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Enhancement of Voltage Stability by Optimal Placement of Shunt Compensation using Bus Voltage Stability Indices and Reactive Power Margin

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Abstract

Voltage stability problem has caused several blackouts in many countries in recent years. Impending voltage instability has been a significant threat to modern power system's security and reliability. Moreover, the operation and planning of large interconnected power systems is becoming increasingly complex as power demand rises, posing a security risk to the grid. Appropriate efforts to improve power system security and increase voltage stability margin should be planned to keep the system secure. This work investigates the voltage stability of a power system with and without a shunt capacitor. The bus voltage stability index, L index, is used to measure the distance of the power system to its stability limit in order to assign the shunt capacitor. The L-index for a particular load state is computed for all load buses, and the greatest L-index indicates the system's approach to voltage collapse. The system's load ability margin is being traced utilizing a static voltage stability evaluation approach, i.e., PV and QV curve analysis. The minimal power loss approach is used to calculate the optimal capacitor size. The effect of shunt compensation was simulated, and the results with and without compensation were compared. The IEEE-9 bus system was employed in this work, and the system was simulated using MATLAB and Power World Simulator. The result demonstrates that the shunt capacitor enhances voltage stability by injecting the appropriate reactive power.

Keywords: Voltage Stability, Voltage Collapse, L index, PV/QV curve.

1. Introduction:

Several blackouts related to voltage stability problems have occurred in many countries in recent years, as reported in many literatures. In order to comprehend why these incidents occur, it is important to remember that today's power systems are operated closer to its thermal and stability limits [1]. Simultaneously, transmission networks are not expanded due to economic and environmental concerns, and only a few lines are built. Furthermore, as the use of renewable energy grows, the network become more stressed, as these sources have more dynamic and unpredictable behavior. Increased demand for electricity has caused power delivery networks to run under strained circumstances that are near to the instability limits [2]. Because of the rapidly rising electricity demand, power networks are now overloaded. Power grids have been subjected to extreme and growing pressure in recent years as a result of inconsistencies between generation and transmission networks. The expansion of generation and transmission capacity is unable to keep pace with the growth of power demand due to a variety of reasons such as high maintenance costs, the time taken to augment current generation and transmission facilities, and so on [3].

The several significant factors that contribute to voltage instability are stressed power system resulted from heavy active and reactive power loads and due to the inability of a portion of the network to satisfy reactive power demand, as well as inadequate reactive power generation. As a generator exceeds the reactive power limit, it can no longer provide reactive power and the terminal voltage declines and the generator shares the reactive power from other generator of the network (droop characteristic) and overloading them which leads to voltage instability. During a voltage drop in the network, the Online Load Tap Changer (OLTC) aim to retain a steady load voltage which allows more current to be drawn from transmission line, rising the voltage drop even more. The power used by the loads continues to be recovered by the load dynamics after some disruption on the grid. The failure of highly loaded lines adds the load on the adjacent lines of the networks [4]. As a consequence, the reactive power requirement in these lines increases, allowing the reactive power demand to rise. Generator failure reduces the amount of reactive power supplied in the network. The rate of increase in reactive power loss is inversely proportional to the voltage cube. As a result, as the terminal voltage decreases, the reactive power losses increase dramatically [5].

2. Voltage Stability Analysis:

2.1. PV/QV Curve:

Calculation of system load margin is the most commonly used approach for determining voltage stability limit. Active power and reactive power margin are the two most often used indicators [6]. The loadability limit is used to measure the load margin. The loadability limit for a specific operating condition is the highest loading point above which there can be no operating point. Beyond the loadability limit, the load flow equation would not have a solution [7]. The PV and QV curves are the most widely used to evaluate a power system's loading margin to each load bus. There are multiple operating equilibrium points before reaching voltage breakdown point and as the loadability limit exceeds, the system will lose the equilibrium [5, 8]. A typical PV and QV curve are shown in Fig. 1 and Fig. 2. The PV curve shows that for the stable operation of power system the bus voltage must be above the critical voltage. The QV curve shows the sensitivity and variation of bus voltages with respect to reactive power injection and absorption.

