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Transmission network voltage stability assessment using a new line stability index

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Abstract :
Voltage stability assessment is one of the critical topics concerning the stability of power systems. With the increasing loading of transmission networks and its impact on downstream networks, the importance of studying this issue has gained attention even more. By presenting a new index, this paper evaluates the voltage stability of transmission systems. Employing the proposed index, network lines can be assessed in terms of voltage stability, and this means identifying weak network lines. Besides decreasing the calculation burden, the proposed index can boost accuracy. The index has been extended to consider the impact of the presence of distributed generations (DGs) and on-load tap changers (OLTC). To analyze and calculate the efficiency of the proposed index, two standard 9-bus and 14-bus transmission networks are utilized and the results are compared with other indices, showing that the results related to this index are reasonable and acceptable in comparison with those of other indices and impose a lower computational burden.

Keywords: Line stability index, Transmission network, Tap changer, Voltage stability, Voltage collapse.

1. Introduction

Voltage stability has become a decisive problem in transmission and distribution networks due to the constant increase in demand, high power transmission between interconnected areas, the high penetration level of renewable energy resources (RESs), and environmental and economic constraints. As the loading level of the network increases, so does the probability of voltage collapse in the power system. Therefore, identifying lines and nodes prone to voltage instability has attracted more attention recently. Voltage stability and stability indices are among the topics that have always been considered by scholars in the past decades [1].

Voltage stability indices play a critical role in predicting the behavior and capability of power transmission in the power system. Lack of continuous monitoring and evaluation of voltage stability can lead to possible instability in the system. Therefore, it is necessary to predict instability and continuously monitor the performance of the power system. Moreover, for a power system to work reliably, all conditions that cause malfunctions in the operation of the system should be carefully identified before taking any corrective action [2].

Voltage stability is defined as the ability of the power system to maintain an acceptable steady-state voltage on all buses under normal and faulty operation conditions [3]. The system encounters voltage instability conditions when the occurrence of perturbation, an increase in the demand, or a

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change in the status of the system causes an increasing and uncontrollable voltage drop [4].

The reason for static voltage instability is that some loads reach their maximum allowable values, where the power flow will no longer converge [5]. Using sequential power flows with increasing system load is one of the first procedures to find the stability limit. Nonetheless, the load flow divergence due to instability may not violate the critical point but remain close to the voltage stability limit due to numerical misbehavior. To address this challenge, continuous power flow is presented [6].

The authors in [7-9] present methods based on power flow equations to investigate the voltage stability in the distribution network. These procedures need to solve a major number of power flow equations. As a result, their calculations are overwhelming and complex. Some researchers use the Jacobin matrix to find the stability margin. The calculations of these indices are complex and need the computation of the Jacobian matrix and the network impedance matrix which might not be inverted or may not be available [10-13].

Voltage stability assessment has also been expressed using P-Q and P-Q-V diagrams [14-17], where the stability margin of the buses is assessed and weak buses are identified. Wang L. et al. [18], proposed an index regardless of the line impedance value. It is also supposed that the sending-end voltage is supplied from an ideal power source. In [19-24], various indices are presented to assess the voltage stability in distribution networks. Additionally, using analytical methods, the index presented in [25] is extended to be employed for smart grids [26]. In [27-30], the authors have also provided indices to assess the voltage stability in the transmission network using the equivalent circuit of the transmission line.

A 2-bus equivalent circuit has also been used to provide stability indices based on the node voltage level, maximum transmission power, and line specifications, such as [31], [32], [33], [34], [35], L1, [36], [37], NLSI [38], NLSI-1 [39], and ENVC [40]. These indices have a low computational burden and can be used to effortlessly compute the stability of all system buses.

Nowadays, the study and analysis of power systems has become more difficult due to the larger size of the system as well as the number of sources and consumers. The escalating penetration of DGs and the increase in the number of tap-changer transformers necessitates considering them to perform the correct analysis of voltage stability. In the literature discussed above, the presented indices are related to the study of voltage stability in distribution and transmission networks. Regarding the latter, some of these papers do not consider any of the mentioned elements and some consider only the presence of DGs.

The current paper proposes a new index for calculating the voltage stability of transmission networks. Using this index, transmission network lines can be classified from the perspective of voltage stability; this means identifying weak system lines. In the following, the presented index is expanded in such a way as to take into account the presence of DGs and OLTC. To assess the presented index and simulate the scenarios, standard 9-bus and 14-bus networks have been implemented in DIgSILENT software. Contributions of the paper are summarized as follows:

- Presentation of a new index for voltage stability assessment in transmission systems that provides high accuracy. This advantage makes it possible to use it in transmission systems, despite the wide range and number of lines.
- Development of the presented index in the presence of DGs and OLTCs. With this index, the effect of these types of equipment on the voltage stability of transmission systems can be checked.

