in terms of calculation and data required. Static analysis, on the other hand, analyzes voltage stability generally based on load flow analyses. It consists of a study of the equilibrium regime and allows us to identify the voltage levels and the power transits through all the buses and lines of the system. Therefore, several studies in the literature have focused on the static model due to the simplicity of the analysis, the lower computational effort, and the accurate results offered, in addition to some practical advantages over the dynamic study [28]. Table 2 presented below explains in detail the comparison between the two approaches of analysis.

Various techniques of static and dynamic analysis have been proposed in the literature [24, 25], which may be classified as shown in Figure 4.

Static analysis of voltage stability is a steady-state study that provides voltage levels and power transit across all buses and lines in the system. The minimum singular value method and P-V, P-Q, and Q-V curves lead to the estimation of power system distance to voltage collapse, but no information about the reasons for the voltage stability problem is provided. The continuation power flow (CPF) method is characterized by its slowness. Additionally, the voltage stability indices play a key role in monitoring and estimating the stability margin of the power system. Dynamic analysis techniques are comparable to power system transient analyses, where the system is modeled by a variety of differential equations. The two primary categories of dynamic analysis are the method of large signal analysis and the method of small signal analysis. Table 3 summarizes the use and limitation of each voltage stability analysis method mentioned above.

3. A Recap of Voltage Stability Indices

3.1. Definition and Classification. Voltage stability indices are useful tools for evaluating voltage stability. They allow monitoring of the power system, estimating the stability margin as well as the maximum loadability, and eventually identifying critical areas such as lines or buses requiring compensation. Voltage stability indices are calculated either for a line, a bus, or the whole network [36] as illustrated in Figure 5. The accuracy and simplicity differ from one index category to another. Indeed, line indices are the simplest indices that are suitable for evaluating the most critical line in an interconnected system. Bus indices are more reliable and they can be used to identify the weak bus in the system. On the other hand, global indices are more effective and accurate in determining the proximity of voltage instability. In general, they are derived from the Jacobian matrix. However, they are time-consuming due to their complexity. The detailed advantages and various limitations of each category of indices are summarized in Table 4.

3.2. Discussion and Comparative Study on Voltage Stability Indices. Numerous research studies in the literature have extensively explored voltage stability indices (VSIs) and provided detailed analyses of their formulation. In [39], a comprehensive analysis of VSIs was conducted, which encompassed various aspects such as assumptions, critical values, and equations. Another study, [37], presented a comparative analysis of more than 40 VSIs, considering factors such as formulation, application, performance, and evaluation parameters. Additionally, Table 5 summarizes the line, bus, and global indices available in the literature, taking into account the expression of the indices, the considered assumptions, the input parameters, as well as the advantages and disadvantages associated with each index. The aim of this summary is to establish a comprehensive and up-to-date knowledge base of voltage stability indices.

The absence of taking into account some variables such as line resistance, reactive and real power variations, shunt admittance, and the difference in transport angle between transmission and reception voltages have

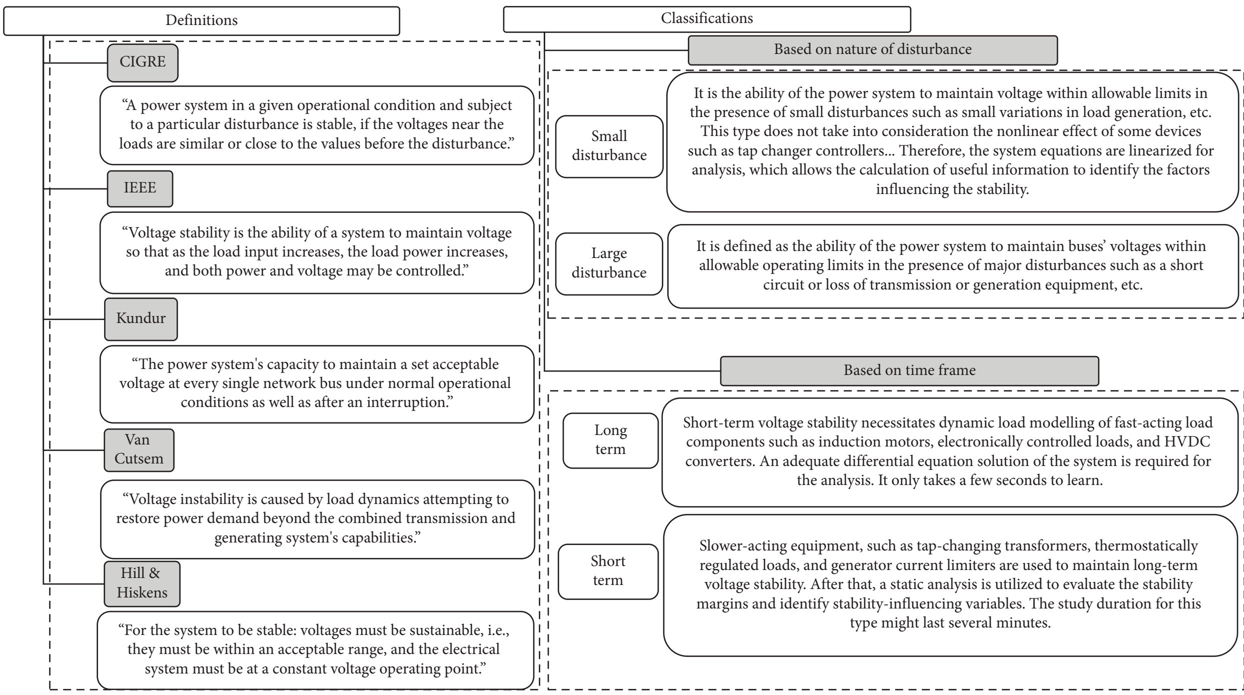

Figure 2: Definitions and classifications of voltage stability.