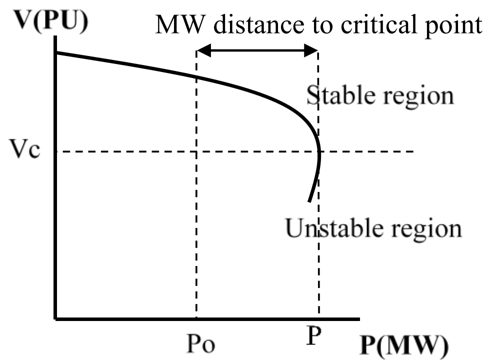

Figure 1: PV Curve

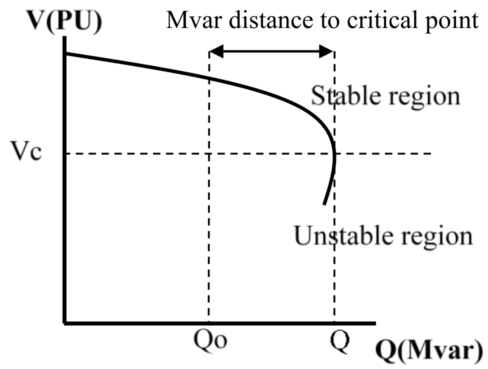

Figure 2: QV Curve

2.2. Voltage Stability Indices:

The indices which determine whether the system voltage is stable and indicate how close the system is from instability or voltage collapse are called voltage stability indices (VSI) [9]. These indices assist the system planner and operators to determine the state of power system voltage stability [10]. The VSI can be used to determine how close a given operating point is from voltage collapse point and related to either bus voltage or a line voltage. These indices are easy to implement, computationally inexpensive and can be derived from basic load flow program [11]. The indices identify the weaker bus as well as the stability state of transmission line in an integrated network.

The different system variable based VSI found on many literatures are summarized in Table 1 and Table 2. This table categories the indices with a reference to their original publication, the equation used to compute them and their stability requirement.

Table 1: System variable-based bus voltage stability indices

Index	Calculation	Stability Threshold	Characteristics
L Index [12]	$L_K = \left\lvert \frac{1}{1+\frac{V_{ok}}{V_k}} \right\rvert$	0<L<1	• Simple to calculate • Low cost of computation • Finds the network's weakest bus • Online use
VCI [3]	$VCI_i = \left[1+\frac{I_i \triangle V_i}{V_i \triangle I_i}\right]^{\alpha}$	1>VCI>0 and $\alpha > 1$	
SI [13]	$SI(r) = 2V_S^2V_r^2 - V_r^4 - 2V_r^2(PR+QX) - \lvert Z^2 \rvert (P^2+Q^2)$	Lower the value of SI, the system is more vulnerable to voltage collapse	

Table 2: System variable-based line voltage stability indices

Index	Calculation	Stability Threshold	Characteristics
L_{mn} [14]	$L_{mn} = \frac{4XQ_r}{[V_s \sin(\Theta-\delta)]^2}$	L_{mn}<1	• Simple to calculate • Low cost of computation • Finds the network's weakest line • Online use
LVSI [15]	$LVSI = \frac{4rP_r}{[V_s \cos(\Theta-\delta)]^2}$	LVSI≤1	
LQP [16]	$LQP = 4\left(\frac{X}{V_i^2}\right)\left(\frac{X}{V_i^2}P_i^2 + Q_j\right)$	LQP<1	
FVSI [17]	$FVSI = \frac{4Z^2Q_r}{V_S^2X}$	FVSI<1	

2.3. Voltage Collapse and Mitigation:

Voltage collapse is a type of system instability that affects a large number of power system components. Voltage collapse is usually caused by a lack of reactive power production and transmission, resulting in the load's reactive power requirement not being met. Low voltage profiles, high reactive power flows, insufficient reactive power support, and overloaded systems are the most common symptoms of voltage collapse [18]. Low-probability single or multiple contingencies are frequently the cause of such a collapse. Long system restoration times are usually required in the event of a system breakdown, leaving significant numbers of consumers without supply. Schemes that protect against collapse must use symptoms to detect the impending collapse and take corrective action in time. When the electrical system is on the point of voltage collapse, action must be taken to remedy the situation and minimize the possibility of voltage collapse. Load shedding, switching reactive power compensation devices, to increase or decrease the amount of reactive power available (from the reactive power capability of generator) and to raise the voltage setpoint of the voltage controlling equipment are the common methods for mitigation of voltage collapse [19].

