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TCSC Incorporated Voltage Stability Assessment under Contingency Condition

Guru Mohan Baleboina[1*], Suresh Babu Daram[2], P.S.Venkataramu[3] and M.S.Nagaraj[4]

[1]PG Student, [2]Assistant Professor, Dept. of Electrical & Electronics Engineering, Sree Vidyanikethan Engineering College, Tirupati*
[3]Director IQAC, REVA University, Bangalore
[4]Professor & Head, Dept. of Electrical & Electronics Engineering Bapuji Institute of Engineering & Technology, Davangere
[1]Corresponding author: gurumohanbaleboina@gmail.com*
[2]sureshbabudaram@gmail.com

Abstract

This paper presents the voltage stability assessment based on the Line Voltage Stability Index (L_{mn}) and Voltage Collapse Proximity Index (VCPI). Thyristor Controlled Series Compensator (TCSC) has been incorporated in the critical transmission line and the enhancement in the stability is observed. The same analysis has been carried out with the improvement in the system load and under single transmission line outage contingency condition. IEEE-14 bus system has been used for simulation purpose.

Keywords: *L_{mn}, VCPI, TCSC, contingency ranking, line outage.*

Nomenclature

S_k	:	Complex power at bus k
V_k	:	Voltage phasor at bus k
V_m	:	Voltage phasor at bus m
δ_k	:	Voltage angle of bus k
Y_{km}	:	Admittance between buses k and m.
L_{mn}	:	Line Voltage Stability Index
X	:	Reactance of the transmission line
Q_r	:	Reactive power at receiving end

1. Introduction

"Voltage stability [1] is concern with the ability of power system to maintain acceptable voltage at the all buses in the power system under normal and being subjected to a disturbance". The reason behind voltage instability is to lagging to supply reactive power. Maximum of the loads are reactive loads, these loads are depends based on voltage profiles. When the disturbance is occur, voltage decrease at a load bus it will cause decrease in power consumption. However loads tend to restore their initial power consumption with the help of Distribution Voltage Regulators, Load Tap Changers (LTC)

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and thermostats. These control devices try to adjust the load side voltage to their reference voltage. As the increment in voltage will goes to an increment in power demand which may lead to weaken the power system stability. Under these conditions voltages undergo a continuous decrease, which is small at starting and leads to voltage collapse.

When a single machine is connected to a load bus then there will be pure voltage instability. When a single machine is connected to infinite bus then there will be pure angle instability. When synchronous machines, infinite bus and loads are connected then there will be both angle and voltage instability but their influence on one another can be separated [2]. The dynamics involved in voltage instability are restricted to load buses with LTC, restorative loads etc. These load voltage control devices are operated for few minutes to several minutes. So, generator dynamics can be substituted by appropriate equilibrium conditions. Under stressed conditions, coupling between voltage and active power is not weak [3]. So, insufficient active power in the system also leads to voltage instability problems.

The following are the main contributing factors [3] to problem of voltage instability.

- Demand is increased cause the heavily burden on networks.
- Lack of reactive power supply.
- Load restoring devices in response to load bus voltages.
- Sudden switching operations and relay operation cause drop in voltage magnitude.
- Line or generator outages.

In defiance of voltage instability phenomenon is progressive in nature, both static and dynamic analysis methods [4] are used. To operate the system safely, system is to be analyzed for various operating conditions and contingencies. In highest cases, the system progressively affecting voltage stability are usually fairly sluggish and much of the problem can be analyzed by static analysis that gives information about the maximum loadability limit and factors contributing to instability problem. Static approach involves calculation of only algebraic equations and it is faster than dynamic approach. Static analysis takes less computational time compared to dynamic analysis and conventional power ow is used in the static analysis. A number of static voltage stability analysis methods [5-6] are proposed in the literature for analyzing the problem.

Different type's voltage stability indices are presented in [7] order to gauge the stability limit. These are, L Index (LI), voltage Collapse Proximity Indicator (VCPI) [8], Line voltage stability index (L_{mn}) [9]. Voltage stability indices are important implements for gauging the closeness of a given operating point to voltage instability. The agenda of voltage stability indices are used to evaluate operating point of the steady state voltage stability margin. Voltage stability indices are used in dynamic operation of the power system or I designing and planning operations. These indices will gives the how close to the particular point shows voltage instability of the system and which could lead to brownout major parts of the power system [10-11].

