

Line Voltage Stability Indices Based on Precautionary Measure Approximation in Smart Grid*

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Abstract: Voltage stability and voltage collapse issues have in recent years begun to constitute an unpleasant warning to the operational security of power systems. In consequence, the significances that would provide a preliminary warning before the voltage collapse had grabbed the attention. This paper considered the implementation of real-time system monitoring methods that able to provide a timely warning in the power system before the voltage collapse occurred. Different line voltage stability indices such as line stability index (L_{mn}) and voltage collapse point indicator (VCPI) were executed to resolve their performance. The main intension is to recognize which index is most applicable for being adopted in power system control and security applications. Therefore, the time-domain results were used to calculate the line stability indices and to ratify with voltage stability indices theory. The line stability indices were tested in the smaller IEEE 9-bus test case and a larger IEEE 30-bus test case. The PowerWorld simulator was used to provide the time-domain results. Then, the results from the simulation were used to calculate the line stability indices by using Matlab. All the indices were found consistent with the theoretical background. In order to differentiate the performance and the robustness of the indices, the line stability indices' accuracy was evaluated. From the results in IEEE 9-bus test case and IEEE 30-bus test case, VCPI was found to have the best accuracy performances in reflecting the stability of the power systems.

Key words: Power systems; Voltage collapse; Voltage stability; Voltage stability indices

1 Introduction

Contemporary, a number of blackouts interconnected to the voltage stability issue have happened in several countries. The greatest quantities of major blackouts took place in the year 2003. The United States (U.S.)-Canadian blackout took place on August 14, 2003. During the blackout, an estimated value of 50 million people was affected in eight U.S. states and two Canadian provinces. Approximately, 63 GW of load was interrupted, which equals to 11 % of the total serving load in the Eastern Interconnection of the North American system. According to the reports, more than 400 transmission lines and 531 generating units at 261 power plants tripped^[1-3]. Subsequently, on September 23, 2003, a major blackout took place in Southern Sweden and Eastern Denmark and has an impact on 2.4 million customers^[2,4]. Five days later on September 28, 2003, some other major blackout began when a tree flash over caused the tripping of a major tie-line between Italy and Switzerland^[5,6].

Essentially, voltage instability is a non-linear phenomenon. The instability is indicated when the network is being fully utilized up until it crosses the maximum deliverable power limits. The pioneer motivations for transmission network improvements and enlargement are dependable considerations and interconnection of new generation resources. Despite that, some economic criteria and environmental consideration should be taken into account and hence will cause the planning to be postponed^[7]. Moreover, the rapid increasing of implementation of renewable energy is prone to cause the transmission network to be more complicated and stressed, since these sources have a higher and random behavior.

Deserved by voltage stability characteristics from 10 seconds up to a few minutes range of time periods^[8], the stability of the stressed power system obliged to be monitored in real time so that

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appropriate counter measures can be implemented in timely manner, or else the system will experience voltage instability and sooner will lead to voltage collapse.

Voltage stability can be classified to have a strong relation linked to the theory of maximum load ability of a transmission network. When the consumption loading is getting high enough, then compulsory measures should be taken in order to reduce the tension of the transmission network^[9, 10]. A major problem related to tracking the maximum loading of the transmission system is that the maximum loading is not a fixed quantity, but relatively relies on the generation and load patterns, network topology and the accessibility of variable resources^[11]. All the mention factors can differ with time due to the unexpected disturbances and scheduled maintenances.

The number of power systems outages throughout the world is illustrated in Figure 1. From Figure 1, it shows a significant growth for the power systems outages during the last decade. Besides that, it also shows the trend still expanding.