3. Methodology:

The enhancement of voltage stability by optimal placement of shunt capacitor using bus voltage stability indices and reactive power margin is described in the flowchart shown in Fig. 3. The overall steps are as follows:

Step 1: Load system data and perform load flow analysis
Step 2: Choose the load bus

Step 3: Calculate L index during different loading condition, generate PV and QV curve
Step 4: Repeat step 2 and step 3 for all load bus
Step 5: Choose the load bus and force outage the most sensitive transmission line for same bus
Step 6: Calculate L index during different loading condition, generate PV and QV curve
Step 7: Identify the weakest bus, identify the optimal size of shunt capacitor
Step 8: Repeat from step 1 with shunt capacitor and compare the result.

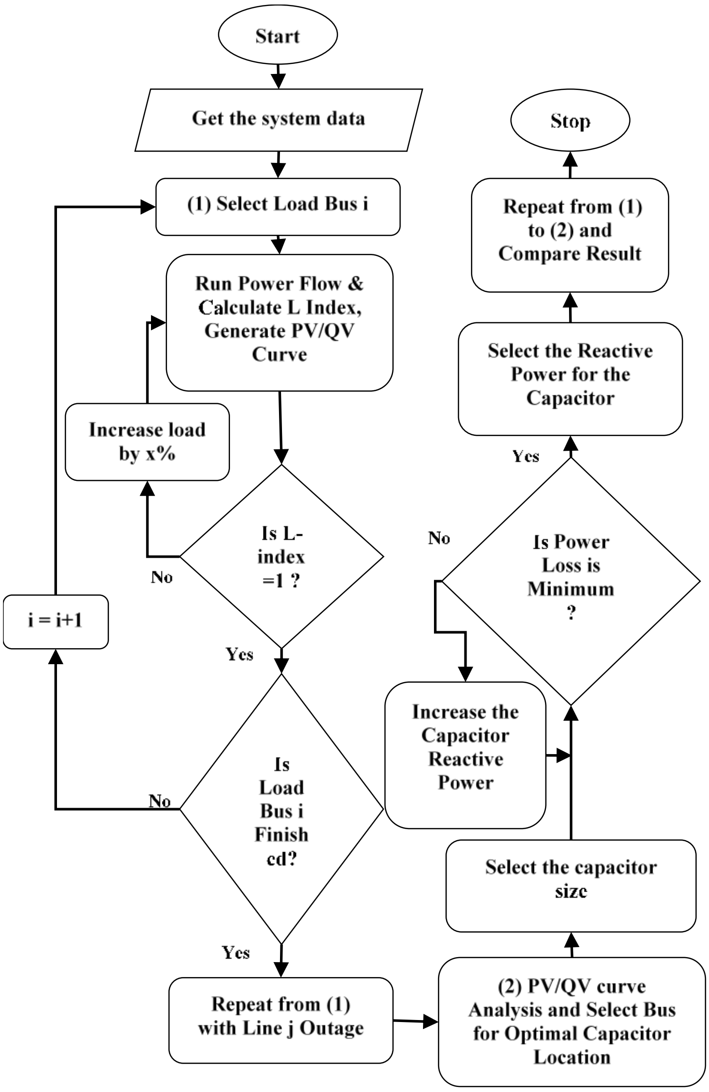

Figure 3: Flowchart for enhancement of voltage stability by optimal placement of shunt capacitor using voltage stability indices and reactive power margin