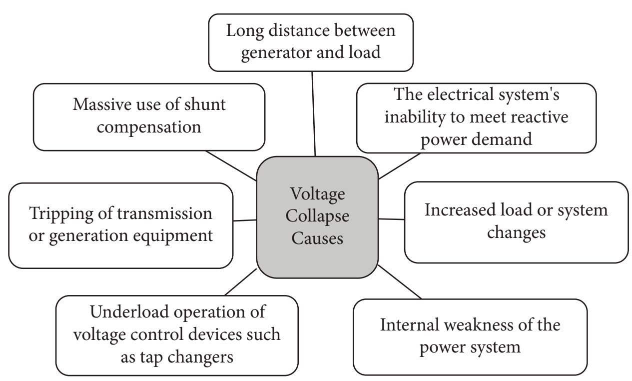

Figure 3: Voltage collapse causes.

Table 2: Comparison between static and dynamic analysis [1, 23].

Method	Advantages	Drawbacks
Static analysis	(i) Examine a variety of system scenarios (ii) Used to analyze various aspects of the problem (iii) Easy to understand and requires fewer data (iv) Identify the primary contributing variables and provide a thorough understanding of the nature of the problem (v) Fast and inexpensive construction	(i) Allows no evaluation of the electrical system's dynamic voltage stability (ii) Less accurate (iii)Approximate results
Dynamic analysis	(i) Detailed study of specific voltage control situations (ii) Presentation of all possible incidents leading to voltage instability in chronological order (iii) More precise (iv) Involves the dynamic elements of the system that are associated with the generation, transmission, distribution, and load	(i) More time-consuming (ii) More expensive (iii) Complex control: require high computational power and a high degree of model accuracy (iv) Requires detailed data (v) More difficult to understand

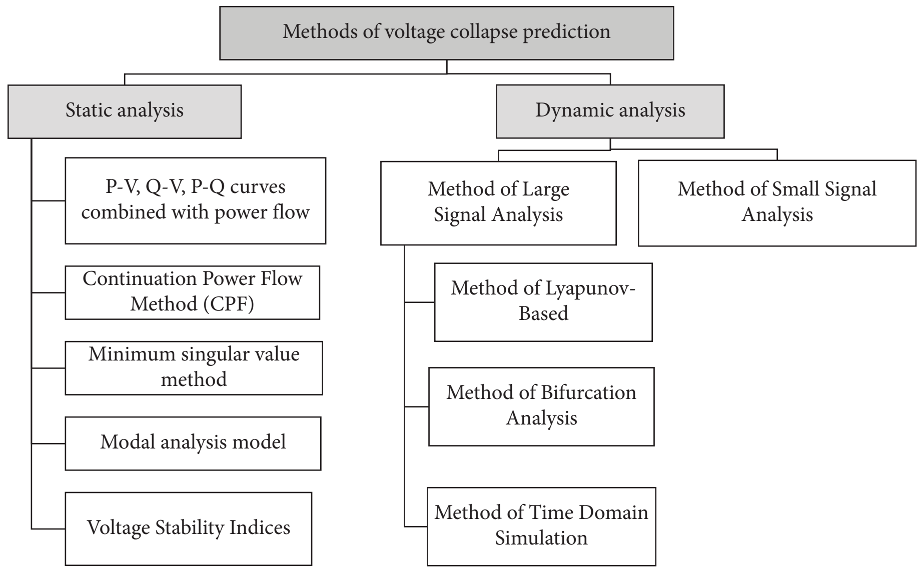

Figure 4: Methods of voltage collapse prediction.

all been observed in the formulation of some voltage stability indices presented in the table below. Indeed, some indices are sensitive to reactive power change and are not sensitive to active power change and vice versa. For example, in Table 5 the indices L_{mn} [40] and FVSI [41] only consider the effect of reactive power flow, and they neglect the effect of active power flow. Therefore, their response may give inaccurate predictions due to a heavy active power load or apparent power load especially when the power factor is near unity. Although some indices depend on the active and reactive power, their response is still weak due to the negligence of significant variables in the network [12]. As an example, the LQP index [42] uses a simplified model of transmission lines and ignores the resistances of transmission lines. This index supposes the line as a lossless line, i.e., the sending power is equal to the receiving power. Due to these assumptions, the LQP gives inaccuracy predictions under certain operating circumstances. The NVSI [43] also may give inaccurate predictions when the resistances of branches are high because it does not consider line resistance. The NLSI [50] is unable to predict the voltage collapse under certain operating cases, as it neglects the difference in voltage angle between the transmitter bus and the receiver bus. Nevertheless, VSLI [49] is unable to predict the voltage collapse in some instances due to heavy reactive power load. Bus indices are more reliable but they can be more sensitive to any change in power system topology as the ISI index [56] and L index [58]. $\mathrm{VSI}_{\mathrm{bus}}$ and Z_L/Z_S are more complex and require a long computation time as it depends on several parameters. Global indices derived in general from the Jacobian matrix are more effective for voltage instability proximity. But, they are complex and require a longer computation procedure since it requires the calculation and the evaluation of the eigenvalues of the reduced matrix $\mathrm{J_R}$.

Other indices reported in the literature [12, 29, 53] are presented in Figure 6.

4. Voltage Stability Control Using FACTS Controllers: A Review

4.1. Benefits of Integrating FACTS Devices into the Electricity Grid. Several methods have been proposed for reactive energy compensation and voltage stability improvement, such as the use of synchronous machines to produce reactive energy, but their reaction speed is quite slow and requires a lot of maintenance. One of the methods that has been used is the insertion of static reactors and capacitors. Their disadvantage is that they are adapted to the variation of slow reactive power consumption which cannot meet the increasing needs of the electrical networks. With the development of FACTS in the mid-1980s by N. Hongorani, a pioneer in the field within the Electric Power Research Institute EPRI [54, 55], it becomes possible to increase the control of power flow and improve the voltage stability of the electrical network. The insertion of FACTS controllers provides several benefits. From the security side, they increase system security while improving the stability margin and maintaining cyber-secure control. Economically, FACTS devices offer good control of the stability of the network against disturbances which minimizes the demand for new transmission and distribution lines and helps prevent economic losses. The power quality is also improved by guaranteeing voltage stability, controlling power flow, and reducing power losses. Features of these advantages are summarized in Table 6.