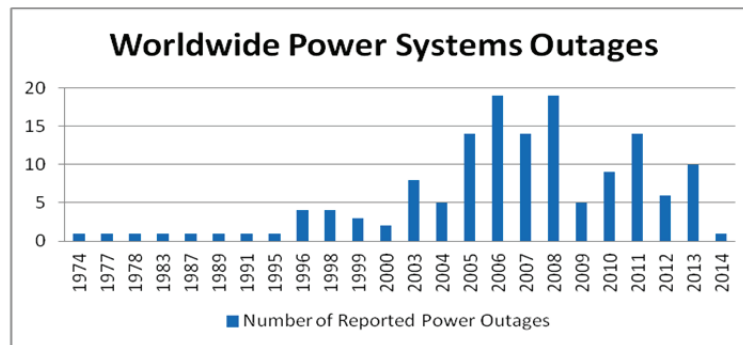


Figure 1 Total Number of Worldwide Power Systems Outages (until February 2014)

After examining the sequence of incidents that caused the major blackout in the year 2003, the causes of the blackouts were due to a shortage of reliable real-time data^[1]. The significant of real-time data is to allow the operators to carry out important and suitable preventive action to avoid cascading or else will lead the system to incorrect or delayed correction actions and thus will give a chance of instability occurrence.

Voltage stability assessment and control are not considered as any new issue^[14], but they have now attained special attentions to maintain the stability of the transmission networks in order to avoid recurrence of major blackouts as experienced by the particular countries. The power system can be classified in the voltage stability region if it can maintain steady acceptable voltages at all buses in the system under normal operating conditions and after being subjected to a disturbance^[8, 15]. In order to be reliable, the power system must be stable most of the time. The study on voltage stability can be break down into various approaches, but the estimation on the power system's distance towards voltage collapse can be very handy to the operators before they take any remedial actions^[16]. The details on the distance towards voltage instability can be obtained by using Voltage Stability Indices (VSI)^[17].

Various causes are the commencement of the power systems outages. Some of the power systems outages can be classified as the unpreventable events from the system operator. During the unpreventable event took place; the system operator cannot control the damaged level happened in the power system. In the meanwhile, in several cases, the power system outages can be prevented with the utilization of the sufficient system protection and situational awareness. If the power system is not equipped with the sufficient system protection, then the power system is prone to critical operational situations and lead to instabilities. Hence, voltage instability is one of the significant problems in causing the power outages.

The main intension of this paper is to validate the performance of the chosen traditional line voltage in the existing power system to resolve the most suitable stability indices for monitoring and controlling purpose in the time-domain simulation situation. The performances of the indices are compared by using the following: the accuracy and usefulness of the indices' values, the reliability towards the load increase and the awareness towards the inadequate lines.

This paper is mainly focused on the system variable – based voltage stability indices. The reason for focusing on system variable – based voltage stability indices is because it requires fewer amount of computing time. Besides, it also can precisely verify the weak bus or lines in the power systems. The simulations were performed by using the PowerWorld. In addition, two test power systems were utilized

in this paper, which are IEEE 9-bus test case^[17] and IEEE 30-bus test case^[18].

The rest of this paper was organized as follows. A background study on the overview of definitions of voltage stability, characteristic of voltage stability analysis and voltage stability indices will be discussed in section 2. The implementation of the voltage stability indices and the details of the simulation cases will be talked about in section 3. Results and discussion will be comprised in section 4. Finally, this paper is concluded in section 5.

2 Background of Study

Prior to describe further in voltage stability, a documented definition of power system stability obliged to be described in order to obtain a clearer outlook. The suggested denotation in^[19] for power system stability is the capability of an electric power system, for a specified starting operating condition, to recover a state of operating balance after being exposed to a physical disturbance, with most system variables required so that practically the whole system remains intact.

Typically, a recent power system is a high-order multivariable operation whose dynamic response is affected by a wide array of devices with various natures and response rate. Initially, the power system stability is a single problem but due to different forms of instabilities that the power system possibly experiences; therefore, there is a necessity to classify the power system into appropriate categories^[8]. The categorization of power system stability is encapsulated in Figure 2. In accordance with Figure 2, power system stability can be categorized into three system variables, which are rotor angle stability, frequency stability and voltage stability. Besides that, the scale of the disturbance can also be divided into two categories, which are either small or large scale. Moreover, the time duration of the disturbances can be classified into short or long term.

