Improved Voltage Collapse Proximity Index for Prediction of Voltage Instability in Distribution Networks

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Abstract–One of the main criteria for voltage stability limit in modern power systems is load-ability limit (LL) real-time monitoring of system status and voltage collapse prediction based on the basic concept of maximum power transfer through a line; reassess to estimate closeness to the nose point of P-V curve in this paper. This article proposes an improved voltage collapse proximity index (IVCPI) that considers the relative direction of active and reactive powers at the receiving end for assessment of the voltage stability status of the system. The proposed approach has been applied to 12-bus distribution systems to validate its practicability. It is proved that the proposed index gives adequate results in finding load-ability margins in all practical cases.

Keywords: Voltage Stability, Line Load-ability, Equivalent Circuit, Load Margin

1. Introduction

Voltage stability refers to the ability of a power system to maintain steady voltages at all buses in the system being subjected to a disturbance from a given initial operation condition [1]. Voltage stability is one of the main factors that indicate the maximum allowable loading of distribution systems. The loads often play an important role in the analysis of voltage stability, which is also known as load-ability [2]. The stability studies are carried out through implementing the stability factor in [3]. It is clear that influence of load levels is important to voltage stability phenomena.

Some efforts to assess voltage stability margin with development of different voltage stability indices using load flow technique in distribution networks are presented in [3-20]. Moghavvemi et al. developed a technique to study voltage collapse situation (L_p) that indicates the severity of the loading situation of the system [4]. It showed the acting of this stability index is greatly influenced by the system power factor. Hence, when the load power factor is reduced to an unrealistic low level; the accuracy of this index is decreased and this index was more suitable for low voltage distribution system where the load is mainly resistive.

Chebbo et al. used the stability index with the ratio of Thevenin's impedance to load impedance that is at maximum of 1.00 [5]. Extreme reactive power absorption by the load and system itself is identified as primary causes of voltage collapse. Although voltage collapse is a slow dynamic phenomenon, typically identified as a decreasing of voltage level and followed by a sudden voltage decay leading to collapse [6]. The relationship between voltage stability and loss minimization presented in [7] that it can be shown the voltage stability is maximized when power losses are minimized in the system.

In [8-9] the voltage stability index, *SI*, is formulated for identifying the sensitive node to voltage collapse. They shown that the node at which the value of index is minimum; is more sensitive to voltage collapse. Banerjee et al. develops *VSI* to identify the weakest branch of a radial distribution system. The concept of local voltage stability indicator is established with the radial characterize of the network in terms of reactive power [10]. In [11] a voltage stability indicator is derived based on the *VSI* to identify the condition of load buses at the voltage collapse point. In [12] the improved voltage stability index, *IVSI*, developed that is used in the same way as indexes *VSI* and L_{mn} from [13]. As this index for every bus is close to 0, the system is stable; and is close to 1, the system is unstable.

The static voltage stability margin (*VSM*) is proposed in [14] to determine the distance to voltage collapse in a radial distribution system. The proposed *VSM* change almost linearly with system load and it needs only the complex bus

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voltages to evaluate. Venkatesh et al.[15]proposed a line load-ability indicator (*MLI*) which can be used to identify system voltage stability, and also to assess the line loading margin. J. Yu et al. present a new line load-ability index, L_s, to identify weak lines and buses due to voltage instability for radial distribution systems. The product of the L_s and apparent power of the line at any operation state is the estimate of maximum load-ability of the line due to voltage instability [16] They illustrated some indices (*MLI* and *Lp*) have an essential deficiency and cannot work properly in some specific cases. In fact, the outcomes of this method on certain cases has been showing an essential deficiency based on its logical structure, same some efforts. It means that the maximum load-ability in each line of system dependent to provide the normal conditions for whole of the system.

Some researchers are accustomed to analyze the voltage stability indicators based on Thevenin equivalent method [17,18]. An effective method for real-time monitoring of system status and thus voltage collapse prediction (*VCPI*) were presented in [19]. In these investigations by using the Thevenin equivalent circuit, the voltage proximity indicator for each load bus is derived by using the maximum power condition. The *VCPI* indicator is capable of identifying the exact location of voltage collapse in a power system. Adjacent to the voltage collapse point, *VCPI* (power) is less sensitive to further loading while *VCPI* (loss) is found to be highly sensitive.