4.2. FACTS' Classification. The different types of FACTS use capacitors or reactors in series, shunt, or mixed configurations depending on the need. Generally, shunt capacitors provide reactive power and locally increase the voltage of the

Table 3: Voltage stability analysis methods: uses and limitations.

Type	References	Method	Utilisations	Limitations
Static	[17] [29] [30] [31]	P-V, Q-V, and P-Q	Widely used methods for evaluating a radial system's voltage stability and a huge mesh network's voltage stability following load variations in the network. They provide the magnitudes of load bus voltages in a given bus at increased power. The criteria of stability for these methods is the "distance" between this curve's extremes and the present operating point	(i) Since the power flow calculations are involved in generating the curves, this is very time-consuming for large networks (ii) A convergence difficulty occurs in the solution of the power flow equation when the system load approaches the critical point (the Jacobian matrix becomes singular) (iii) Only the closeness to the critical point is mentioned, but no information about the reasons for voltage stability issues is provided
	[30] [32]	Continuation power flow method CPF	CPF method is an iterative process used to solve the singularity problem of the Jacobian matrix in the stability limit. It consists in computing the new situation starting from an initial situation. Prediction and correction are the two steps of iteration	(i) The time required for execution (ii)The inability to quickly locate the fragile area of the network (iii) The difficulty to determine the distance to the critical point (iv) Less accurate (v)No information about the reasons for the voltage stability issue is provided
	[30] [33]	Minimum singular value method	The voltage stability margin is calculated using Thomas and Lof's minimal singular value approach, which involves analyzing how near the Jacobian matrix is to be singular. When the smallest singular value of the Jacobian matrix J is 0, the load limit has been reached	(i) This method cannot identify the exact reasons for voltage instability, but it does estimate the voltage stability limit's vicinity. However, the measurement is not exact. This is due to the system's nonlinear behavior from a stable operating point to the bifurcation point
	[30] [34]	Modal analysis model	The reactive power margin and the factors contributing to voltage instability are calculated using the modal analysis model. The system's Jacobian matrix J is used in this method. Indeed, the voltage is steady if the matrix's minimal eigenvalue is well over 0	(i) Any change in topology causes the Jacobian matrix to change, which has to be recalculated. Thus, the computation time increases (ii) Do not give an absolute estimate of voltage collapse closeness
	[30] [29]	Voltage stability indices	Indices of voltage stability have a crucial function in electrical networks. They allow us to monitor the electrical network and estimate the stability margin, the maximum loadability, and finally the location of fragile areas, whether they are lines or buses requiring special attention	(i) Dilemma (precision and simplicity): some indices are more precise but more complex and opposite

Table 3: Continued.

Type	References	Method	Utilisations	Limitations
Dynamic	[1] [16]	Method of small signal analysis	Useful analysis tool that evaluates the stability of the system to small perturbations by analyzing the eigenvalues of the linear algebraic differential equations of the system	(i) Challenges in establishing an accurate load model (ii) Only suitable for small disturbances: the nonlinearity of large signals is not taken into account
	[1] [16]	Method of Lyapunov-based	Widely used method to evaluate the stability of nonlinear systems based on the Lyapunov direct method. it calculates the voltage stability margin by showing the distance between the current operating point and the point of voltage collapse	(i) The establishment of a proper energy function is more difficult because of the factors affecting voltage stability
	[1] [16] [20] [21] [35]	Method of bifurcation analysis	A robust method for systematically identifying regions of stable and multiple stable solutions. In addition, this method provides a practical tool to describe the properties and changes of a dynamical system with variation of a parameter	(i) The symbolic and analytical processes used in this method are in general infeasible (ii) Complex and requiring more computing time
	[1] [16]	Method of time domain simulation	A powerful method for studying the mechanism and dynamic processes of voltage stability by solving the nonlinear algebraic differential and continuous-discrete time equations of the dynamic model of a system. It can also be used to evaluate the effectiveness of other voltage stability assessment methods. It is suitable for any dynamic model of an electrical system	(i) Time frame and load modeling problems (ii) Diverse findings due to different loading models used (iii) The computational effort required for execution

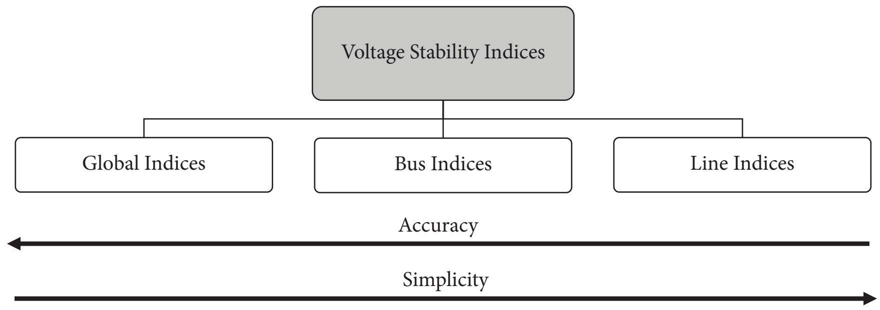

Figure 5: Classifications of voltage stability indices.

Table 4: Voltage stability indices: types, uses, benefits, and drawbacks [29, 37, 38].