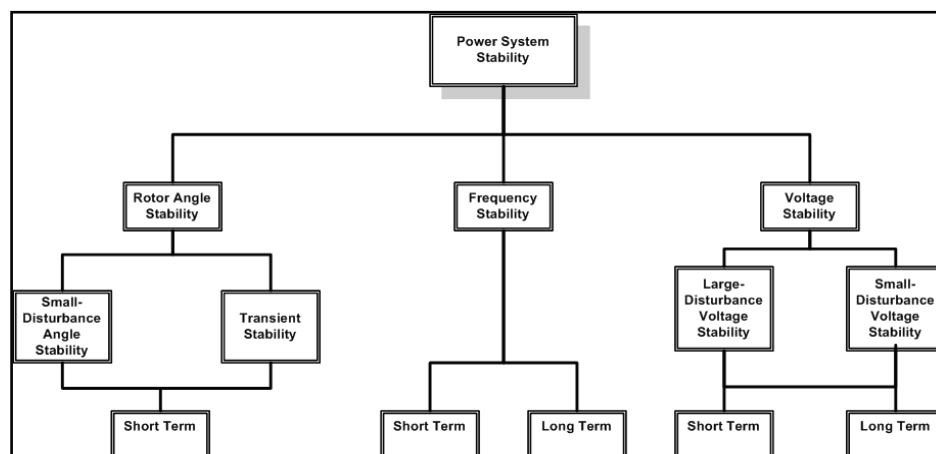


Figure 2 Categorization of Power System Stability [8]

2.1 Definitions of voltage stability

Voltage stability can be explained as the potential of the power system to sustain steady voltages at all buses in the system after being vulnerable to a disturbance from a given initial operating condition. Besides that, voltage stability is resultant on the ability of the power system to maintain or restore the equilibrium between the load demand and load supply^[8, 19].

During the occurrence of voltage instability, then the progressive fall or rise of voltages at some buses can be detected. The potential consequence of voltage instability is due to loss of load in the certain area, or tripping of transmission lines and other elements by the protection systems contributed to the cascading outages. Moreover, loss of synchronization for some generators may lead to the outages as well^[20]. In addition, voltage stability can also be considered as load stability. If the power system lacks of the capability to transfer an infinite amount of electrical power to the loads, hence voltage instability will present. The main reason for contributing to voltage instability is the inability of the power system to meet the requirements for reactive power in the extremely stressed system keeping the desired voltages^[21]. In order to restore the increasing demand of loads in the systems will cause further voltage decrement^[19]. When there is at least one bus in the system encounter bus voltage decreases as the reactive power injection in the same bus is increased, and then the system is regarded as experiencing voltage instability.

2.2 Characteristics of voltage stability analysis

Many different analysis methods have been proposed in the previous research works aiming to provide a better understanding of the phenomenon; to evaluate the systems operating conditions, and to come up with appropriate control measures to keep systems from experiencing voltage instability situations. In organizing and performing power system scheme, the investigation of voltage stability can be associated with two different aspects^[8, 19]:

a) Proximity to voltage instability: How close is the system towards voltage instability?

b) Mechanism of voltage instability: During voltage instability occurs, what are the fundamental elements that contributing to instability? What are the weak voltage areas? What computational methods are most efficient in enhancing voltage stability?

2.3 Voltage stability indices

Voltage stability indices are very applicable in order to retrieve the voltage stability of the power system. Voltage stability indices are the scalar magnitudes that being implemented to observe the changes of the parameters in the system. Besides that, the indices are also used to quantify the distance of the particular operating point with the point of voltage collapse^[22]. These indices will be very handy to the operators before they started to implement the prevention actions^[15].

According to^[23, 24], the authors mentioned that voltage stability indices particularly can be subdivided into two parts, which are Jacobian matrix based voltage stability indices and system variables based voltage stability indices.

Jacobian matrix based voltage stability indices are able to calculate the voltage collapse point or maximum load ability of the system and discover the voltage stability margin. However, these indices required high computational time and for this particular reason, the Jacobian matrix based voltage stability indices are not appropriate for online assessment. In the meanwhile, system variables based voltage stability indices required less computational time. The reasons are due to the system variable based voltage stability indices used the elements of the admittance matrix and some system variables such as bus voltages or power flow through the lines. With the benefit of less computational time, system variables based voltage stability indices are suitable to be implemented on the online assessment and monitoring purposes. However, system variables based voltage stability indices cannot efficiently estimate the margin because their responsibilities more to determine the critical lines and buses.