The paper is organized as follows. Section 2 introduces the conventional indices used for voltage stability assessment. Section 3 deals with the analytical discussion concerning the proposed indices. The numerical results and conclusions are reported in Sections 4 and 5, respectively.

2. Existing voltage stability indices

This part briefly addresses some conventional voltage stability indices of transmission networks. These line indices were proposed to assess the voltage stability status of power systems based on transmission line capability. To compare the performance of the proposed index, four well-known voltage stability indices are reviewed.

2.1. VCPI_1 index

Voltage stability index VCPI_1 proposed by Wang L., Liu Y., and Luan Z. [18] is defined as:

$$VCPI\_1 = V_r \cos(\delta) - 0.5V_s \tag{1}$$

In this index, by using the values of the sending end and receiving end bus voltages plus the phase angular difference between the two buses, the desired line stability value can be obtained. The closer the value of the index is to 1, the more stable the line is.

2.2. VSM index

The VSM index is based on the stability margin and is presented for the transmission network, the equations of which are given as follows [41]:

$$VSM = \frac{S_{cr} - S_L}{S_{cr}} \tag{2}$$

$$S_{cr} = \frac{V_1^2}{2Z(1+\cos(\theta-\varphi))} \tag{3}$$

In the above index, S_L is the apparent load power, θ represents the phase angle difference between the two buses, and φ is the load angle. Also, the closer the value of this index is to 1, the more stable the line is.

2.3. LQP index

The LQP index as a factor to assess the voltage stability of the lines is presented below [42]:

$$LQP = 4\left(\frac{X}{V_i^2}\right) * \left(\frac{XP_i^2}{V_i^2} + Q_j\right) \tag{4}$$

This index also calculates the stability index using the information of the considered line as well as the power passing through it. Thus, the closer the value of this index is to zero, the more stable the line is.

2.4. FVSI index

This index, similar to the previous index, has been presented to assess the stability of transmission network lines [43]:

$$FVSI = \frac{4Z^2 Q_j}{V_i^2 X} \tag{5}$$

the closer this index value is to zero, the more stable the line is and it performs voltage stability calculations using the line data.

3. Proof of the proposed index

This section provides an analytical discussion of mathematical proof of the proposed index to evaluate the voltage stability of lines in the transmission network. Initially, the proof of the proposed index is presented in the absence of DGs and OLTCs. Next, the proposed index is developed in the presence of DGs and OLTCs.

3.1. Formulation of the proposed index

To calculate the proposed index, a typical one-line transmission line model has been employed. In this model, the line impedance is considered as follows:

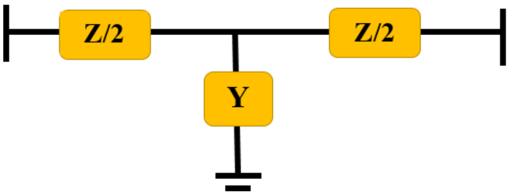


Fig. 1. Equivalent circuit T of a transmission line

The above circuit is converted to a new circuit using the star-delta transformation:

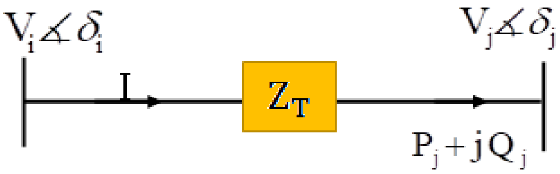


Fig. 2. Single-line model of the two-bus system

By simplifying the above equation, the following equation is obtained:

$$Z_T = \frac{\frac{Z}{2} * Z_Y + \frac{Z}{2} * Z_Y + \frac{Z^2}{4}}{Z_Y} \tag{6}$$

$$\begin{aligned} P_j &= P_G - P_D \\ Q_j &= Q_G - G_D \end{aligned} \tag{7}$$

In the above equation, the value of impedance Z_Y is the equivalent impedance of the line admittance.