3.1. Formulation of L Index:

The L index [12] is the most widely used indices well suited for online purpose. It is the local indicator that does not depends on the Thevenin equivalent and was derived from one source one load two bus system. This indicators calculation is simple and quick and can be simply estimated using normal load flow data [20, 21]. For every power system.

$$I_{bus} = Y_{bus}V_{bus} \tag{1}$$

This equation can be rewrite as

$$\begin{bmatrix} I_L \\ I_G \end{bmatrix} = \begin{bmatrix} Y_1 & Y_2 \\ Y_3 & Y_4 \end{bmatrix} \begin{bmatrix} V_L \\ V_G \end{bmatrix} \tag{2}$$

After the load buses and generator buses have been separated Eq. 2 become

$$\begin{bmatrix} V_L \\ I_G \end{bmatrix} = \begin{bmatrix} H_1 & H_2 \\ H_3 & H_4 \end{bmatrix} \begin{bmatrix} I_L \\ V_G \end{bmatrix} \tag{3}$$

Where V_L = load bus voltage, I_L = load bus current, V_G = generator bus voltage, I_G = generator bus current. H_1, H_2, H_3 and H_4 = submatrices of Y_{bus} inversion.

For load bus

$$V_{ok} = \sum_{i=1}^{N_G} (H_2)_{ki} V_i \quad (4)$$

Where N_G = number of generators and H_2= $-Y_1Y_2$

The L-index for bus K is given by

$$L_K = \left| \frac{1}{1+\frac{V_{ok}}{V_k}} \right| \quad (5)$$

For the stable operation of power system, the value of L index must be less than 1.

3.2. System Constraints:

- Under normal condition, the L-index below 1 means the system is stable
  $$0 < \text{L-index} < 1 \quad (6)$$
- The system is more secure if
  $$\text{L-index} \approx 0 \quad (7)$$
- The system is unstable if
  $$\text{L-index} > 1 \quad (8)$$
- Minimum MW loss for optimal size of shunt capacitor

4. Result and Discussion:

The IEEE-9 bus system was employed in this paper and the branch data and bus data are taken from [22]. The IEEE 9-bus power system is a simplified approximation of a comparable system with nine buses and three generators shown in Fig. 4.

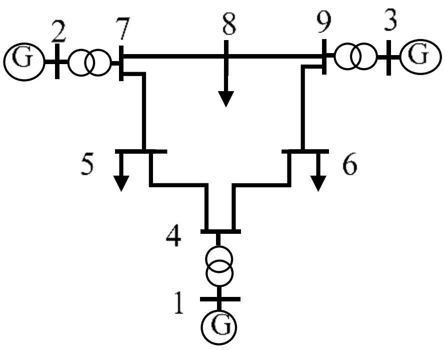

Figure 4: Single line diagram of IEEE 9 bus system

A program for calculating L-index was developed in MATLAB environment and the program was tested to determine L index for IEEE-6 bus system to validate the developed code. The result was then compared to the L index found in [23] and the correspondence is excellent, implying that the code generated is valid.

The following situations are used to run the simulation:

- The base case
- The load increasing case: The MW load growing on each load bus until the system reaches the collapse point
- The contingency case: The most sensitive transmission to each load bus outage from service and MW load growing on same load bus until the system reaches the collapse point.

The QV curve is plotted on each load bus for the identification of the most sensitive transmission line. The transmission line was considered the most sensitive line if the reactive power margin available on the load bus was less than the other transmission lines taken out of service. A sensitive transmission line is described as a transmission line that, if taken out of operation, will have the greatest impact on the power system. In each of the transmission line outage cases, the QV curve is given in Fig. 5, and in a similar way, the most sensitive transmission line was identified on each load bus, and the result is tabulated in Table 3.