Table 1 Differentiation Between Jacobian Matrix Based Voltage Stability Indices and System Variables Based Voltage Stability Indices

Jacobian matrix based voltage stability indices	System variables based voltage stability indices
Require more amount of computing time	Require less amount of computing time
Suitable for offline monitoring purpose	Suitable for online monitoring purpose
Discover voltage stability margin (Proximity towards voltage collapse)	Discover weak buses and lines (Mechanism of voltage instability)

The differentiation between Jacobian matrix based voltage stability indices and system variables based voltage stability indices is being cataloged in Table 1. The differentiation is more likely based on the two aspects which were being defined in^[8]. The two aspects are proximity towards voltage collapse – (How close is the system to voltage instability?) and mechanism of voltage instability – (How and why does instability occur?).

3 Methodologies

3.1 Implementation of voltage stability indices

Basically in this research, two different types of line voltage stability indices were implemented. They are L_{mn} index and VCPI(1) index. The data was gathered by using time step simulation in PowerWorld simulator and then was exported into Matlab to calculate the particular indices.

3.1.1 L_{mn} index

This index was proposed by Moghavvemi in^[25]. This index is based on the model of power flow through a single line as shown in Figure 3.

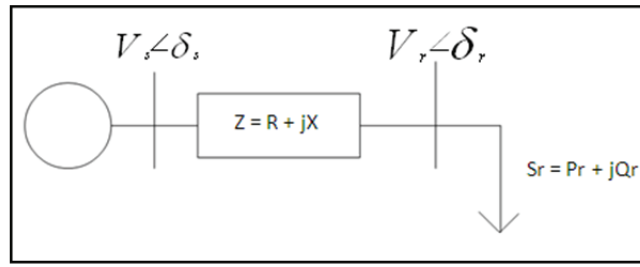


Figure 3 Two Bus System

Where:

V_s and V_r are the sending end and receiving end voltages respectively

δ_s and δ_r are the phase angle at the sending and receiving buses

Z is the line impedance

R is the line resistance

X is the line reactance

θ is the line impedance angle

P_r is the active power at the receiving end

Q_r is the reactive power at the receiving end

$$L_{mn} = \frac{4 X Q_r}{[V \sin(\theta - \delta)]^2} \leq 1 \quad (1)$$

The L_{mn} index as shown in Equation (1) is used to find the stability index for each line connection between two bus bars in an interconnected network. As long as L_{mn} index remains less than one, then the system is consider to be stable.

3.1.2 Voltage collapse point indicators (VCPI) index

Moreover, VCPI(1) index was implemented as well in this part in order to determine the voltage stability of the particular lines in the systems. VCPI(1) can be obtained by using the Equation (2).

$$VCPI(1) = \frac{P_r}{P_{r(max)}} \quad (2)$$

The denominator is the maximum power that can be transferred to the receiving end. Hence, the maximum power at the receiving end can be calculated by using Equation (3).

$$P_{r(max)} = \frac{V_s^2 \cos \phi}{Z \cdot 4 \cos^2\left(\frac{\theta - \phi}{2}\right)} \quad (3)$$

Where:

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

$$\cos^2\left(\frac{\theta - \phi}{2}\right) = \frac{1}{2} + \frac{1}{2} \cos(\theta - \phi)$$

The VCPI(1) index is used to find the stability index for each line connection between two bus bars in an interconnected network. As long as VCPI(1) index remains less than one, then the system is considered to be stable.

3.2 IEEE 9-bus system

At first, a 9-bus test system network was used for the simulation. This IEEE 9-bus system represents a portion of the Western System Coordinating Council (WSCC) 3-Machines 9-Bus system. Basically, this 9-bus system contains of three generators, nine buses and three loads. The wiring diagram for IEEE 9-bus system is illustrated in Figure 4.