In this paper is proposed an improved voltage collapse proximity index (*IVCPI*) to predict the occurrence of voltage collapse in the line. It is based on equivalent circuit of network which appropriately represents a distribution line that transmitted to each its node. The proposed technique is considered the effects of reactive as well as active power flow of line on voltage stability which were neglected by some previous indices. The effectiveness of proposed index have been investigated on 12-bus and 69-bus distribution systems and compared with some existing indicators to validate its feasibility.

2. Mathematical model of line stability index

Figure 1 illustrates the one section of radial distribution networks between two buses (sending bus *m* and receiving bus *k*), Where V_m and V_k are voltage in nodes *m* and *k* respectively, $Z = r_k + jx_k$ is impedance between node m and *k*, P_k is sum of the real power loads of all the nodes beyond node *k* plus the real power load of node *k* itself (P_{Lk}) plus the sum of the real power losses of all the sections beyond node *k*.Q_k is sum of the reactive power loads of all the nodes beyond node *k* plus the reactive power load of node *k* itself (Q_{Lk}) plus the sum of the reactive power losses of all the sections beyond node *k*.

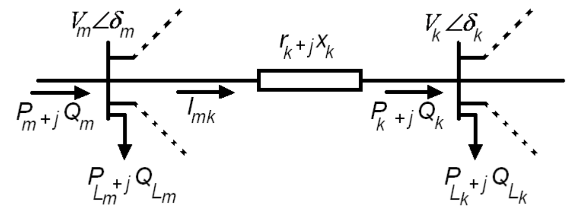

Fig 1. Model of line section of radial distribution system.

2.1 Line Stability index L_p[4]

L_p is the stability index that indicates the status of the system line and approximately show how close the operating point is to the limit of instability. The system is considered unstable when the values of L_p become greater than one.

$$L_P = \frac{4r_k P_k}{\left[V_m \cos\left(\theta - \left(\delta_k - \delta_m\right)\right)\right]^2} \le 1.00 \tag{1}$$

Where δ_m and δ_k are phase angle of sending and receiving end bus voltages, and $\theta = \tan^{-1}\left(x_k / r_k\right)$.

2.2 Line Stability index L_s[16]

The proposed load-ability index L_s in [16] is based on power flow equation. This index identifies weak lines and buses of radial distribution systems at voltage instability conditions and when its value approaches 1.00, the line, and thus the system, will become to collapse point.

$$L_s = \frac{V_m^2}{2\left[r_k P_k + x_k Q_k + \sqrt{\left(r_k^2 + x_k^2\right)\left(P_k^2 + Q_k^2\right)}\right]} \ge 1.00 \tag{2}$$

Although the both of active and reactive power is applied in this method; but the values of this index have e little non-conformance at collapse point, especially.

2.3 Line Stability index L_{mn} [13]

Moghavvemi and Omar [13] were derived L_{mn} by utilizing the concept of power flow in a single line. In order to obtain real values of V_k in terms of Q_k in the equation derived from power flow by them, the discriminant of voltage quadratic equation must be have real roots.

$$L_{mn} = \frac{4x_k Q_k}{\left[V_m \sin\left(\theta - (\delta_k - \delta_m)\right)\right]^2} \le 1.00 \quad (3)$$

As long as L_{mn} remains less than unity, the system is stable and when this index exceeds the value one, the whole system loses its stability and voltage collapse occurs.

3. Proposed index *IVCPI*

In the past section some Indicators is described that almost have ignored the relative direction of active or reactive power flow in the line of the system for deriving, and some another even with considering these issues have insignificant values when the system confront to collapse point in certain cases. In this section, an improved voltage collapse proximity index (*IVCPI*) is developed which both real and reactive power flow in the line are taken into account for assessment of voltage stability status based on equivalent circuit of the system.