Conventionally electro mechanical devices are used to control reactive power and to provide steady state voltage stability in addition to reduce the transmission losses and improves the system stability. Electronic devices have some drawbacks, they are Ageing, Lower rate of speed, Reliability of control, they do not gratify the working flexibility and adaptability requirements to meet the changing reactive power needs of the modem power systems. These drawbacks overcome by using Flexible AC Transmission System (FACTS) controllers [12]. These are used to provide voltage and enhance power flow control in many utilities. The application of FACTS device to improve voltage stability margins in vastly developed networks. The features of FACTS technology, i) Fast voltage regulation ii) Increase power transfer capacity iii) Hampering of active power oscillations and iv) Power flow control in interconnected networks [13-18].

2. Modeling of TCSC

Thyristor Controlled Series Compensator (TCSC) [12] provides controlling and increasing power transfer level of a system by varying the apparent impedance of a specific transmission line. A TCSC can be utilized during contingencies to enhance power system stability. Using TCSC, it is possible to operate stably at power levels well beyond those for which the system was originally intended without endangering system stability. It consists of series controlled capacitor which is shunted by a Thyristor controlled Reactor. TCSC [18] acts as the inductive or capacitive compensation by modifying the reactance of the transmission line and the reactance of the transmission line is adjusted by TCSC directly. The rating of TCSC depends on the reactance of the transmission line where the TCSC is located.

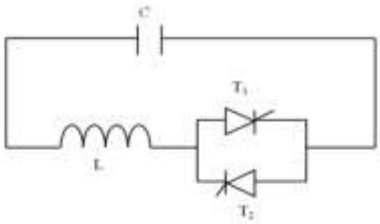


Figure 1. A Schematic Diagram of TCSC

1) Inductive Mode:

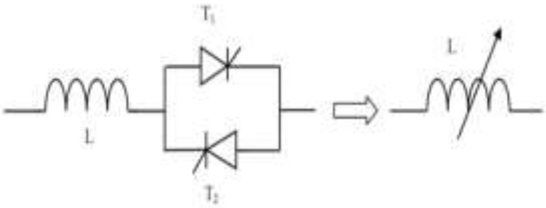


Figure 2. TCSC Inductive Mode

TCR is a variable inductive reactor $X_L(\alpha)$, tuned at firing angle, as shown in Figure 2. The variation of X_L with respect to alpha (α) can be given as:

$$X_L(\alpha) = X_L \frac{\pi}{\pi - 2\alpha - \sin 2\alpha} \tag{1}$$

$$X_C = \frac{1}{2\pi fC} \tag{2}$$

For the variation of (α) from 0 to 90, $X_L(\alpha)$ varies from actual reactance (X_L) to infinity.

2) Capacitive Mode:

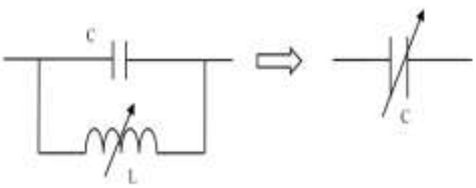


Figure 3. TCSC Capacitive Mode

The controlled reactor is connected across the series capacitor, so that the variable capacitive reactance, as shown in Figure 3, is possible across the TCSC which modifies the transmission line impedance.

3. Line Voltage Stability Index (L_{mn})

Moghavvemi [9] developed a voltage stability problem based on a power transmission perception. In this case, all the power transmission network is reduced to single-line network to evaluate system stability. Consider a single-line representation of transmission network of power system as shown in Figure 4.

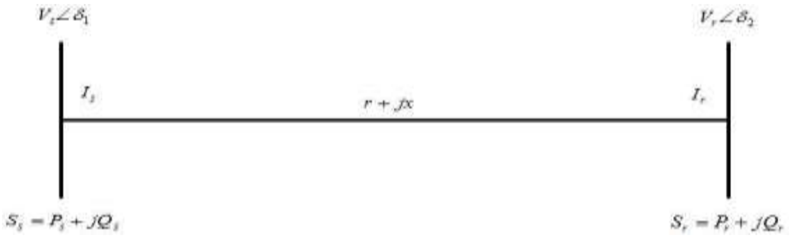


Figure 4. Single-line Representation of Transmission Network

The apparent power at the receiving and sending end for the given transmission line in Figure 4 considering as nominal-π model is given below in equation (3) and (4).