Type	Uses	Advantages	Drawbacks
Line voltage stability indices	These indices prevent blackouts caused by overloaded lines. The margin between the operating point and the maximum transferable power is computed by using the values of these indices for each line. The most crucial line may then be determined and the index value of this line is used to conclude the entire power system's stability	(i) Simple (ii) Easy to implement (iii) Reduced computation time (iv) Appropriate tools to detect the stability state of the network (v) Identification of sensitive lines	(i) Most of these indices are unable to forecast the behavior of the system beyond the collapse point due to the energy flow constraint (singularity) (ii) Less accurate
Bus voltage stability indices	These indices identify the nearest bus to the critical stability point. They quantify the distance between a PQ bus's operating point and the maximum load that this bus can support without the voltage becoming unstable	(i) Simple (ii) Requires less computation (iii) Allows determining the weakest buses (iv) Suitable for real-time applications	(i) The implementation of these indices is more complicated and their calculation time is more important than that of the line stability indices
Global voltage stability indices	This category of indices is not associated with either the system's buses or lines. Generally, it is based on the use of certain functions such as modal analysis, power ratio, test functions, and the Jacobian matrix's singularity of the power flow after certain transformations	(i) A suitable instrument for estimating instability and power transmission capacity within static analysis settings (ii) More accurate indices	(i) Any change in topology causes the Jacobian matrix to change, which has to be recalculated (ii) Limited for the application of radial systems (iii) More complex indices

network used during periods of high consumption or in areas far from the production centers. Shunt reactors consume reactive power, which decreases the voltage of the network in periods of low consumption. The series capacitors allow to decrease in the impedance of the electrical lines and increase the power transmissible by these lines. Series reactors increase the impedance of an electrical line to better distribute the currents on the different lines. According to the literatures [59–61], the most appropriate FACTS device classification is based on three generations: generation one, generation two, and the last generation of FACTS devices also known as D-FACTS [65].

The first generation of FACTS devices, which were developed in the 1980s and 1990s, focused on controlling the transmission lines' reactive power flow. By incorporating the aforementioned power system devices, notable enhancements were achieved, including the improvement of power system stability, the elevation of power transfer capacity, and the minimization of voltage fluctuations. The second generation of FACTS devices, developed in the late 1990s and early 2000s, added the capability to control active power flow in addition to reactive power flow. This generation of devices was able to provide even greater control over power flow and improve system stability. The most recent generation of FACTS devices is commonly known as D-FACTS (distributed FACTS) devices. These devices were developed in the early 2000s and provide even greater flexibility and control over power flow in transmission systems. These devices can be installed at multiple locations throughout a power system, allowing for more precise control over power flow and voltage stability. Overall, each generation of FACTS devices has built upon the previous generation's capabilities, providing increasingly sophisticated methods for controlling power flow in transmission systems. The

Table 5: Line, bus, and global voltage stability indices summary.

Type	References	Index/Formula	Nature of inputs	Number of inputs	Assumption	Critical value	Advantages	Disadvantages
Line	[40]	$L_{mn} = 4Q_r X/(V_s . \sin(\theta - \delta))^2$	Q, V, X, θ, and δ	5	$Y = 0$, effect of active power neglected	1	(i) Simple mathematical formulation (ii) Requires less effort in the calculation (iii) Flexible with topological and load changes	(i) Sensitive only to the variation of the reactive power and not the active power
	[41]	$\text{FVSI} = 4\text{Qr}Z^2/Vs^2 X$	Q, V, X, and Z	4	$Y = 0$, $\delta = 0$	1	(i) It can identify the voltage collapse point, the maximum permitted load, the fragile bus, and the most crucial line in an interconnected system	(i) Do not give a true assessment of voltage stability near voltage collapse in case of active power increment
	[41]	$\text{Lsr} = 4\text{Qr}Z^2 X/Vs^2 (X \cos(\delta) - R \sin(\delta))^2$	Z, X, Q, V, and δ	5	$Y = 0$	1	(i) Simple, easy to understand, and easy to compute; (ii) It can correctly identify the critical contingencies for voltage stability	(i) Sensitive only to the variation of the reactive power and not the active power
	[42]	$\text{LQP} = 4X/\text{Vs}^2 (Qr + \text{Ps}^2 X/\text{Vs}^2)$	P, Q, V, and X	4	$Y = 0$, $R = 0$	1	(i) Rapid calculation (ii) Identification of the source of voltage collapse, as well as the weak zones functioning in a stressed state near the bifurcation point	(i) LQP provides a less accurate result under heavy loading
	[43]	$\text{NVSI} = 2X\sqrt{\text{Pr}^2 + \text{Qr}^2}/2\text{Qr}X - Vs^2$	X, P, Q, and V	4	$Y = 0$, $R = 0$	1	(i) Fast computation (ii) Sensitive to reactive power variation as well as active power	(i) For longer transmission lines, it provides less accurate stability prediction
	[44]	$L_p = 4P_r R/V_s (\cos(\theta - \delta))^2$	P, R, θ, δ, and V	5	$Y = 0$, effect of active power neglected	1	(i) This index is quite easy to calculate and can be implemented in practice (ii) Reflects the transmission line's state and estimated distance from the instability limit	(i) It uses an approximate model (neglects the effect of active power). Therefore, it gives a pessimistic prediction of voltage stability when active power increases (i) The system's power factor has a significant impact on the stability index's performance
	[45]	$V_{\text{QILine}} = 4Q_r/\lvert B\rvert V_s^2$	Q, B, and V	3	$\delta \approx 0$, $Y = 0$	1	(i) Precise, fast, and simple (ii) Calculating voltage stability at each line and determining correct voltage collapse locations (iii) VQI and L_{mn} are quite comparable. However, VQI allows a more efficient and quicker analysis than L_{mn}	(i) The accuracy level in VQILine decreases as the distance from the voltage collapse bus increases
	[46]	$\text{VCPI}(1) = P_r/P_{r(\max)}$, $\text{VCPI}(2) = Q_r/Q_{r(\max)}$ $\text{VCPI}(3) = Q_l/Q_{l(\max)}$, $\text{VCPI}(4) = P_l/P_{l(\max)}$	Q and P	2	Constant power factor, $Y = 0$	1	(i) Detect areas susceptible to collapse while identifying critical lines (ii) Simple and easy to calculate due to less parameter involvement	(i) In varying load situations (ii) VCPI produces less reliable results
	[47]	$\text{PTSI} = 2S_r Z(1 + 2\cos(\theta - \Phi))/V_s^2$	Z, θ, V, and S	4	$Y = 0$	1	(i) When compared to the VCPI, the PTSI is considered to be more accurate	(i) Low accuracy in predicting voltage stability in the case of high-line admittance
	[48]	$\text{LCPI} = 4A\cos(\alpha)/[V_s \cos(\delta)]^2 [\text{P}_r\lvert B\rvert \cos\beta + Q_r\lvert B\rvert \sin\beta]$	A, α, δ, β, P, Q, V, and B	8	Lines are considered pie modeled	1	(i) This index provides accurate information on the status of a line voltage stability	(i) For a power system with a large number of linked lines, the LCPI computation time is longer
	[49]	$\text{VSLI} = 4V_s . V_r \cos(\delta) - V_r^2 \cos^2(\delta)/v_s^2$	V and δ	2	$Y = 0$	1	(i) It provides real-time measurement	(i)Because PMUs require distinct approaches for optimal placement, VSLI is more complicated
	[50]	$\text{NLSI} = 4\text{P}_r R + Q_r X/V_s^2$	P, R, Q, X, and V	5	$Y = 0$, $\delta = 0$	1	(i) Because it is sensitive to both reactive and active power variations, this index delivers more accurate findings than indices that consider only reactive power	(i) It gives a less accurate prediction of the voltage stability because it uses an approximate model (it neglects the effect of the line admittance)
	[51]	$\text{VSI} - 1 = \min(P_{\text{margin}}/P_{\max}, \text{Q}_{\text{margin}}/Q_{\max}, S_{\text{margin}}/S_{\max})$	P, Q, and S	3	$Y = 0$, $R = 0$	0	(i) Can be easily used in online applications	(i) Less accurate in varying power load
	[52]	$\text{VSI} - 2 = 4Q_r R^2 + X^2/X(V_s^2 + 8RQ_r)$	Q, R, X, and V	4	$Y = 0$, $\delta = 0$	1	(i) It can identify the weakest line of the electrical network	(i) This index is difficult to analyze in the case of a low load value
	[53]	$\text{VSMI} = \delta_{\max} - \delta/\delta_{\max}$ with $\delta\max = 0.5 \quad \text{atan}(X/R) - \varphi_L$	δ	1	$Y = 0$, $R = 0$	0	(ii) Identify weak areas and calculate the voltage stability margin	(ii) Less reliable results due to negligence of line resistance and admittance