Let's up illustrate the system reduced to simple two buses given in Figure2 by the equivalent Thevenin impedance Z_s and an electromotive force V_S, where was because complexity of the supplying system to the load buses [20]. $V_s\angle\delta_s$ and $V_r\angle\delta_r$ are the sending and receiving end voltages and $Z_s\angle\theta = r + jx$ is the line impedance between two buses. The $Z_r\angle\phi$ is the corresponding equivalent load impedance with $\phi = \tan^{-1}(Q_r/P_r)$.

The receive currents to sending and receiving buses can be writing as follow:

$$\vec{I}_s = \frac{V_s\angle\delta_s}{Z_s\angle\theta + Z_r\angle\phi} \quad (4)$$

$$\vec{I}_r = \frac{V_r\angle\delta_r}{Z_r\angle\phi} \quad (5)$$

Where Z_s can be calculated as

$$Z_s\angle\theta = \frac{(S_s - S_r)\times|V_s|^2}{\left(P_s^2 + Q_s^2\right)} \quad (6)$$

From equations 4 and 5, the voltage V_r by rearrangement it and apparent load power S_r can describe as

$$\left|\vec{I}_s\right| = \left|\vec{I}_r\right| \quad \Rightarrow$$

$$|V_r| = \left|\frac{Z_r}{Z_s}\right| \frac{|V_s|}{\left[1 + (Z_r/Z_s)^2 + 2\,(Z_r/Z_s)\,\cos(\beta)\right]^{0.5}} \quad (7)$$

$$|S_r| = \left|\frac{Z_r}{Z_s}\right| \frac{(V_s)^2/|Z_s|}{\left[1 + (Z_r/Z_s)^2 + 2\,(Z_r/Z_s)\,\cos(\beta)\right]} \quad (8)$$

Where $\beta = \theta - \phi$ and

$$|Z_s| = \frac{\sqrt{(P_s - P_r)^2 + (Q_s - Q_r)^2}\cdot|V_s|^2}{\left(P_s^2 + Q_s^2\right)} \quad (9)$$

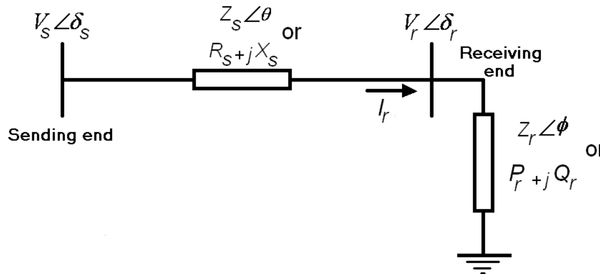

Fig. 2. One line diagram of a reduced system

$$|Z_r| = \frac{|V_r|^2}{\sqrt{\left(P_r^2 + Q_r^2\right)}} \quad (10)$$

The maximum apparent power that can be transferred to the receiving end can be obtained using the boundary condition $\partial S_r/\partial Z_r = 0$. That leads into $|Z_r/Z_s| = 1$. Substituting $|Z_r/Z_s| = 1$ in equation 8, the maximum transferable power $S_{r(Max)}$is obtained as follows;

$$S_{r(Max)} = \frac{|V_s|^2}{2\,|Z_s|\,\left(1 + \cos(\theta - \varphi)\right)} \quad (11)$$

Now, based on these maximum permissible quantities, the improved voltage collapse proximity index can derive as follows;

$$IVCPI = \frac{Apparant\ power\ transferred\ to\ bus\ r}{Maximum\ apparant\ power\ transferred\ to\ bus\ r} = \frac{S_r}{S_{r(Max)}} \quad (12)$$

Where the values of $S_r = \sqrt{P_r^2 + Q_r^2}$ are founded from conventional power flow calculations.

With the increasing power flow transferred in the line the value of *IVCPI* increase gradually. Then, voltage collapse will occur when they reach unity.

4. Validation and Simulation

In Figure 2, it is assumed that sending bus is a bus with given voltage and receiving bus is a *PQ* load bus with values $P_r + jQ_r = 0.5 + j1.0$ (*p.u.*). Also, $R_s + jX_s = 0.05 + j0.10$ (*p.u.*) and $V_s\angle\delta_s = 1.0\angle 0.0$ (*p.u.*). At this initial load state, $\phi = \theta = 63.4^\circ$, Table 1, 2, and 3 present two voltage solution of receiving load bus from *PV* curves, the Proposed technique *IVCPI* and load-ability indicators L_s, L_p and L_{mn} in three scenario.