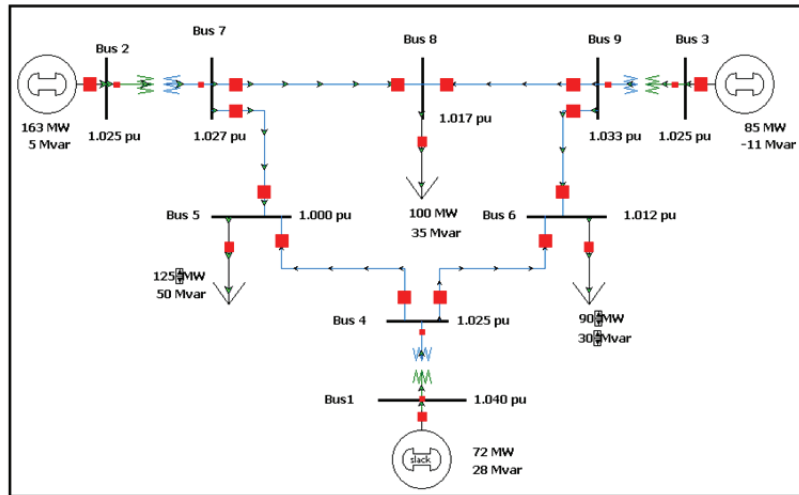


Figure 4 9-bus test network

3.3 IEEE 30-bus system

IEEE 30-bus test case represents a portion of the American Electric Power System (in the Midwestern US). Basically, IEEE 30-bus test case consists of two generators, three synchronous condensers, 30 buses and 21 loads. The wiring diagram for IEEE 30-bus system is illustrated in Figure 5.

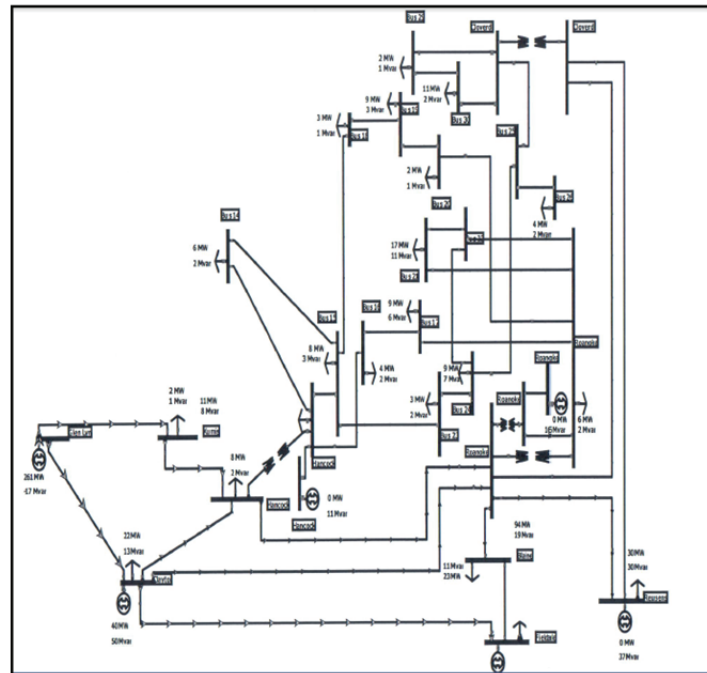


Figure 5 0-bus test network

3.4 Simulation cases

In this section, the simulation cases used and the computed indices in each are summarized in Table 2. The main intension of providing Table 2 is to give an initial perception of the simulation cases before the results are presented.

Table 2 Simulation Cases and the Summary for the Implemented Indices

Test network	Cases	Implemented indices
IEEE 9-bus	Case 1: Large load increase (5%)	L_{mn} , VCPI(1)
	Case 2: Small load increase (2.5%)	L_{mn} , VCPI(1)

	Case 3: Only Q load increase (5%)	L_{mn} , VCPI(1)
IEEE 30-bus	Case 1: Large load increase (10%)	L_{mn} , VCPI(1)

As shown in Table 3.1, there are two types of test networks which will be implemented in this research. They are IEEE 9-bus system and IEEE 30-bus system. For the IEEE 9-bus system, there will be three test cases, which mainly depended on their load variation at each step change. For case 1 the large load increase (5%), while for case 2 there will be a small load increase (2.5%). In other words, case 1 and case 2 will be mainly focused on the increment of the active and reactive power loads. Lastly, case 3 is just focused on Q load increase (5%).

In the meanwhile, the IEEE 30-bus system used one test case, which is a large load increase for the active power and reactive power load with the incremental of 10% at each step.