Table 5: Continued.

Type	References	Index/Formula	Nature of inputs	Number of inputs	Assumption	Critical value	Advantages	Disadvantages
Bus	[54]	$SDC = \lvert 1 + \underline{\Delta U_j^{(k+1)}} \cdot \underline{I_j^{(k)^*}} / \underline{\Delta U_j^{(k)}} \cdot \underline{I_j^{(k+1)^*}} \rvert$	I and U	2	—	0	(i) Using just local data (i.e., voltage and current phase measurements on each selected line), this index guards against voltage instability (ii) It is simple to implement in a digital relay due to its computational simplicity	(i) Its implementation requires two consecutive recordings of local phasors
	[55]	$VSIbus = [1 + I_i \Delta V_i / V_i \Delta I_i]^{\alpha}$	I and V	2	$\Delta Vr \approx \Delta Ir$	0	(i) This index can be used reliably, especially at high load levels, to estimate the critical load of the system at the voltage collapse point using linear extrapolation	(i) Since the index depends on several parameters, the calculation process is complex
	[56]	$ISI = 1 - \lvert I_r \Delta V_r \rvert / \lvert V_r \Delta I_r \rvert$	I and V	2	System topology remains unchanged after a disturbance	0	(i) It is extremely appealing for PMU-based online monitoring and protection programs (ii) Simple, very fast in terms of calculations, and easy to implement	(i) Very sensitive to topology changes
	[57]	$Z_L/Z_S = M + 1/ - M\cos\beta + [(M\cos\beta)^2 - M^2 + 1]^{0.5}$	M and β	2	$73^{\circ} \leq \varphi s \leq 87^{\circ}$	0	(i) Can estimate with sufficient accuracy (ii) It is based on real load admittance and power values	(i) It is complex because it requires various parameters
	[58]	$L = \lvert 1 - \sum_{i \in \alpha_G} \underline{F_{ji}} \cdot \underline{V_i} / V_j \rvert$	$\underline{F}_{ji}$ and V	2	All generator voltages remain unchanged	1	(i) Simple structure and reasonable calculation time (ii) It is easy to handle (iii) The accuracy of the limit state prediction is very satisfactory	(i) Sensitive to the topology
Global	[59]	$\Delta V = J_{RQ}^{-1} \Delta Q$	Q and ${J_{RQ}}^{-1}$	2	$\Delta P = 0$	—	(i) Identifies the bus that participates the most in the excitation of the unstable mode, in other words, the most fragile bus in the network;	(i) Long computation time since it requires the calculation and evaluation of the eigenvalues of the reduced matrix J_R (ii) Neglects the effect of active power
	[60]	$\Delta V = J_{RP}^{-1} \Delta P$	P and ${J_{RQ}}^{-1}$	2	$\Delta Q = 0$	—	(i) Calculates the participation factor of each bus in the unstable mode	(i) Long computation time since it requires calculation and evaluation of the eigenvalues of the reduced matrix J_R (ii) Neglects the active power's effect
	[61]	$S_{Gp} = P_{gt}/P_{dt}, S_{Gq} = P_{gt}/Q_{dt}$	P and Q	2	Power system efficiency is constant	S_{Gp} and S_{Gq} increment gradually towards infinite values	(i) Predicts the voltage instability and the point of voltage collapse (ii) Sensitive to active and reactive power variations	(i) No specific value at the critical point (ii) Abrupt variation at the limit (iii) Less sensitive at low loads
	[62] [63]	$\tau_{lk} = \lvert e_c^T J J_{lk}^{-1} e_l \rvert$	J and e	2	l = k	0	(i) Practical and it provides information on how many parameters variation the system can handle before it collapses	(i) Complex because it needs several parameters; (ii) Long computation time
	[64]	$i = -1/i_0 \sigma_{max} / d\sigma_{max} / d\lambda_{total}$	σ, λ, and i_0	3	—	0	(i) Identifies areas that require compensation (ii) Remedy the problem of high nonlinearity	(i) Complex because it needs several parameters; (ii) Long computation time