Table 1 shows the results of two bus test system when both active and reactive loads are emphasized with a scaling factor, λ, and with constant power factor, in this case always we have $(\phi = \theta)$; Table 2 and Table 3 gives the results when only the active load and reactive load is stressed in this test system, respectively. It seems two indicators, *IVCPI* and L_s will be utilized in all cases before the *PV* curve reaches its nose point. In the other word, these two indicators are precisely consistent with the *PV* curve in determination of load-ability or voltage collapse point in this simple case study. It is because of the relative direction of active and reactive power that is considering in them structure. In Table 2 and Table 3 can infer when just active or reactive load is increased with a scaling factor it makes$(\phi \neq \theta)$. From Table 2 can observe that effectiveness of L_p index is just on high resistive systems due to crossing over of its value from unity before another indicators. Also, Table 3 illustrates that L_{mn}index has usage for assessment of voltage stability in low resistance system where reactive load power is high at the system. In continue with testing on certain cases, it will prove that some *L* indicators such as L_s have illusive value faced with actual distribution system, too.

Figure 3 shows the 12 bus radial distribution system as a first case study that the line and nominal load data gives in [9].

Table 4 illustrate the values of two indicators by increasing the scaling factor that it is multiplied to both active and reactive load until load flow converged.

It is clearly observed when the load flow converged because the minimum value of voltage in this system (Voltage in Bus 12 across from 0.5, *i.e.* nose point of *PV* curve), the line load-ability indicators L_s don't reach to critical value (unity). In this case the maximum of scaling factor is 5.235 but the value of this indicator is 2.17 in the worst case.

Also, in this table developed index, *IVCPI*; actually present the accepted result at load margin point when scaling factor reached to 2.408. It demonstrates that the *IVCPI* indicator in bus 7 passed from unity and collapse point for this system appeared. The value of voltage in the worst case is 0.8510 in bus 12 when both active and reactive loads increased by same scaling factor.

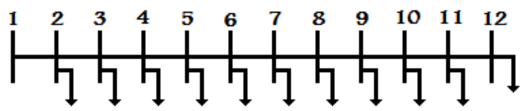

Fig 3. Schematic diagram of 12 bus radial distribution network.

Table 1. Validity of Results for two bus test system with increasing both active and reactive load andthe constant Power factor

	PV Curve		Indicators			
λ	*V(High, p.u)*	*V(Low, p.u.)*	*IVCPI*	L_s	L_p	L_{mn}
1.0000	0.8536	0.1464	0.5000	2.0000	0.5000	0.5000
1.2513	0.8059	0.1941	0.6256	1.5983	0.6256	0.6256
1.4735	0.7565	0.2435	0.7367	1.3573	0.7367	0.7367
1.6111	0.7205	0.2795	0.8055	1.2414	0.8055	0.8055
1.7977	0.6590	0.3410	0.8988	1.1125	0.8988	0.8988
1.9094	0.6064	0.3936	0.9547	1.0474	0.9547	0.9547
2.0000	0.5000	0.5000	1.0000	1.0000	1.0000	1.0000

Table 2. Validity of results for two bus test system with increasing just active load

	PV Curve		Indicators			
λ	*V(High, p.u)*	*V(Low, p.u.)*	*IVCPI*	L_s	L_p	L_{mn}
1.0000	0.8536	0.1464	0.5000	2.0000	0.5000	0.5000
1.2558	0.8443	0.1564	0.5268	1.8982	0.5916	0.5078
1.8992	0.8183	0.1884	0.6033	1.6575	0.7730	0.5303
2.1013	0.8092	0.2004	0.6294	1.5888	0.8173	0.5384
2.9094	0.7670	0.2573	0.7402	1.3510	0.9443	0.5781
3.8700	0.6957	0.3501	0.8805	1.1357	1.0000	0.6525
4.6603	0.5324	0.5324	1.0000	1.0000	---	0.8494

Table 3. Validity of results for two bus test system with increasing just reactive load