4 Results

4.1 Results and analysis for IEEE 9-bus test cases

In IEEE 9-bus test system, three test cases have been carried out. Initiate from the steady state based case by referring to Figure 4, the active and/or reactive power utilization of the load at bus 5, bus 6, and bus 8 are increased. Up until some particular operating point, the three units of generators are no longer to sustain the voltage with sufficient reactive power due to the rapid increasing of the loads. Hence, the voltage instability occurred and voltage collapse took place once the load demands further across the limit of the system. For case 1, the active and reactive power loads are increased stepwise by 5% load increment every five seconds and by 2.5% load for case 2. Meanwhile, case 3 mainly focused on 5% reactive power increment for every five seconds. The loads in base case and the loads' increment information are provided in Table 3 and Table 4.

Table 3 Load in Base Case and Load Increase Information for Case 1 and Case 2

Bus	Load in base case		Large load increase (5%)		Small load increase (2.5%)	
	P(MW)	Q(MVar)	ΔP (MW)	ΔQ (MVar)	ΔP (MW)	ΔQ (MVar)
5	125	50	6.25	2.5	3.125	1.25
6	90	30	4.5	1.5	2.25	0.75
8	100	35	5	1.75	2.5	0.875
Total	315	115				

Table 4 Load in Base Case and Load Increase Information for Case 3

Bus	Load in base case		Reactive load increase (5%)	
	P(MW)	Q(MVar)	ΔP (MW)	ΔQ (MVar)
5	125	50	0	2.5
6	90	30	0	1.5
8	100	35	0	1.75
Total	315	115		

The first case in IEEE 9-bus system increases each load node by a constant rate of 5% of the load base case for every five seconds. In this test case, the simulation runs for 180 seconds. Besides that, the second case increases each load node by a constant rate of 2.5% of the load base case for every five seconds and the simulation runs for 360 seconds. From the bus voltages' profiles for second case, the voltage collapse point is observed during 290 seconds. The third case in IEEE 9-bus system increases each of the reactive load nodes by a constant rate of 5% of the load base case for every five seconds. In this test case, the simulation runs for 1050 seconds. From the bus voltages' profiles, the voltage collapse point is observed during 390 seconds.

The L_{mn} and VCPI(1) time plots for the case 1 are illustrated in Figure 6. According to the instability state for the indices, these indices should cross 1 during the voltage collapse point. During the steady-state condition, these indices remain the value under 1, and will cross 1 during unstable condition. As initiated before, these indices are used to investigate the weakest line in the system. Line 7-5 is the weakest line in the system while line 7-8 is the strongest line. Besides that, L_{mn} index showed the most convincing result in test case one as compared to the VCPI(1) index.

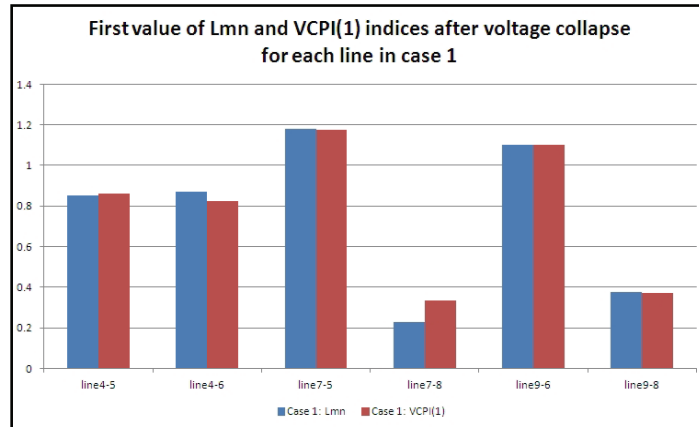


Figure 6 IEEE 9-Bus Test Case L_{mn} and VCPI(1) Indices Results for Case 1

The L_{mn} and VCPI(1) time plots for the case 2 are presented in Figure 7. According to the instability state for the indices, these indices should cross one during the voltage collapse point. During the steady-state condition, these indices remain the value under 1, and will cross 1 during unstable condition. As mention before, these indices are used to investigate the weakest line in the system. Line 7-5 is the weakest line in the system while line 7-8 is the strongest line. Besides that, L_{mn} index showed the most convincing result in test case two as compared to the VCPI(1) index.