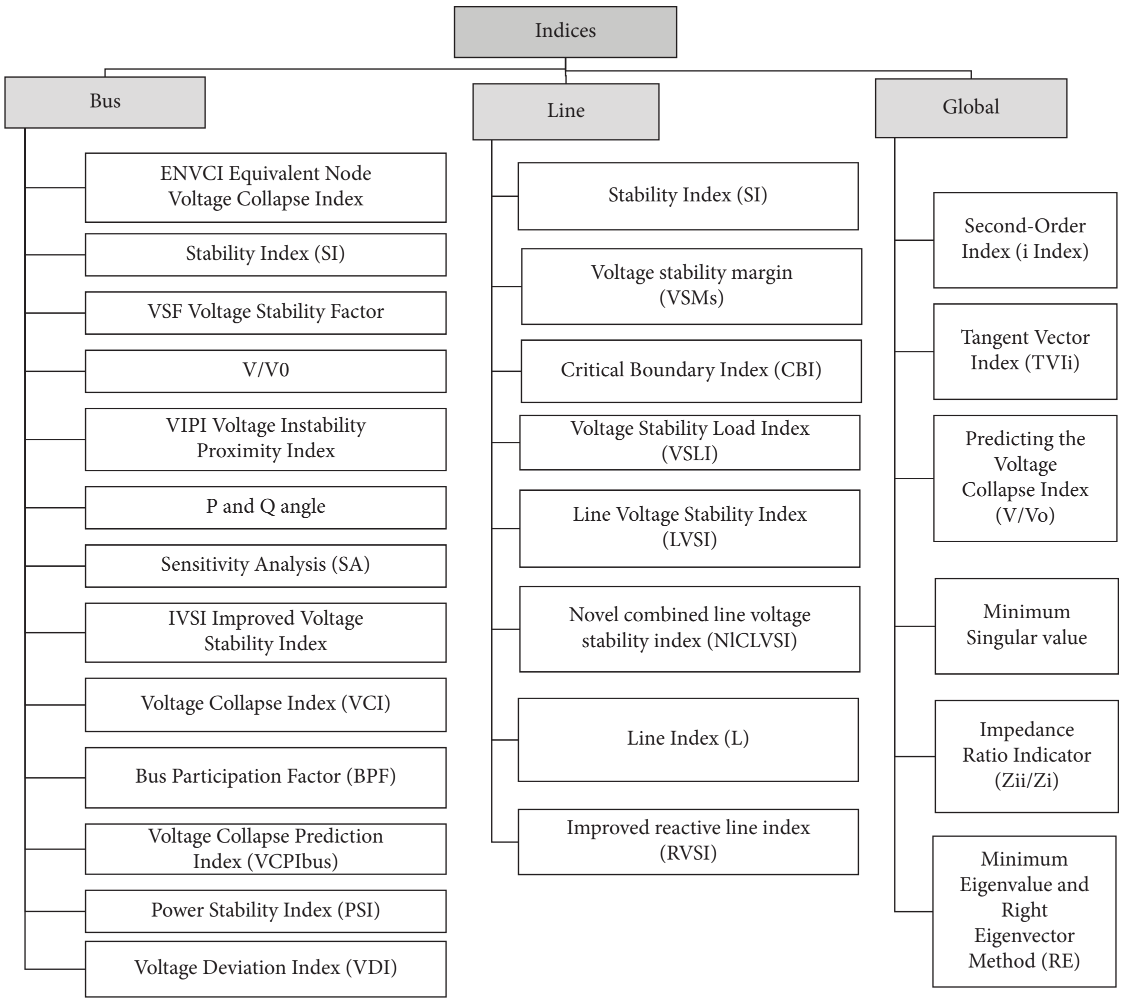

Figure 6: Taxonomy of different voltage stability indices.

Table 6: Main benefits of FACTS integration [57, 59, 60].

Economic	Security	Quality
(i) Minimize production cost by choosing the optimal location of FACTS in the network (ii) Minimize the demand for new transmission and distribution lines (iii) Improve productivity (iv) Assistance in preventing major economic losses in the event of unforeseen circumstances	(i) Increase the protection of critical loads (ii) Increase the safety of the system by increasing the transient stability limit and the load capacity of the lines (iii) Keep the network stable and improve its stability margin (iv) Reinforcing the network against disruptions (v) Development of a cyber-secure control approach (vi) Development of a cyber-secure control approach	(i) Solve the problem of voltage fluctuations and improve power quality (ii) Reduce active and reactive power losses (iii) Improve voltage stability as a result of its capacity to generate reactive power (iv) Improve the capacity of the power transit (v) Improve the dynamic performance of the network (vi) When employing an energy storage device, there is no interruption in power transmission (vii) Controlling the line's active and reactive power flow