$$S_r = \frac{|V_s||V_r|}{Z}\angle(\theta - \delta_1 + \delta_2) - \frac{|V_r|^2}{Z}\angle\theta \tag{3}$$

$$S_s = \frac{|V_s|^2}{Z}\angle\theta - \frac{|V_S||V_r|}{Z}\angle(\theta + \delta_1 - \delta_2) \tag{4}$$

The receiving end active and reactive power are given in equation (5) to (6)

$$P_r = \frac{V_s V_r}{Z}\cos(\theta - \delta_1 + \delta_2) - \frac{V_r^2}{Z}\cos\theta \tag{5}$$

$$Q_r = \frac{V_s V_r}{Z}\sin(\theta - \delta_1 + \delta_2) - \frac{V_r^2}{Z}\sin\theta \tag{6}$$

Putting $\delta_1 - \delta_2 = \delta$ in equation (6) and solve for V_r

$$V_r = \frac{V_s \sin(\theta - \delta) \pm \left\{[V_s \sin(\theta - \delta)]^2 - 4ZQ_r \sin\theta\right\}^{0.5}}{2\sin\theta} \tag{7}$$

Now for $Z\sin\theta = X$, we have

$$V_r = \frac{V_s \sin(\theta - \delta) \pm \left\{[V_s \sin(\theta - \delta)]^2 - 4XQ_r \sin\theta\right\}^{0.5}}{2\sin\theta} \tag{8}$$

To obtain real values of V_r and Q_r the equation must have real roots. Thus the following conditions, which can be used as a stability criterion, needs to be satisfied:

$$\left\{[V_s \sin(\theta - \delta)]^2 - 4XQ_r\right\} \geq 0 \qquad \text{Or}$$

$$\frac{4XQ_r}{[V_s \sin(\theta - \delta)]^2} = L_{mn} \leq 1.00 \tag{9}$$

4. VCPI (Voltage Collapse Proximity Index)

V.Balamourougan et.al [6 & 7] has proposed a technique through Voltage Collapse Proximity Indicator (VCPI) for online voltage stability monitoring. The technique is derived from the basic power flow equation. The technique is applicable for any number of buses in a system. It needs the voltage phasor information of the participating buses in the system and the network admittance matrix. Using the measured voltage phasors and the network admittance matrix of the system, the voltage collapse prediction index (VCPI) is calculated at every bus. The values of these indexes determine the proximity to voltage collapse at a bus.

For an N-bus system the complex power at bus k is given by,

$$S_k^* = |V_k|^2 - (|V_k|\cos\delta_k) - j|V_k|\sin\delta_k \left[\sum_{\substack{m=1 \\ m\neq k}}^{N} (|V_m^{'}|\cos\delta_m^{'} + j|V_m^{'}|\sin\delta_m^{'} \right] Y_{kk} \tag{10}$$

$V_m^{'}$ in equation (10) is given by

$$V_m^{'} = \frac{Y_{km}}{\sum_{\substack{j=1 \\ j\neq k}}^{N} Y_{kj}} V_m \tag{11}$$

The right-hand side of (10) is a complex quantity, which is of the form a-jb. The following two equations with two unknowns (V_k , δ) can be written

$$f_1(|V_k|,\delta) = |V_k|^2 - \sum_{\substack{m=1 \\ m\neq k}}^{N} |V_m^{'}||V_k|\cos\delta \tag{11}$$

$$f_2(|V_k|,\delta) = \sum_{\substack{m=1 \\ m\neq k}}^{N} |V_m^{'}||V_k|\sin\delta \tag{12}$$

Solving the two equations for determining the unknowns using the Newton–Raphson technique, a partial derivative matrix is obtained. The determinant of the matrix is equal to zero at voltage collapse resulting in the following equation.

$$\frac{|V_k|\cos\delta}{\sum_{\substack{m=1 \\ m\neq k}}^{N} |V_m^{'}|} = \frac{1}{2} \tag{13}$$

Manipulating (13), the voltage collapse prediction index (VCPI) is obtained at bus k, which is given by

$$VCPI_{k^{th}bus} = \left| 1 - \frac{\sum_{\substack{m=1 \\ m\neq k}}^{N} V_m^{'}}{V_k} \right| \tag{14}$$

Equation (12) represents the condition for voltage collapse at the kth bus. The right-hand side of (12) is termed as the VCPI, which will vary from 0 to 1. If the index is 0, the bus is voltage stable and if the index is 1 the voltage at a bus has collapsed.