	PV Curve		Indicators			
λ	*V(High, p.u)*	*V(Low, p.u.)*	*IVCPI*	L_s	L_p	L_{mn}
1.0000	0.8536	0.1464	0.5000	2.0000	0.5000	0.5000
1.2995	0.8081	0.1926	0.6212	1.6097	0.5394	0.6381
1.4017	0.7908	0.2104	0.6631	1.5080	0.5553	0.6838
1.5188	0.7696	0.2323	0.7113	1.4059	0.5756	0.7353
1.8547	0.6955	0.3088	0.8505	1.1758	0.6527	0.8761
2.2071	0.5289	0.4784	0.9974	1.0026	0.8538	1.0000
2.2132	0.5037	0.5037	1.0000	1.0000	0.8834	---

In Table 5 and Table 6 the comparison of these two indices with increasing just active power loads and reactive power loads in all buses presented, respectively. Another time, the weakest point of L_s indicator which must be equal to own critical value (1.00) when the voltage reached to nose point of *PV* curve is clarified.

In these tables the L_s index presents the line terminated to bus 5 is critical in normal case but with increasing the loads it shoot suddenly to bus 9 as a critical point; that even after nose point of *PV* curve and collapse point, the value of this index didn't reach to unity.

In practical case of radial distribution system, it is clearly that the far off buses to feeder bus have a lower voltage than other buses; because the voltage loss in the lines. Therefore, we can observe a deficiency to find the maximum load-ability based on *L* indicators. Therefore, since the safe operation of whole system is vital, these indicators are not sufficient for determining of actual maximum load-ability and the load margin of the system.

Table 7 illustrates the critical line and maximum load-ability in 12 bus system by increasing loads in whole of system. Also, the maximum of scaling factor in this system is captured for three scenarios of load variation.

Furthermore, the line maximum load-ability for this radial distribution system will be obtained when is utilized the *IVCPI* as a voltage stability indicator condition, which $\left(1/IVCPI\right)\times S_r$ represent the line maximum load-ability and $\left(\left(1/IVCPI\right)-1\right)\times S_r$ is the line loading margin text.

Table 4. Performance of proposed technique for 12 BUS Radial Distribution Network whit increasing the both active and reactive load

	λ	BUS 2	BUS 3	BUS 4	BUS 5	BUS 6	BUS 7	BUS 8	BUS 9	BUS 10	BUS 11	BUS 12	Voltage in BUS 12 (p.u.)
IVCPI	1.000	0.0232	0.5045	0.7204	0.9313	0.9855	0.9987	0.9503	0.8114	0.6168	0.4085	0.1331	0.9434
L_s		43.04	45.78	28.60	22.36	71.82	84.24	27.20	28.46	80.57	251.76	1053.42	
IVCPI	2.408	0.0590	0.5272	0.7503	0.9496	0.9928	1.0000	0.9341	0.7843	0.5898	0.3880	0.1256	0.8510
L_s		16.94	17.71	10.98	8.44	26.15	30.40	9.80	10.04	27.64	85.47	356.35	
-	5.235	-	-	-	-	-	-	-	-	-	-	-	0.4999
L_s		5.93	5.82	3.50	2.52	6.64	7.39	2.37	2.17	4.92	14.05	56.96	

Table 5. Performance of proposed technique for 12 BUS Radial Distribution Network with increasing just active power loads

	λ	BUS 2	BUS 3	BUS 4	BUS 5	BUS 6	BUS 7	BUS 8	BUS 9	BUS 10	BUS 11	BUS 12	Voltage in BUS 12 (p.u.)
IVCPI	1.000	0.0232	0.5045	0.7204	0.9313	0.9855	0.9987	0.9503	0.8114	0.6168	0.4085	0.1331	0.9434
L_s		43.04	45.78	28.60	22.36	71.82	84.24	27.20	28.46	80.57	251.76	1053.42	
IVCPI	2.987	0.0577	0.5177	0.7543	0.9486	0.9919	1.0000	0.9367	0.7927	0.6069	0.4029	0.1221	0.8466
L_s		17.33	18.07	11.25	8.61	26.60	31.03	9.67	9.81	26.51	81.50	357.29	
-	6.791	-	-	-	-	-	-	-	-	-	-	-	0.4999
L_s		6.15	6.03	3.65	2.62	6.95	7.77	2.40	2.16	4.77	13.45	57.80	