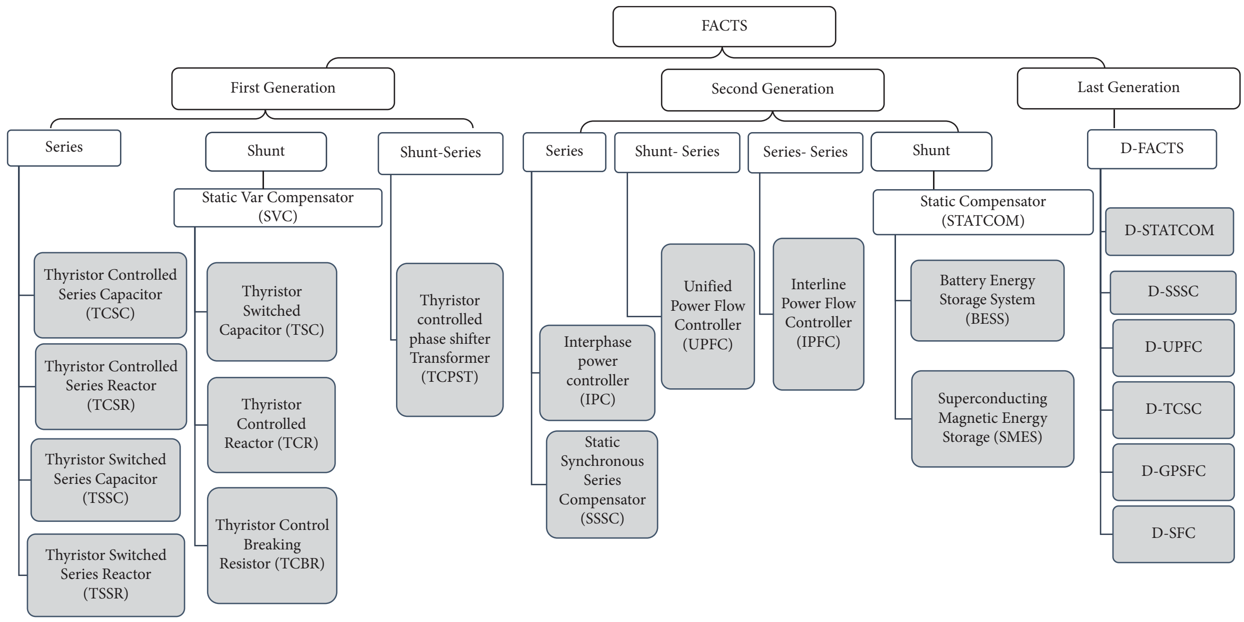

Figure 7: Classification of FACTS controllers.

most known FACTS devices in each generation are presented in Figure 7.

4.3. Discussion and Comparative Study on FACTS Controllers. Flexible AC Transmission Systems (FACTS) devices as previously mentioned are electronic devices used in power systems to enhance the power transfer capability, voltage regulation, stability, and reliability of the power system. They can be broadly classified into three main categories: shunt devices, series devices, combined series, and shunt devices.

Shunt FACTS are devices that are connected in parallel to transmission lines and are primarily designed to improve the system power factor and control the voltage level. The most commonly used shunt device is the static var compensator (SVC) [66, 67], which controls the flow of reactive power in the system and improves the voltage level after disturbances. To enhance the voltage profile, several studies have been conducted in the literature using various optimization techniques to determine the optimal location and capacity of SVC devices to be installed. For example, [68] proposes a novel approach to determine the optimal number, location, and capacity of SVCs for enhancing voltage stability by employing voltage stability indices and the PSO algorithm. Another study employs the harmony search algorithm to identify the optimal location and capacity of SVCs to reduce voltage variation at buses and decrease active losses [69].

Serial FACTS are connected in series to transmission lines to enhance the system power transfer capacity by controlling the line impedance. The thyristor-controlled series capacitor (TCSC) is the most commonly used series device that regulates line reactance. A study was conducted to examine the effect of TCSC on the stability of power systems when subjected to load disturbances. The investigation utilized the IEEE 14-bus test system, and the results of simulations indicated that the use of TCSC can improve the voltage profile and bolster power system stability in the face of load disturbances [70]. In [71], the installation costs of FACTS combined with a voltage stability index were targeted to install TCSC in the IEEE 6- and 30-bus test networks. Another study optimized and regulated the voltage deviation and excessive flow in lines in the IEEE 14- and 39-bus networks by placing TCSC and other FACTS devices [72]. In addition, the installation of several FACTS devices, namely, TCSC, TCPST, TCVR, and SVC, to reduce the amount of active power loss in the transmission lines of the IEEE 30-bus test network was the subject of [73].

Hybrid-type FACTS are combined series and shunt devices used to control both the voltage level and the system power transfer capability. The most commonly used combined device is the unified power flow controller (UPFC), which can control the power flow simultaneously with independent voltage control. A study on the effects of UPFC placement on power flow control as well as on voltage profile is presented in [74]. This study showed that the electrical network performance is better with the UPFC model than without the UPFC model. In [75], the load capacity of the network was formulated as a single objective to be maximized using the UPFC in the IEEE 14-bus network.

In terms of performance and cost, each device has its advantages and disadvantages. For shunt devices, the STATCOM is often the most cost-effective solution for voltage regulation [76], but it may not be suitable for applications where there are high levels of power flow. SVCs are generally less expensive than series devices such as TCSCs or combined devices such as UPFCs. SVCs are very effective in controlling the reactive power flow in the system [77], but they may not be able to handle large power transfer capacities. On the other hand, series devices such as TCSCs are very effective in increasing the power transfer capability of the system, but they may not be able to control the voltage

Table 7: Comparative study of FACTS controllers.