P_j shows the active power of the receiving end bus, and Q_j is the reactive power of the receiving end bus. The proof of the index is as follows:

$$P_j + j\,Q_j = V_j * I^* \tag{8}$$

$$I = \frac{P_j - jQ_j}{|V_j| \angle -\delta_j} \tag{9}$$

$$I = \frac{|V_i| \angle \delta_i - |V_j| \angle \delta_j}{Z_T} \tag{10}$$

By equating Eqs. (9) and (10):

$$\frac{|V_i| \angle \delta_i - |V_j| \angle \delta_j}{Z_T} = \frac{P_j - jQ_j}{|V_j| \angle -\delta_j} \tag{11}$$

By sorting the above equation:

$$|V_i||V_j| \angle (\delta_i - \delta_j) - |V_j|^2 = (R_T + jX_T).(P_j - jQ_j) \tag{12}$$

Then, by solving Eq. (12), the result is obtained as follows:

$$VSI_1 = (|V_i| \cos \delta_{ij})^2 - 4(R_T.P_j + X_T.Q_j) > 0 \tag{13}$$

Finally, using the index presented in Eq. (13), the stability of transmission network lines can be calculated. After calculating and studying the load flow, the index is calculated for each transmission network line. When the index is computed, the line with the smallest index value is weaker in terms of voltage stability than other lines. In contrast, the closer the calculated value for the line index is to unity, the more stable that line is. This index also has a critical value of zero. This means that if the value of this index is zero for a line, that line is subject to voltage collapse.

3.2. Extension of the proposed index in the presence of OLTCs and DGs

Due to the extension and complexity of transmission systems and the presence of OLTCs and DGs in these systems, the study of the voltage stability of transmission systems will not be straightforward. Consequently, the indices presented in the introduction may lack suitable efficiency.

In the following, with the expansion of the suggested index, the impact of the presence of DGs and OLTCs is considered. This index can be used to monitor the effect of DGs and OLTCs on the network voltage stability. Fig. 3 depicts the circuit used for obtaining the mathematical equations of the index. Then, all of the equipment on the primary side of the transformer is transferred to its secondary side.

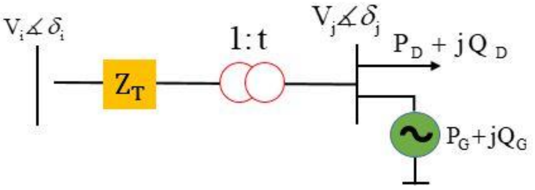


Fig. 3. Typical one-line diagram of transmission line in the presence of OLTCs and DGs

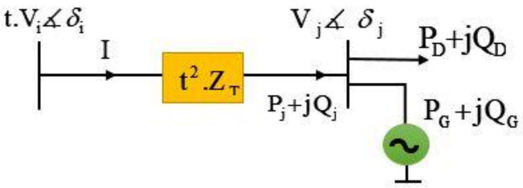


Fig. 4. One-line diagram of the transmission line after the elimination of the transformer

The proof of the index according to Fig .4 is as follows:

$$I = \frac{t.|V_i| \angle (\delta_i) - |V_j| \angle \delta_j}{(t)^2.Z_T} \tag{14}$$

$$I = \frac{P_j - jQ_j}{|V_j| \angle -\delta_j} \tag{15}$$

By equating the sides of Eqs. (14) and (15), the following equation is obtained:

$$|V_i|^2 - t|V_i||V_j|\cos(\delta_i - \delta_j) + (t)^2(R_T P_j + X_T Q_j) = 0 \tag{16}$$

By solving Eq. (16), the result is obtained as follows:

$$VSI_2 = [t|V_i|\cos(\delta_i - \delta_j)]^2 - 4(t)^2[R_T P_j + X_T Q_j] > 0 \tag{17}$$

Eq. (17) shows the VSI in the presence of DGs and OLTCs. With this formulation, the effect of DGs and the operation of OLTC on the voltage stability of the transmission system can be studied. The values of Pj and Qj are the amount of active and reactive power received at the end of the transmission line

4. Numerical results and discussion

The results related to the efficiency assessment of the suggested methods are presented. In each scenario, two proposed indices are assessed and compared with other indices.

4.1. Computation of the suggested index

The proposed method is tested on two standard 9-bus and 14-bus transmission networks have been used. Its results are also compared with [18] and [42-44]. The capability of the proposed index is analyzed in the following cases.

- Computation of the suggested index in the baseload mode
- Computation of the suggested index in the critical mode
- Contingency analysis
- Investigation of indices in different power factors

In each of the above modes, first, the power flow is executed and then the value of the indices in different lines is calculated.

4.1.1. Computation of the suggested index in the baseload mode

In this part, without changing the amount of active and reactive loads of the system, the suggested index is computed and compared with [18] and [42-44]. As can be seen in Tables 1 and 2, at this level of network load, the voltage stability situation is desirable based on most indices. Only the VCPI-1 index provides an incorrect estimate of the network voltage stability. This indicates the low accuracy of this index and its incorrect efficiency at the baseload.