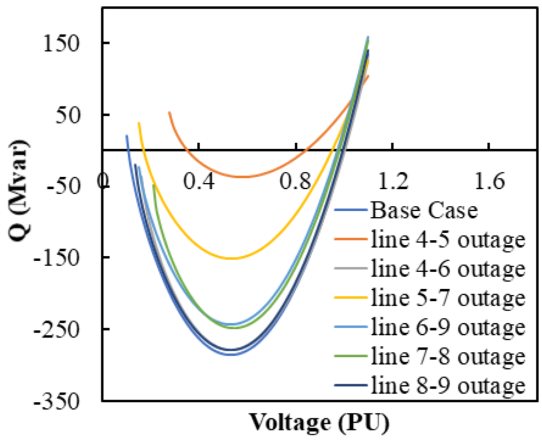

Figure 5: QV curve of bus 5 during different line outage case

At base case condition, bus 5 of the IEEE 9 bus system has 124 MW of active load and 50 MVAR of reactive load. The nose point of QV curve of bus 5 during base case condition is at 285.772 MVAR with bus voltage 0.5297 PU. It is observed that when the line 4-5 is out of service, the reactive power margin available on bus 5 will be minimum than other line outage condition. Hence, line 4-5 has a high impact on bus 5, line 5-7 has medium impact and line 6-9, line 7-8, line

8-9 and line 4-6 has the low impact on bus 5. Hence, line 4-5, line 4-6 and line 7-8 is considered as most sensitive line for load bus 5, load bus 6 and load bus 8 respectively.

Table 3: Most sensitive line for load bus

Outage line	High Impact on
Line 4-5	Bus 5
Line 4-6	Bus 6
Line 7-8	Bus 8

For identification of the weakest bus, the L-index is calculated on each load by increasing the load step by step until the system become collapsed. The PV curve and L-index curve for each load bus are given in Fig. 6, which shows that when the L-index reaches the threshold point (Value 1), the PV curve also reaches the nose point, and after that point, the system becomes unstable and collapse. At the same time, the PV curve is also generated to validate the result, i.e., when the L index reaches the threshold point, the PV curve also has to reach the nose point.

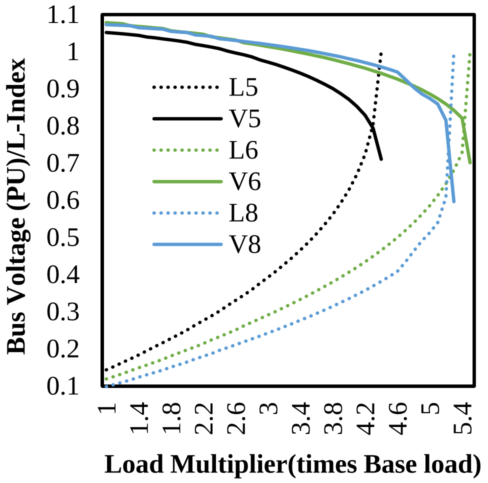

Figure 6: PV curve and L-index of bus 5, bus 6 and bus 8

Table 4: Comparison of active and reactive power margin of load buses

Bus	Case	PV curve nose point (MW)	QV curve nose point (MVAR)	Base load (MW)	Loadability Margin (times base load)
5	Normal	545.65	285.772	125	4.37
	Contingency	186.7	36.31	125	1.49
6	Normal	494.227	285.77	90	5.49
	Contingency	180.4	68.68	90	2
8	Normal	524.628	370.79	100	5.25
	Contingency	244.446	124.4	100	2.44

From the Table 4 and Fig. 6, it is observed that the load bus 5 can increased by 4.37 times of base load during normal condition but can only increase by 1.49 times of base load during the most sensitive line 4-5 outage condition as shown in Fig.10. Similarly, the load on bus 6 can increased by 5.49 and 2 times of base load during normal condition and contingency condition respectively. Likewise, the load on bus 8 can increased by 5.25 and 2.44 times of base load during normal condition and contingency condition respectively. Hence, bus 5 is considered as the weakest bus of IEEE 9 bus systems. Table 5 shows the rank of buses of the IEEE 9 bus system.

To determine the optimal size of shunt capacitor, the load flow study was conducted by injecting various shunt capacitor values at the weakest bus 5, and MW power loss was observed. The MW losses are plotted in the Fig. 7 for various injected capacitor value.