References	FACTS	Definitions	Advantages	Drawbacks
[82]	TSR	It is a reactance coupled to a bidirectional thyristor device in theseries. By controlling the thyristor in phase, the value of the reactive power supplied is adjusted to meet the varying conditions of the system	(i) This controller uses thyristors without firing control; hence, lowering cost and losses (ii) It is used for the compensation, regulation, and damping of oscillations in electrical systems (iii) Simple operating principle	(i)Inability to prevent overvoltage (ii) It may interact with the system at low frequencies (iii) Its performance is variable
[83] [77]	TSC	The TSC circuit consists of a bank of capacitors placed in series with thyristors mounted in the antiparallel. There is a small inductance connected in series with the capacitors to limit transient overvoltage and to provide resonance effects in the network	(i) Limit the current in case of abnormal operation (ii) Cheaper devices that provide suitable results in reactive power compensation (iii) This controller offers low losses	(i) The reactive power can only be changed in steps (ii) For a continuously variable reactive power generation, a TCR is necessary to compensate for the limits of the TSC
[77] [84]	SVC	SVC appeared in the seventies. The first SVC was installed in western Nebraska, North America, to meet the need for voltage stabilization due to highly fluctuating industrial loads such as rolling mills or arc furnaces. According to the IEEE, it is a shunt-connected static generator or absorber of reactive energy	(i) Increases the active power transmission capacity of the network (ii) Provides more smooth and accurate control than conventional compensation (iii) Reduce time surges (iv) Low cost and loss compared to STATCOM; (v) Improve voltage stability (vi) Easy to implement in a load flow calculation program (vii) It can be considered an important FACTS controller suitable for voltage stability at an average cost compared to other FACTS	(i) The SVC allows controlling only voltage among the three important parameters (impedance, voltage, and angle). For the other two parameters, other systems are needed to control them (ii) Requires a lot of work for installation and a lot of floor space. In addition, they are very expensive (iii) Slower than STATCOM (iv) It does not take into account active losses due to SVC components
[84] [85]	STATCOM	The STATCOM, developed with the advent of GTO thyristors, is a static synchronous generator operating as a shunt-connected static reactive energy compensator. It is regarded as a variable voltage source that is automatically adjusted to reach the desired voltage	(i) Produce or absorb the reactive power Q according to the need (ii) Maintenance cost is minimal (iii) Does not require large capacitors for energy storage, which results in a reduction in size (iv) No capacitor is needed to produce the reactive power (v) Shorter response time (vi) Limit voltage fluctuation and flicker (vii) Its operating characteristics are far superior to those of a conventional static compensator (SVC)	(i) Higher cost and loss than SVC (ii) Does not take into account active losses due to the STATCOM's components (iii) Slower than BESS
[86]	BESS	It is a chemical source energy storage system, that collects energy from a variety of sources, retains this energy in rechargeable batteries, and then uses it later	(i) Ability to handle extremely high DC voltage during and after the contingency (ii) Able to prevent unexpected voltage decreases in the early moments of an emergency, whereas STATCOM cannot (iii) Regulating and adjusting the energy flow in the loaded transmission line (iv) BESS's response is faster than STATCOM's response	(i) Overcharging of the battery was observed leading to overheating (ii) Interactions between the BESS device and the other elements
[87] [88]	SMES	It includes two coupling transformers (Δ.Y/Δ.Δ), and two converters based on SCR or GTO thyristors associated with a superconducting energy storage coil on the DC side	(i) Very short response time (ii) Active and reactive power control (iii) Very high yield (iv) Long service life (almost infinite cyclability) (v) No environmental problems (vi) Dynamic control of power flow in electrical systems	(i) Very fast discharging operation

Table 7: Continued.

References	FACTS	Definitions	Advantages	Drawbacks
[85] [89]	TCSC	It is a capacitive reactance compensator that appeared in the mid–80s. It consists of a series of capacitors in parallel with thyristor-controlled inductors to ensure a homogeneous variation of the capacitive reactance	(i) The TCSC can maintain good compensation when the line current decreases within limits defined by the electrical characteristics of thyristors (ii) Reduce overloads and limit circuit load (iii) Control line power flow using the TCSC's high-speed switching capability	(i) Cannot exchange active power with the transmission line (ii) Its size is large compared to the SSSC
[90] [89]	TSSC	The TSSC is the first to appear in the family of serial compensators, it is defined by IEEE as a capacitive compensator that consists of several capacitors in series. A thyristor switch controls the capacitor and offers step correction	(i) Energy flow control (ii) Energy storage by converter (iii) Stabilize the voltage by generating or absorbing reactive energy (iv) Fault current limitation	(i) Cannot exchange active power with transmission line
[80]	TSSR	It is an inductive reactance composed of a series reactor shunted by a thyristor. This thyristor is switched between completely ON and OFF states to create stepped series inductance	(i) Current control (ii) Transient and dynamic stability (iii) Voltage stability (iv) Fault current limiting	(i) Introduction of harmonics
[91]	SSSC	It consists of a static converter connected in series with the transmission line via a voltage transformer. It is similar to the STATCOM, except instead of a shunt, it is serially linked	(i) Ability to keep the inserted voltage value constant, independent of the current. Therefore, it is effective for small loads (low currents) as well as for large loads (ii) Its size is reduced in comparison to that of the TCSC (iii) Load balancing in interconnected networks (iv) produce or absorb reactive power according to the need	(i) It makes the network vulnerable to overvoltage due to repetitive commutations (ii) High cost compared to that of TCSC
[92]	UPFC	The UPFC appeared at the beginning of this decade. It is defined according to IEEE as a combination between a STATCOM and an SSSC, to enable active power to flow in both directions between the output of the SSSC and the STATCOM. It consists of two three-phase GTO thyristor voltage inverters, which are capable of varying active and reactive power	(i) Ability to adjust the voltage, impedance, and angle of the transmission line, as well as the actual and reactive power flow in the line (ii) Increase the capacity of transmission lines (iii) Reduce operating costs (iv) It is the most adaptable and powerful FACTS device	(i) Owing to its complicated configuration, it has a substantial cost (ii) Complex operating principle; due to the control of two inverters operating simultaneously
[80]	IPFC	The IPFC is composed of 2 or more SSSCs connected by a shared DC connection to facilitate bidirectionally active power flow between the SSSCs' alternative terminals	(i) Balance the reactive and real power flow between lines (ii) Correcting the imbalance between overloaded and underloaded lines (iii) Increasing the efficiency of the overall system (iv) Compensate voltage drops on resistive lines and the corresponding reactive power demand	(i) Owing to its complicated configuration, it has a substantial cost (ii) Complex operating principle (iii) More technological and requires a great deal of research

level of the system effectively. The SSSC is often the most cost-effective solution for power flow control, but it may not be suitable for applications where voltage regulation is required. For hybrid devices, the UPFC is often the most expensive solution, but it provides the most comprehensive control over both voltage and power flow [78, 79]. The IPFC is a newer technology that is still being developed, but it has the potential to provide a cost-effective solution for power flow control in multiline systems [80, 81]. To deepen, a detailed comparative study on the advantages and disadvantages of FACTS devices related to voltage stability was conducted and presented in Table 7.

5. Conclusions

This study gives an overview of the methods that are used to control and improve voltage stability. On one hand, various definitions have been presented and briefly summarized to derive a new definition that takes into account the process and the involved factors. On the other hand, an outlook of different analyses and prevention methods of voltage stability has been proposed. An exhaustive classification of voltage stability indices as well as their different advantages and limitations has been given to provide a general baseline for decision-making in choosing appropriate VSIs for identifying the weak area in the system. Furthermore, a well-detailed comparative study of the different FACTS dispositive existing in the literature has been developed to help identify the contribution of each device in voltage stability and its compatibility with different network parameters and configurations.

Data Availability

No underlying data was collected or produced in this study.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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