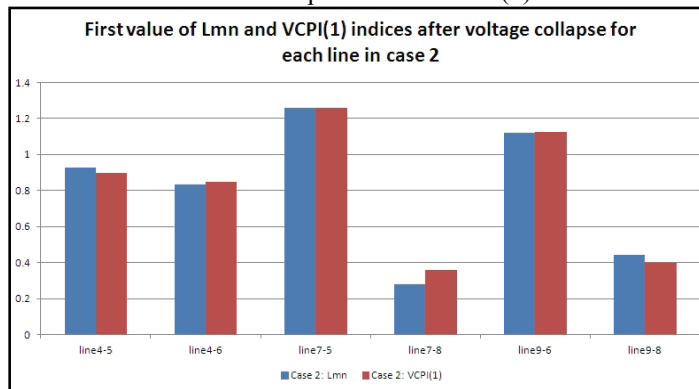


Figure 7 IEEE 9-Bus Test Case L_{mn} and VCPI(1) Index Results for Case 2

The L_{mn} and VCPI(1) time plots for the case 3 are presented in Figure 8. According to the instability state for the indices, these indices should cross one during the voltage collapse point. During the steady-state condition, these indices remain the value under 1, and will cross 1 during unstable condition. As mention before, these indices are used to investigate the weakest line in the system. Line 4-5 is the weakest line in the system while line 7-8 is the strongest line. Besides that, VCPI(1) index showed the most convincing result in test case three as compared to the L_{mn} index.

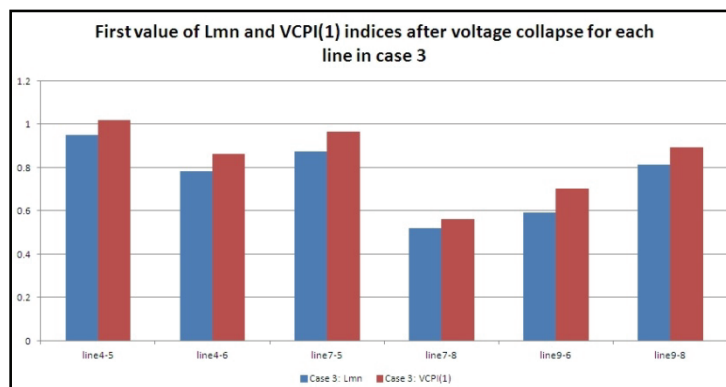


Figure 8 IEEE 9-Bus Test Case L_{mn} and VCPI(1) Index Results for Case 3

Table 5 The Summary Of The Last Value Before and First Value after Voltage Collapse in the Weakest Lines Occurred in IEEE 9-Bus System

Test network	Cases	Last value before voltage collapse		First value after voltage collapse	
		L_{mn}	VCPI(1)	L_{mn}	VCPI(1)
IEEE 9-bus system	Case 1: Large load increase (5%)	0.7347	0.7278	1.178	1.177
	Case 2: Small load increase (2.5%)	0.9130	0.9070	1.257	1.258
	Case 3: Only reactive load increase (5%)	0.9200	0.9861	0.9504	1.017

According to Table 5, the L_{mn} index showed the most convincing results for case 1 and case 2. However, VCPI(1) showed the more accurate results for case 3 as compared to L_{mn} . In case 3, the VCPI(1) initiated the line 4-5 was the weakest and unstable during the time point, but the L_{mn} showed the line 4-5 still in stable condition. The last value before the voltage collapse is very vital for the operator because it alerts that the system is close to collapse and also on the particular lines as well. Therefore, the operators should implement the prevention methods in order to avoid the system from experiencing any voltage instability and voltage collapse incidents.

4.2 Results and analysis for IEEE 30-bus test case

In IEEE 30-bus test system, one test case has been carried out. Initiate from the steady state based case by referring to Figure 5, the active and reactive power utilization of the load at bus 2, bus 3, bus 4, bus 5, bus 7, bus 8, bus 10, bus 12, bus 14, bus 15, bus 16, bus 17, bus 18, bus 19, bus 20, bus 21, bus 23, bus 24, bus 26, bus 29 and bus 30 are increased. Up until some particular operating point, the five units of generators are no longer to sustain the voltage with sufficient reactive power due to the rapid increasing of the loads. Hence, the voltage instability occurred and voltage collapse took place once the load demands further across the limit of the system. For case 1, the active and reactive power loads are increased stepwise by 10 % load increment every five seconds. The loads in base case and the loads' increment information are provided in Table 6.