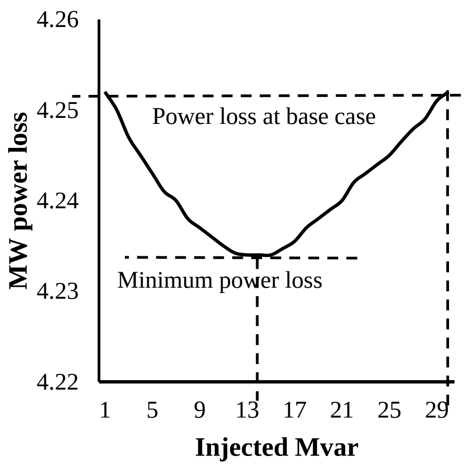

Figure 7: MW losses during different value of injected shunt capacitor

Table 5: Ranking and strength of load buses

Bus	Ranking	Strength
5	1st	Weakest
8	2nd	Moderate
6	3rd	Strong

Optimal size of shunt capacitor = 15 MVAR (for Minimum power loss) to 30 MVAR (for power loss equal to base case power loss).

The enhancement of loadability margin of the system and enhancement of reactive power margin is tabulated in the Table 6. After injecting the 15 MVAR of shunt capacitor (Considering minimum power loss in the system) at bus 5, the loadability of bus 5 (Location of shunt capacitor) is enhanced by 11.9 MW and the reactive power margin is enhanced by 13.8 MVAR as shown in Fig. 8 and Fig. 9.

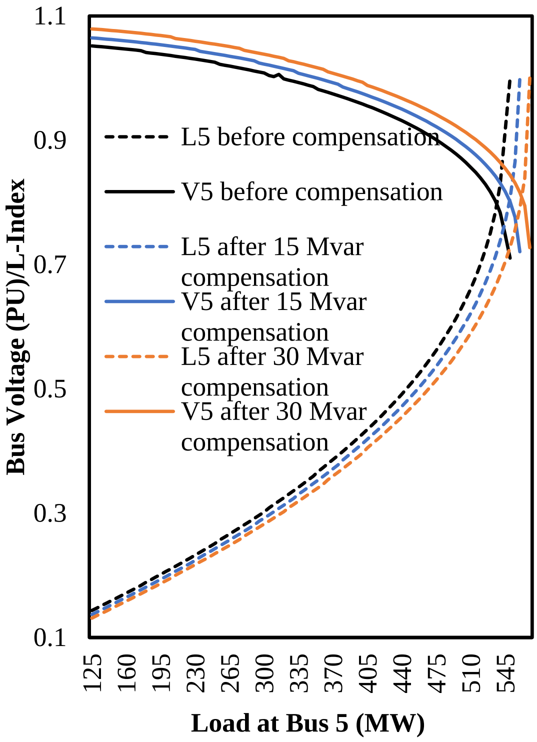

Figure 8: L-index and PV curve of bus 5 before and after compensation

If the injected shunt capacitor is 30 MVAR (Considering the base case power loss in the system) at bus 5, the loadability of bus 5 (Location of shunt capacitor) is enhanced by 23.41 MW and the reactive power margin is enhanced by 35.2 MVAR.

Similarly, after injecting the 15 MVAR shunt capacitor at bus 5, the loadability of bus 6 (Distance of 411 KM from the shunt capacitor) is enhanced by 4.48 MW and the reactive power margin is enhanced by 6.41 MVAR. If the injected shunt capacitor is 30 MVAR at bus 5, the loadability of bus 6 (Distance of 411 KM from the shunt capacitor) is enhanced by 10.27 MW and the reactive power margin is enhanced by 12.06 MVAR.