The performance of the proposed index seems desirable and according to this index, line 6-9 in the 9-bus network and line 1-2 in the 14-bus network are the weakest. Other indices also show relatively acceptable performance, the results of which are tabulated in Tables 1 and 2.

Table (1): Line stability indices for a 9-bus test system for baseload mode

Line (from-to)	Proposed index	VCPI-1	VSM	LQP	FVSI
4-5	0.9038	0.4823	0.9045	0.1291	0.1264
4-6	0.9701	0.4995	0.9347	0.0606	0.0597
7-5	0.8086	0.4744	0.8164	0.1333	0.0567
7-8	0.9927	0.5014	0.9497	0.0402	0.0297
9-6	0.7977	0.4918	0.8797	0.1588	0.1263
9-8	0.9554	0.4988	0.9651	0.0143	0.0932

4.1.2. Computation of the suggested index in the critical mode

To analyze the index in the critical mode, the load value of the two considered buses is increased in the way mentioned earlier. First, without changing the active power, the reactive power is increased, then both active and reactive power are increased simultaneously with the constant power factor to such an extent that the load side no longer converges. After that, in each case, the value of the suggested index is computed and compared with [18] and [42-44]. The results are presented in Tables 3-6.

As one can observe, the value of the VSM index is negative in several cases, which indicates the poor performance of this index in critical conditions. Furthermore, by observing the value of the VCPI-1 index, in critical conditions, the operator has the impression that the network is still far from the instability point, even though the network is approaching the collapse point. The FVSI index in some values, as given in Table 4, is greater than one, which indicates the poor performance of this index. The LQP index also behaves relatively well, but its value in the critical lines is still far from the critical values, for which the operator may have an incorrect perception of the network. Eventually, by investigating the provided index, one can see that this index has a very good performance and provides the operator with correct information about the network conditions.

Table (2): Line stability indices for a 14-bus test system for baseload mode

Line (from-to)	Proposed index	VCPI-1	VSM	LQP	FVSI
1-2	0.7085	0.5105	0.8989	0.2617	0.1505
1-5	0.9036	0.4726	0.9387	0.1225	0.0219
2-3	0.9116	0.4774	0.3168	0.0964	0.0199
2-4	0.9376	0.4858	0.6799	0.0462	0.0107
2-5	0.9674	0.4911	0.9497	0.0388	0.0212
3-4	0.8991	0.5072	0.6609	0.0621	0.063
4-5	0.9705	0.5093	0.9871	0.0234	0.0228
6-11	0.9973	0.5189	0.9738	0.032	0.0387
6-12	0.9977	0.8182	0.9419	0.0342	0.0297

6-13	0.9757	0.513	0.9338	0.0379	0.0452
9-10	0.9997	0.5206	0.9710	0.0114	0.0129
9-14	0.975	0.5049	0.8460	0.0318	0.0358
10-11	0.997	0.5191	0.9333	0.0185	0.0216
12-13	0.9463	0.5215	0.8603	0.0065	0.0144
13-14	0.9267	0.5064	0.7991	0.0306	0.0362

Table (3): Comparison of voltage stability indices with increasing reactive power in the standard 9-bus network

Loading (p.u.)	Line (from-to)	Proposed index	VCPI-1	VSM	LQP	FVSI
Q=2.545 p.u. at bus 5	7-5	0.0005	0.1609	-0.5501	0.9794	0.9030
	4-5	0.1266	0.1851	0.1206	0.8288	0.8242
	9-6	0.5759	0.4046	0.8595	0.3534	0.3286
Q=2.631 p.u. at bus 6	9-6	0.0006	0.121	-0.5966	0.9787	0.9621
	4-6	0.0705	0.1514	0.0253	0.8919	0.8967
	7-5	0.4759	0.3820	0.7794	0.4499	0.3823

Table (4): Comparison of voltage stability indices with increasing reactive power in the standard 14-bus network

Loading (p.u.)	Line (from-to)	Proposed index	VCPI-1	VSM	LQP	FVSI
Q=1.916 p.u. at bus 10	11-10	0.0799	0.3347	-0.1497	0.8514	0.9944
	9-10	0.1118	0.1635	0.4217	0.7837	0.8914
	9-14	0.1954	0.4668	0.6899	0.6305	0.7696
Q=1.245 p.u. at bus 14	13-14	0.0263	0.1017	-0.6293	0.9496	1.1412
	9-14	0.0385	0.1143	-0.0136	0.9332	1.1123
	6-13	0.6313	0.3819	0.7037	0.384	0.4764

Table (5): Comparison of voltage stability indices with increasing active and reactive power in the standard 9-bus network