5. Proposed Algorithm

The proposed algorithm for obtaining the critical line, critical bus and the Lmn, VCPI is given below respectively.

5.1. Proposed Algorithm for Critical Line Ranking through Line Voltage Stability Index (L_{mn})

The computational methodology has been carried out through following steps.

1. Read line and bus data of the given system and assume that system angle, load (MW & MVAR) and generator (MW & MVAR, Qmin & Qmax) data are constant.
2. Run the load flow without line outage contingency and use the results as base case.
3. Connect N-1 line outage contingency among any two buses.
4. Calculate Line Voltage Stability Index (L_{mn}) for each line outage condition.
5. Rank the more sensitive line under each line outage condition having maximum L_{mn}.
6. Connect TCSC in the system and calculate the value of Lmn.
7. Compare L_{mn} with and without TCSC.

5.2. Proposed Algorithm for Critical Bus Ranking through Voltage Collapse Proximity Index (VCPI)

The computational methodology has been carried out through the following steps.

1. Read line and bus data of the given system and assume that system angle, load (MW & MVAR) and generator (MW & MVAR, Qmin & Qmax) data are constant.
2. Run the load flow without line outage contingency and use the results as the base case.
3. Connect N-1 line outage contingency among any two buses.
4. Calculate Voltage Collapse Proximity Indicator (VCPI) of Jacobian matrix for each line outage condition.
5. Rank the more sensitive line under each line outage condition having maximum VCPI.
6. Connect TCSC in the system and calculate the value of VCPI.
7. Compare VCPI with and without TCSC.

6. Case Study

In this case IEEE-14 bus system is considered for the simulation purpose. Line voltage stability index (L_{mn}) can be used to evaluate voltage stability at a system lines. Based on the severity of L_{mn} value, the TCSC is connected in series with line to enhance the stability. VCPI can be used to evaluate the critical bus in the system, by using TCSC compensation to enhance the stability.

The study has been carried out in four different cases as mentioned below:

Case 1. Critical Line Ranking through L_{mn} without and with TCSC under system loading condition for Base case

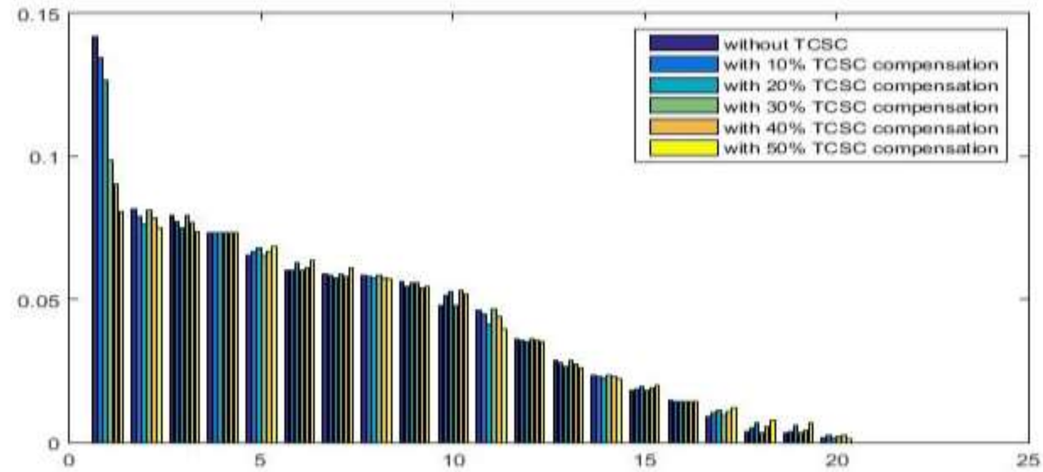
Case 2. Critical Bus Ranking through VCPI without and with TCSC under system loading condition for Base case

Case 3. Critical Line Ranking through L_{mn} without and with TCSC under Contingency condition for system loading

Case 4. Critical Bus Ranking through VCPI without and with TCSC under Contingency condition for system loading

Case 1. Critical Line Ranking through L_{mn} without and with TCSC under system loading condition for Base case

In this case L_{mn} can be used to evaluate the critical branch in the system under different loading conditions without any contingency. TCSC is connected in series to improve power flows in transmission line. By varying the percentage compensation of TCSC the severity of line should be decreased as shown in Figure 5.