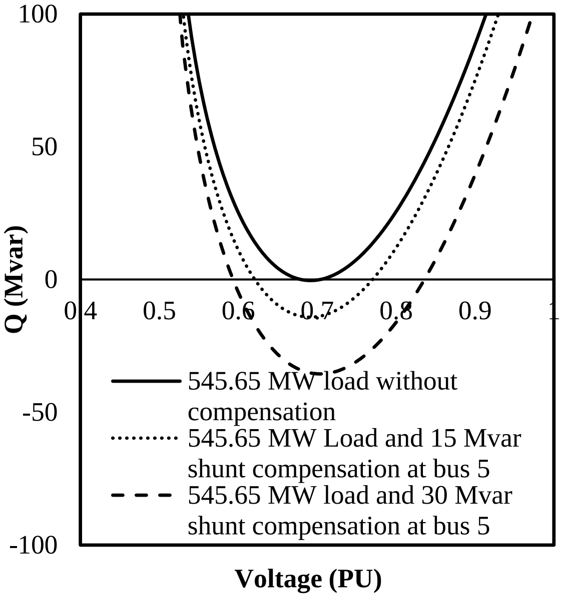

Figure 9: QV curve of bus 5 before and after compensation

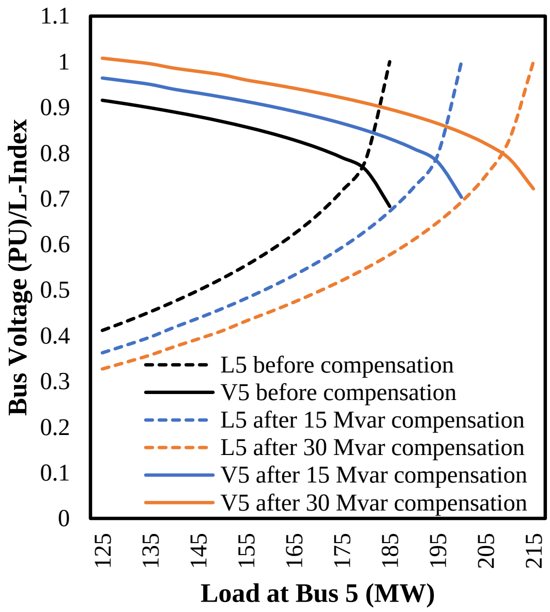

Figure 10: L-index and PV curve of bus 5 before and after compensation (Contingency case)

Similarly, after injecting 15 MVAR shunt capacitor at bus 5, the loadability of bus 8 (Distance of 192 KM from the shunt capacitor) is enhanced by 6.21 MW and the reactive power margin is enhanced by 8.74 MVAR. If the injected shunt capacitor is 30 MVAR at bus 5, the loadability of bus 8 (Distance of 192 KM from the shunt capacitor) is enhanced by 12.13 MW and the reactive power margin is enhanced by 26.9 MVAR. However, the margin can be increased more by injecting the higher value of shunt capacitor since system security was more important than the power loss for saving the system from voltage collapse.

Bus	Loadability Enhancement		Reactive power margin Enhancement		Minimum distance from shunt capacitor
	At 15 MVAR compensation	At 30 MVAR compensation	At 15 MVAR compensation	At 30 MVAR compensation	
5	11.9 MW	23.41 MW	13.8 MVAR	35.2 MVAR	0 KM
6	4.48 MW	10.27 MW	6.41 MVAR	12.06 MVAR	411 KM
8	6.21 MW	12.13 MW	8.74 MVAR	26.9 MVAR	192 KM

5. Conclusion:

This paper investigates the voltage stability of a power system with and without a shunt reactive power compensation device. The L-index for a particular load state is computed for all load buses, and the greatest L-index indicates the system's approach to voltage collapse. The system's loadability margin is traced utilizing a static voltage stability evaluation approach, i.e., PV and QV curve analysis. The minimal power loss approach is used to calculate the optimal capacitor size. The effect of shunt compensation was simulated, and the results with and without compensation were compared. The IEEE-9 bus system was employed in this work and the result demonstrates that the shunt capacitor enhances voltage stability by injecting the appropriate reactive power.

References:

[1] Taylor, C. W. (1999). Improving grid behaviour. IEEE Spectrum, 36(6), 40-45.