Loading (p.u.)	Line (from-to)	Proposed index	VCPI-1	VSM	LQP	FVSI
Q=P=1.834 p.u. at bus 5	7-5	0.0576	0.1759	-0.5191	0.9303	0.7652
	4-5	0.1214	0.1832	0.1319	0.8857	0.6333
	9-6	0.5211	0.4121	0.8165	0.4272	0.4397
Q=P=1.885 p.u. at bus 6	9-6	0.0176	0.1017	-0.6293	0.9515	0.8389
	4-6	0.1043	0.1143	-0.0136	0.8787	0.5958
	7-5	0.4855	0.3819	0.7037	0.446	0.4374

Table (6): Comparison of voltage stability indices with increasing active and reactive power in the standard 14-bus network

Loading (p.u.)	Line (from-to)	Proposed index	VCPI-1	VSM	LQP	FVSI
Q=P=1.377 p.u. at bus 10	11-10	0.0956	0.1495	-0.3865	0.7239	0.7086
	9-10	0.1293	0.1726	0.3215	0.6547	0.6175
	9-14	0.2379	0.4701	0.7389	0.4906	0.5901
Q=P=0.862 p.u. at bus 14	13-14	0.0145	0.1028	-0.4287	0.6615	0.8184
	9-14	0.0259	0.1113	-0.1589	0.854	0.7515
	6-13	0.6291	0.4788	0.9397	0.341	0.4042

4.1.3. Contingency analysis

To evaluate the effectiveness of the proposed index in predicting the voltage collapse due to the outage of the system lines, the performance of the index is evaluated in this section using Contingency analysis. To this end, a standard 9-bus network is utilized. Initially, one of the lines is tripped in the baseload mode and then the stability index is calculated in the other lines [2]. This method is repeated for all the lines. Table 7 presents the results of the lines with the lowers stability level based on the proposed index. Moreover, comparing the results shows that other indices in these lines are close to their critical values. Additionally, for a more comprehensive analysis, the reactive power at bus 5 of the 9-bus network has been increased by half the critical power. Then, in each step, one of the network lines is disconnected and the value of the stability index for the other lines is calculated. The results are presented in Table 8. The same process is performed for bus 6 in the 9-bus network, the results of which can be seen in Table 9.

Table (7): Analysis of stability indices in the baseload

Line outage (from-to)	Most stressed line (from-to)	Proposed index	VCPI-1	VSM	LQP	FVSI
4-5	7-5	0.4588	0.3991	0.7016	0.5161	0.3417
4-6	9-6	0.664	0.4219	0.8223	0.2926	0.2079
7-5	9-6	0.715	0.4358	0.9274	0.2717	0.0476
7-8	7-5	0.7312	0.4401	0.9177	0.3053	0.0516
9-6	4-6	0.8332	0.4589	0.9235	0.1369	0.1129
9-8	9-6	0.8626	0.4821	0.9417	0.1266	0.0563

Table (8): Analysis of stability indices in the presence of reactive load at bus 5

Line outage (from-to)	Most stressed line (from-to)	Proposed index	VCPI-1	VSM	LQP	FVSI
With reactive load at bus 5 Q = 0.485 p.u						
4-5	7-5	0.0001	0.0958	0.3117	1.0713	0.7867
4-6	9-6	0.6571	0.4195	0.8186	0.2952	0.2092
7-5	4-5	0.5277	0.3611	0.7681	0.4174	0.3668
7-8	7-5	0.6815	0.3985	0.9113	0.3399	0.0717
9-6	4-5	0.6977	0.4284	0.8107	0.2752	0.2784
9-8	7-5	0.7042	0.4425	0.8792	0.2421	0.2093

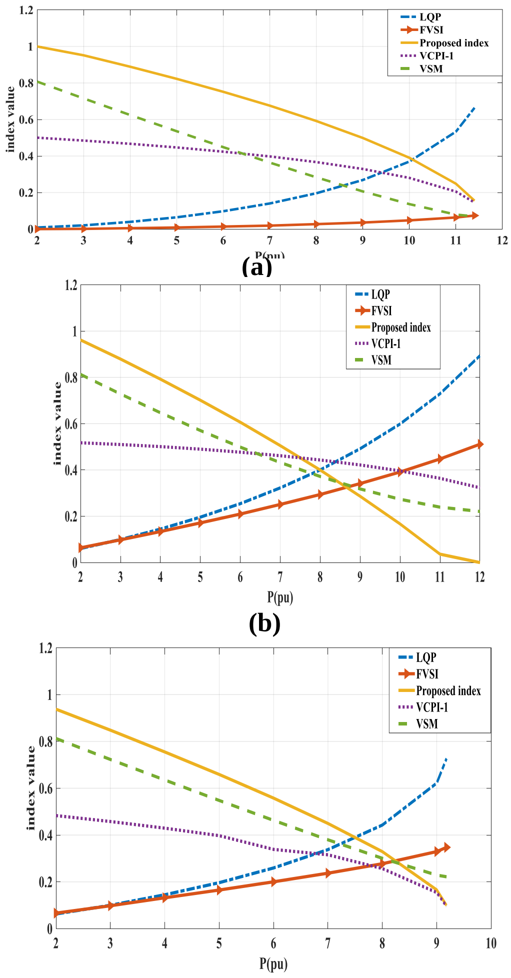
Table (9): Investigation of stability indices in the presence of reactive load at bus 6