Table 6. Performance of proposed technique for 12 BUS Radial Distribution Network with increasing just reactive power loads

	λ	BUS 2	BUS 3	BUS 4	BUS 5	BUS 6	BUS 7	BUS 8	BUS 9	BUS 10	BUS 11	BUS 12	Voltage in BUS 12 (p.u.)
IVCPI	1.000	0.0232	0.5045	0.7204	0.9313	0.9855	0.9987	0.9503	0.8114	0.6168	0.4085	0.1331	0.9434
L_s		43.04	45.78	28.60	22.36	71.82	84.24	27.20	28.46	80.57	251.76	1053.42	
IVCPI	4.994	0.0715	0.5407	0.7454	0.9511	0.9941	1.0000	0.9309	0.7737	0.5670	0.3684	0.1307	0.8672
L_s		13.99	14.72	9.11	7.11	22.25	25.79	8.82	9.32	26.79	84.10	318.10	
-	10.925	-	-	-	-	-	-	-	-	-	-	-	0.5314
L_s		4.83	4.71	2.85	2.09	5.46	6.08	2.11	2.09	5.36	16.26	59.63	

Table 7. Effect of load increasing on 12 BUS Radial Distribution Network with line loading margin of system

Increasing both of P and Q			Increasing just on P			Increasing just on Q		
λ	IVCPI,C Bus 7	$((1/IVCPI)-1)\times S$ for Bus 7 (KW)	λ	*IVCPI,C* Bus 7	$((1/IVCPI)-1)\times S$ for Bus 7 (KW)	λ	*IVCPI,C* Bus 7	$((1/IVCPI)-1)\times S$ for Bus 7 (KW)
1.000	0.9987	0.42870	1.000	0.9987	0. 42870	1.000	0.9987	0. 42870
1.719	0.9996	0.19449	1.853	0.9995	0.22081	2.816	0.9995	0.34651
2.408	1.0000	0.000	2.987	1.000	0.000	4.994	1.0000	0.000

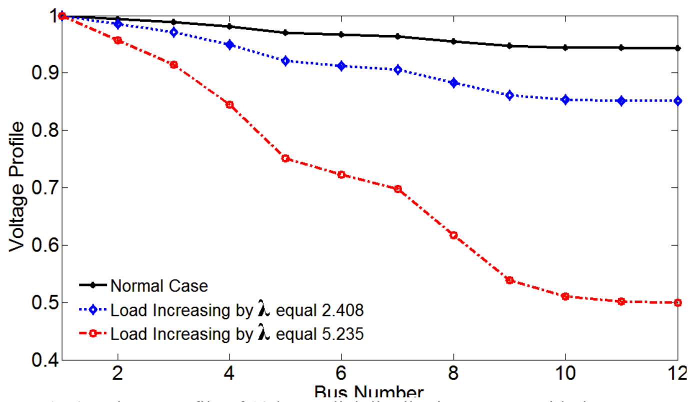

Fig 4. Voltage Profile of 12 bus radial distribution system with three different scaling factors

Figure 4 shows the voltage profile of 12 bus radial distribution system when the both active and reactive loads increased by scaling factor, λ. It shows when λ arrived to 5.235 the load flow converged and the minimum voltage in bus 12 cross over from 0.4999 (p.u.).

5. Conclusion

An improved technique to calculate load-ability margin and monitoring of power system status as point of view voltage collapse proximity is developed. This is based on the concept of maximum power transferred through the lines of the network. *IVCPI* is calculated for each line to represent the stressed conditions of the lines. When this indicator is equal to unity, the point of voltage collapse is reached.

This article also presents the estimate of maximum load-ability of the line due to voltage instability and shows $((1/IVCPI)-1)\times S_r$ to calculate the line loading margin. The results are compared with the L_s indicator and tested for the radial distribution system. It is proved that the L_s index gives inadequate results in comparison to the *IVCPI* index for finding load-ability margins on certain cases.

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