Table 6 Load in Base Case and Load Increase Information for Case 1

Bus	Load in base case		Large load increase (10%)	
	P(MW)	Q(MVar)	ΔP (MW)	ΔQ (MVar)
2	21.7	12.7	2.17	1.27
3	2.4	1.2	0.24	0.12
4	7.6	1.6	0.76	0.16
5	94.2	19.0	9.42	1.9
7	22.8	10.9	2.28	1.09
8	30.0	30.0	3.0	3.0
10	5.8	2.0	0.58	0.2
12	11.2	7.5	1.12	0.75
14	6.2	1.6	0.62	0.16
15	8.2	2.5	0.82	0.25
16	3.5	1.8	0.35	0.18
17	9.0	5.8	0.9	0.58
18	3.2	0.9	0.32	0.09
19	9.5	3.4	0.95	0.34
20	2.2	0.7	0.22	0.07
21	17.5	11.2	1.75	1.12
23	3.2	1.6	0.32	0.16
24	8.7	6.7	0.87	0.67
26	3.5	2.3	0.35	0.23
29	2.4	0.9	0.24	0.09
30	10.6	1.9	1.06	0.19
Total	283.4	126.2		

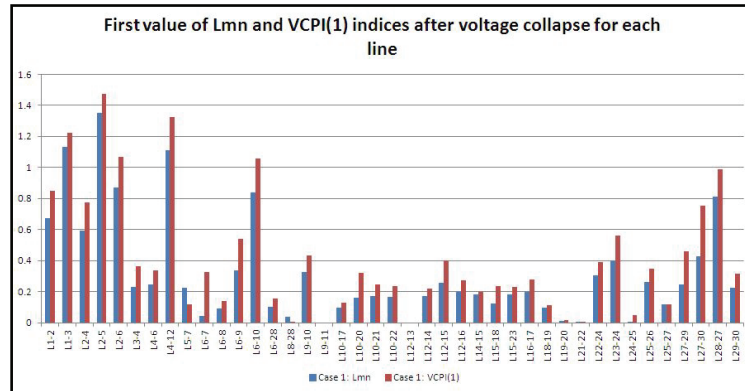


Figure 9 IEEE 30-Bus Test Case L_{mn} and VCPI(1) Indices

The L_{mn} and VCPI(1) time plots for IEEE 30-bus test case is presented in Figure 9. According to the instability state for the indices, these indices should cross 1 during the voltage collapse point. During the steady-state condition, these indices remain the value under 1, and will cross 1 during unstable condition. As mention before, these indices are used to investigate the weakest line in the system. Line 2-5 is the weakest line in the system while line 7-8 is the strongest line. Besides that, VCPI(1) index showed the most convincing result as compared to the L_{mn} index.

Table 7 The Summary of the Last Value Before and First Value after Voltage Collapse in the Weakest Lines Occurred in IEEE 30-Bus System

Test network	Cases	Last value before voltage collapse		First value after voltage collapse	
		L_{mn}	VCPI(1)	L_{mn}	VCPI(1)
IEEE 30-bus system	Case 1: Large load increase (10%)	0.5500	0.9714	1.352	1.474

By referring to Table 7, the VCPI(1) index showed the most convincing results in case 1. The last value before voltage collapse is very vital for the operator because it alerts that the system is close to collapse and also on the particular lines as well. Therefore, the operators should implement the prevention methods in order to avoid the system from experiencing any voltage instability and voltage collapse incidents.

5 Conclusions

This paper compared the performance of two different line stability indices which are L_{mn} and VCPI(1). The indices were tested and validated on the IEEE 9-bus test system and also in a larger IEEE 30-bus system. In terms of general performance, both indices are coherent with the theoretical background. When the system is stable, then these line stability indices will present the value below zero and cross one when the system facing voltage collapses. This should be clear on how much does the indices indicate about the stability of the system, without viewing any other measure or parameters of the system. The function of the indices also presented the identical classification of the lines regarding to their weakenss From this, the VCPI(1) index provided the best yet accurate results and followed by L_{mn} index.

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