Line outage (from-to)	Most stressed line (from-to)	Proposed index	VCPI-1	VSM	LQP	FVSI
With reactive load at bus 6 Q = 0.7 p.u						
4-5	7-5	0.4486	0.3449	0.6913	0.5234	0.3451
4-6	9-6	0.0156	0.0936	0.3621	0.9574	0.8163
7-5	9-6	0.5384	0.3655	0.8877	0.3869	0.152
7-8	9-6	0.5895	0.4308	0.7285	0.3761	0.3926
9-6	4-6	0.4869	0.3515	0.7491	0.4342	0.4125
9-8	9-6	0.6514	0.4216	0.8724	0.3044	0.2379

4.1.4. Investigation of the indices in different power factors

In this section, the load at bus 14 in the 14-bus test system is gradually increased to the voltage collapse. Then, at each step, the values of indices are calculated. For a more comprehensive analysis of the indices, this load increase has been carried out in three loading modes (different power factors): 0.95 lag, 0.95 lead, and unity power factor. The values of the indices are obtained for lines 13-14 and 9-14 and illustrated in Figs. 5 and 6.

Referring to Figs. 5 and 6, the FVSI index shows poor performance, especially in the case of unity and lag power factors (parts A and B in Figs. 5 and 6), where the index does not behave properly near the instability point. Also, the VCPI-1 index generally behaves inappropriately and cannot accurately express the line conditions. The VSM index also presents a poor performance in the lead power factor mode (part C in Figs. 5 and 6), due to the increase in the load. Besides, the LQP index does not perform well in the case of the unity power factor (part A in Figs. 5 and 6), near the instability point. Finally, according to the above figures, it can be seen that the proposed index has acceptable performance and can express the network conditions correctly.

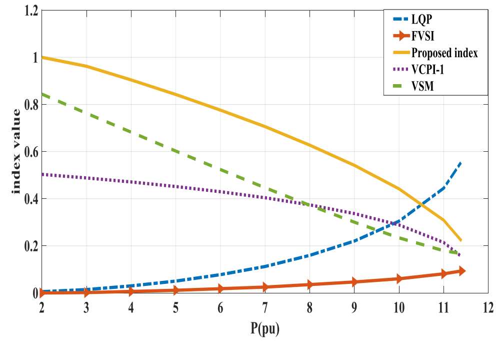


(a)

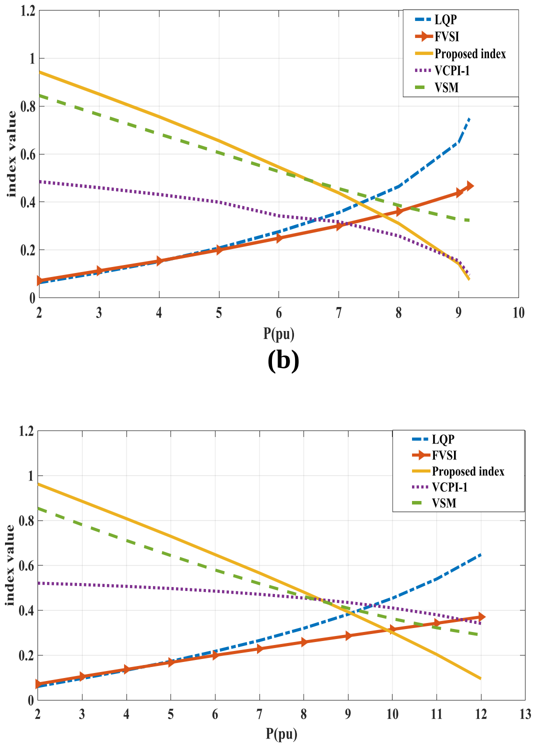
(b)

(c)