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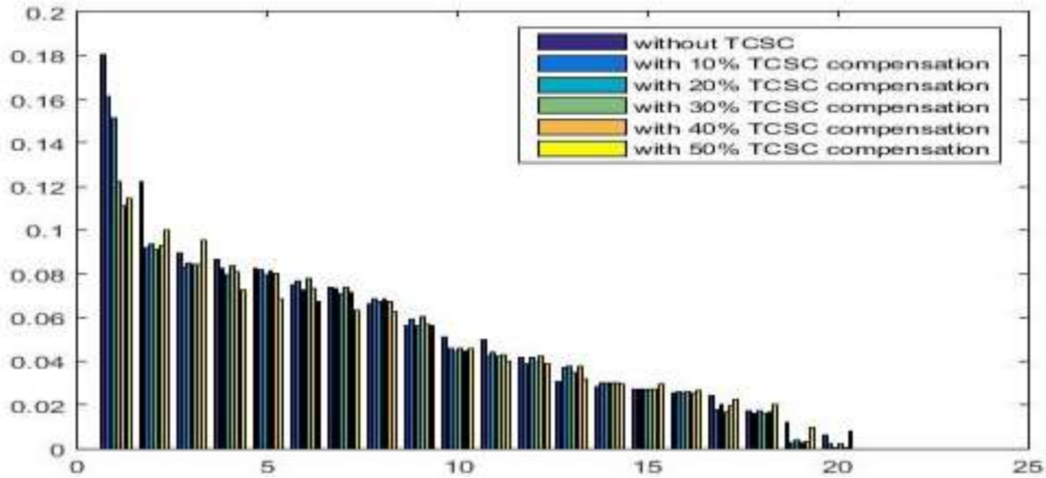

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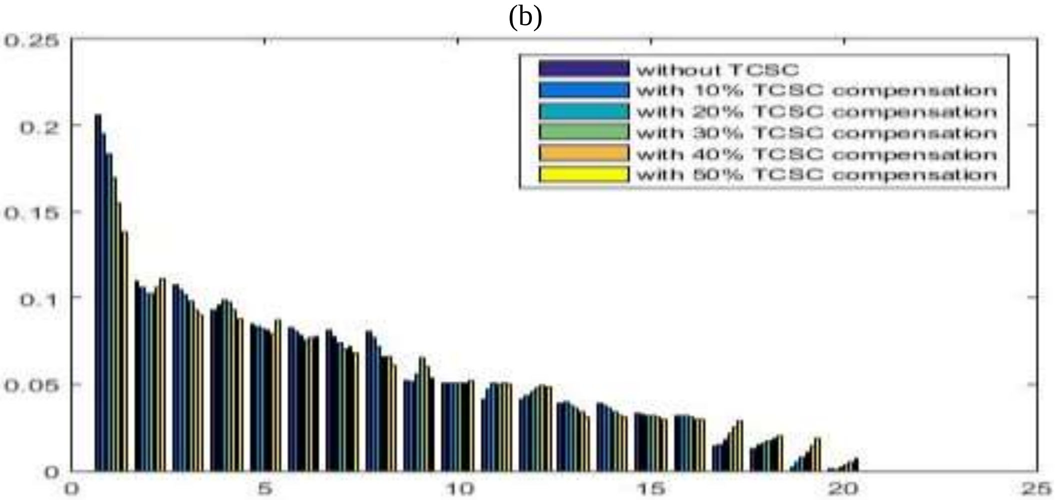