[2] Althowibi, F. and M. Mustafa. Voltage stability calculations in power transmission lines: Indications and allocations. in 2010 IEEE International Conference on Power and Energy. 2010. IEEE.

[3] Haque, M., Use of local information to determine the distance to voltage collapse. International Journal of Emerging Electric Power Systems, 2008. 9(2).

[4] Chakrabarti, A. and S. Halder, Power System Analysis: Operation And Control 3Rd Ed. 2010: PHI Learning Pvt. Ltd.

[5] Kundur, P., Power system stability. Power system stability and control, 2007. 10.

[6] Adewuyi, Oludamilare Bode, Mir Sayed Shah Danish, Abdul Motin Howlader, Tomonobu Senjyu, and Mohammed E. Lotfy. "Network structure-based critical bus identification for power system considering line voltage stability margin." Journal of Power and Energy Engineering 6, no. 09 (2018): 97.

[7] Bhaladhare, S. B., Telang, A. S., & Bedekar, P. P. (2013). Pv qv curve-a novel approach for voltage stability analysis. In National Conference on Innovative Paradigms in Engineering & Technology (NCIPET-2013), International Journal of Computer Applications®(IJCA) (pp. 31-35).

[8] Van Cutsem, T. and C. Vournas, Voltage stability of electric power systems. 2007: Springer Science & Business Media.

[9] Suganyadevia, M. and C. Babulalb. Estimating of loadability margin of a power system by comparing Voltage Stability Indices. in 2009 International Conference on Control, Automation, Communication and Energy Conservation. 2009. IEEE.

[10] Musirin, I. and T.A. Rahman, Estimating maximum loadability for weak bus identification using FVSI. IEEE power engineering review, 2002. 22(11): p. 50-52.

[11] Van Cutsem, T., Voltage instability: phenomena, countermeasures, and analysis methods. Proceedings of the IEEE, 2000. 88(2): p. 208-227.

[12] Kessel, P. and H. Glavitsch, Estimating the voltage stability of a power system. IEEE Transactions on power delivery, 1986. 1(3): p. 346-354.

[13] Eminoglu, U. and M. Hocaoglu. A voltage stability index for radial distribution networks. in 2007 42nd International Universities Power Engineering Conference. 2007. IEEE.

[14] Moghavvemi, M. and G. Jasmon. New method for indicating voltage stability condition in power system. in Proc. Third Int. Power Engineering Conf., Singapore. 1997.

[15] Hang, N., et al., The analysis of abundance index of voltage stability based circuit theory. Guangxi Electric Power, 2006. 2: p. 002.

[16] Mohamed, A., G. Jasmon, and S. Yusoff, A static voltage collapse indicator using line stability factors. Journal of industrial technology, 1989. 7(1): p. 73-85.

[17] Musirin, I. and T.A. Rahman. Novel fast voltage stability index (FVSI) for voltage stability analysis in power transmission system. in Student conference on research and development. 2002. IEEE.

[18] Balamourougan, V., Sidhu, T. S., & Sachdev, M. S. (2004). Technique for online prediction of voltage collapse. IEE Proceedings-Generation, Transmission and Distribution, 151(4), 453-460.

[19] Pourbeik, P., P.S. Kundur, and C.W. Taylor, The anatomy of a power grid blackout-root causes and dynamics of recent major blackouts. IEEE Power and Energy Magazine, 2006. 4(5): p. 22-29.

[20] Yadav, S.K. and A. Soni, Voltage Stability Estimation of Electric Power System Using L-Index.

[21] Yahia, E.Z., M.A. Elsherif, and M.N. Zaggout, Detection of Proximity to Voltage Collapse by using L-index. International Journal of Innovative Research in Science, Engineering and Technology, 2015. 4(2): p. 1333-1343.

[22] Kamel, S., et al. Power system voltage stability based on optimal size and location of shunt capacitor using analytical technique. in 2019 10th International Renewable Energy Congress (IREC). 2019. IEEE.

[23] Belhadj, C. and M. Abido. An optimized fast voltage stability indicator. in Electric Power International Conference on Engineering, PowerTech Budapest. 1999.