Fig. 5. Comparison of the stability indices of line 9-14 in the 14-bus network
a) Unity power factor loading conditions, b) Lag loading conditions, and c) Lead loading conditions



(a)



(b)

(c)

Fig. 6. Comparison of the stability indices of line 13-14 in the 14-bus network
a) Unity power factor loading conditions, b) Lag loading conditions, and c) Lead loading conditions

4.2. Assessment of the suggested index in the presence of DGs and OLTCs

This section addresses the assessment of the index proposed in part 3.2. To this end, a 9-bus transmission network is utilized. To assess the suggested index, three scenarios are considered. First, the proposed method is studied in the presence of DG in the network. Then, the effect of changing the transformer tap on the stability index is evaluated separately. Finally, the proposed stability index is examined with the presence of both of the above elements.

4.2.1. Analysis of the performance of the index in the transmission network with DGs

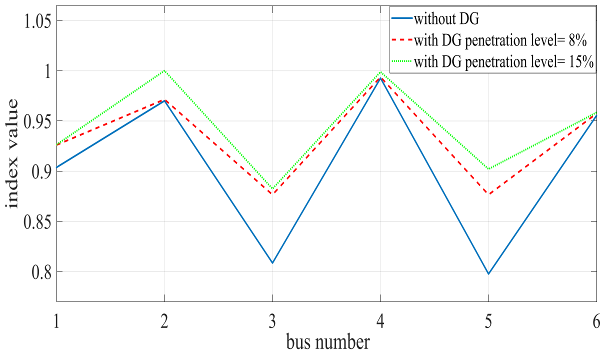


Fig. 7. Computation of the suggested index in the 9-bus test system in the presence of DGs

In this section, DGs with a rated power of 25 MW and with penetration factors of 8% and 15% at bus 5 have been used [44]. To compute the proposed method, first, the stability of the transmission system with DGs has been investigated without changing the OLTC. The related conclusions are illustrated in Fig. 7. As can be seen, with increasing the level of DG penetration in the transmission network, the level of network stability has improved, which indicates the correct and accurate performance of the proposed index.

4.2.2. Analysis of the performance of the proposed method in the transmission system when changing the OLTC

In this case, the stability of the network is investigated without DGs and by changing the OLTC. At each step of the OLTC change, the voltage level changes by one percent. To this end, the value of the index was first obtained without changing the OLTC and then the suggested index value was computed by changing one step in the OLTC. The results are presented in Fig. 8 and it can be seen that with increasing (decreasing) the tap, the stability improves (deteriorates), indicating the correct performance of the index. Also, using this proposed method, the effect of changes in the OLTC on the stability of the system can be analyzed before making any changes in the OLTC.

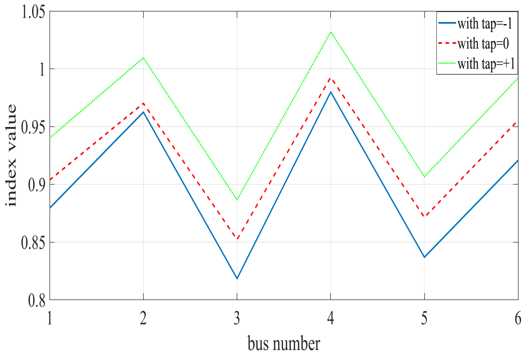


Fig. 8. Computation of the suggested index in the 9-bus test system by changing the OLTC

4.2.3. Analysis of the proposed method in the transmission network with DGs and changing the OLTC

In the end, the presence of both factors (the presence of DGs and changing the OLTC) is considered to assess the developed index in the network. To do this, a power source with an 8% penetration at bus 5 has been considered, and the OLTC has been increased by one unit. Then, the index value is calculated for the above conditions. According to the results in Fig. 9, this case shows the greatest stability changes at bus 5.

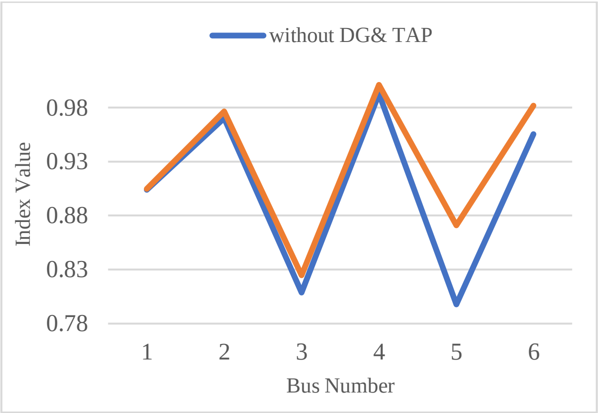


Fig. 9. Investigation of the proposed method in the presence of distributed generations and changing the OLTC

Table (10): General comparison of the indices used in the study

index	Formulation	Used variables	Assumptions	Critical value	Base loading	Critical loading
Index 2005	$VCPI\_1 = V_j \cos(\delta) - 0.5V_i$	V_i, V_j, δ	Y≈0,	0	*	*
Index 2009	$VSI = \frac{S_{cr} - S_L}{S_{cr}}$	S_L, S_{cr}, Z, V_i	Y≈0, constant power factor	0	**	*
Index 1995	$LQP = 4\left(\frac{X}{V_i^2}\right) * \left(\frac{XP_i^2}{V_i^2} + Q_j\right)$	P_i, Q_j, X, V_i	Y≈0, R≈0	1	***	**
Index 2002	$FVSI = \frac{4Z^2 Q_j}{V_i^2 X}$	Q_j, X, V_i, Z	Y≈0, δ≈0	1	**	*
Proposed index	$VSI_1 = (\lvert V_i \rvert \cos\delta_{ij})^2 - 4(R_T.P_j + X_T.Q_j) > 0$	V_i, δ, P_j, Q_j, R_T, X_T	-	0	***	***

4.3. Discussion

In this part of the paper, indices are summarized, and a general comparison is made. Finally, we provide an available summary of the indices after briefly evaluating them.

As mentioned in the previous section, to evaluate voltage stability in a transmission network, VSI, VCPI_1, LQP, and FVSI are useful indices, but all of them have problems in critical loading. On the other hand, the proposed index gives the best results. One of the reasons for the low efficiency of the existing indices is the use of simplifying assumptions in the stages of creating the indices. According to the presented results, the proposed index can assess the voltage stability of the network more precisely than other indices, and it has acceptable performance and can express the network conditions correctly (*** very good performance; ** medium performance, * poor performance).

5. Conclusions

Two VSIs are proposed in this paper for the transmission system. A new index has also been suggested for the static assessment of voltage stability in the transmission network. The proposed index can introduce weak lines in a transmission system and can supply the operator with accurate information about the stability conditions of the lines. After calculating the proposed index on all network lines, the line with the lowest value is introduced as the weaker line. In the following, due to the increasing penetration of distributed generations in the transmission network, the suggested index has been developed to study the effect of the simultaneous presence of DGs and the OLTC on the voltage stability of the transmission system. The obtained results show the efficiency and proper performance of this index. Moreover, as was indicated, using this index, the effect of changing the OLTC and increasing the penetration level of distributed generations on network stability can be investigated. Then, by examining and implementing these indices on standard 9- and 14-bus networks, it was shown that these indices, in addition to leading to simplicity and low computational burden, have a logical performance. Also, their accuracy is desirable, both in the case of baseload and critical load. To prove the efficiency level, their performance in different conditions was compared with that of other indices.

Nomenclature

acronyms	
SI	Stability index
VSI	Voltage stability index
VCPI	voltage collapse proximity index
NVSI	New voltage stability index
OLTC	on-load tap changers
LQP	Line Stability Factor LQP
LVSI	Line voltage stability index
VSM	Voltage stability margin
DG	Distributed generation
FVSI	Fast Voltage Stability Index
CP	Constant power
CC	Constant current
CI	Constant impedance
NLSI	New line Stability Index
ENVCI	equivalent node voltage collapse index
PU	Per unit
symbols	
P_G	Active power generated by DG
Q_G	Reactive power generated by DG
P_D	Active power demand
Q_D	Reactive power demand

P_j	active power at the receiving bus
Q_j	reactive power at the receiving bus
t	Tap position of the transformer
Z	Line impedance
Δ	Delta method
P	Active power
Q	Reactive power
S	Apparent power
R	Line resistance
X	Line reactance
V_i	Sending end bus voltage
V_j	Receiving end bus voltage
P_{Loss}	Active power losses
Q_{Loss}	Reactive power losses
I	Current flowing between two buses
L_P	Line stability index
L_{mn}	Line stability index
P_0	Base active power
S_{cr}	Critical apparent load power
S_L	apparent load power
Q_0	Base reactive power
V_0	voltage reference
φ_2	Phase angle difference between the voltage and current of bus 2
λ	Load factor
δ_i , δ_j	Voltage angle at the sending and receiving buses respectively
a_P, b_P, c_P	Coefficients related to constant power, constant current, and constant impedance components of active power respectively
a_q, b_q, c_q	Coefficients related to constant power, constant current, and constant impedance components of reactive power respectively

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