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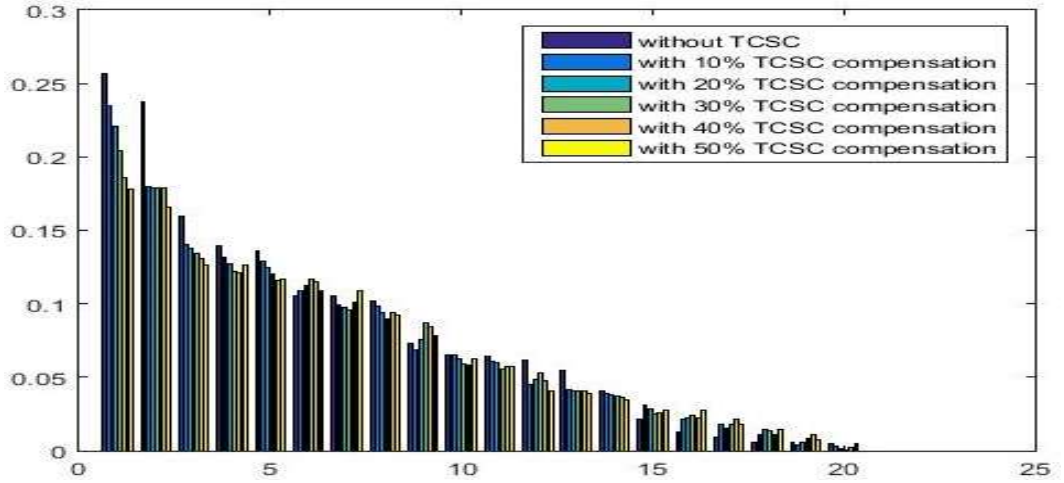


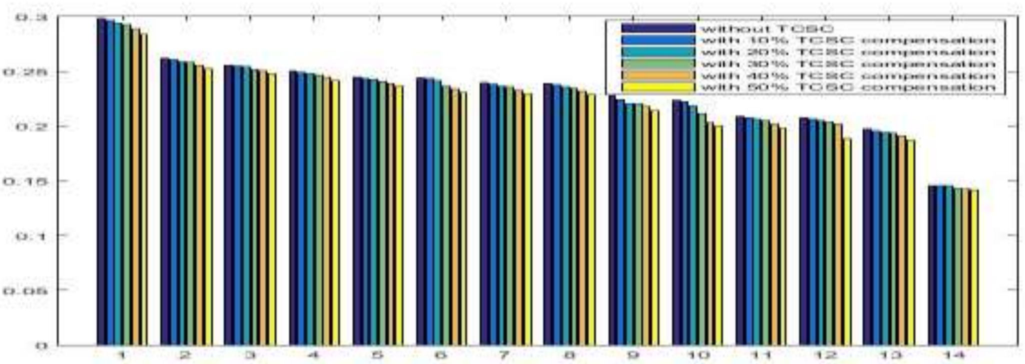
(d)

Figure 5. a) 100%, b) 120%, c) 140% and d) 160% System Loading Condition with Varying TCSC Compensation

Figure 5. (a), (b), (c) and (d) represents 100%, 120%, 140%, and 160% system loading condition under various percentage compensation of TCSC. It can be observed that as the compensation is varied, the line voltage stability index also varies and the rank has been changed slightly.

Case 2. Critical Bus Ranking through VCPI without and with TCSC under system loading condition for Base case

In this case VCPI can be used to evaluate the critical branch in the system under different loading conditions without any contingency. TCSC is connected in series to improve power flows in transmission line. By varying the percentage compensation of TCSC the severity of bus should be decreased as shown in Figure 6.



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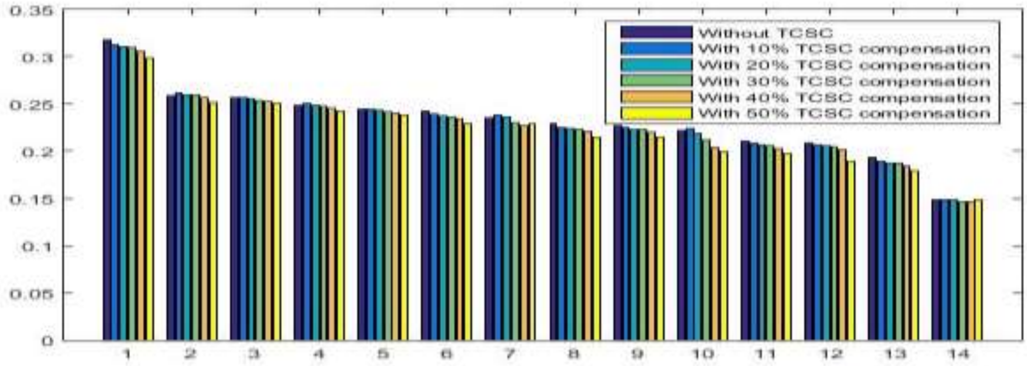

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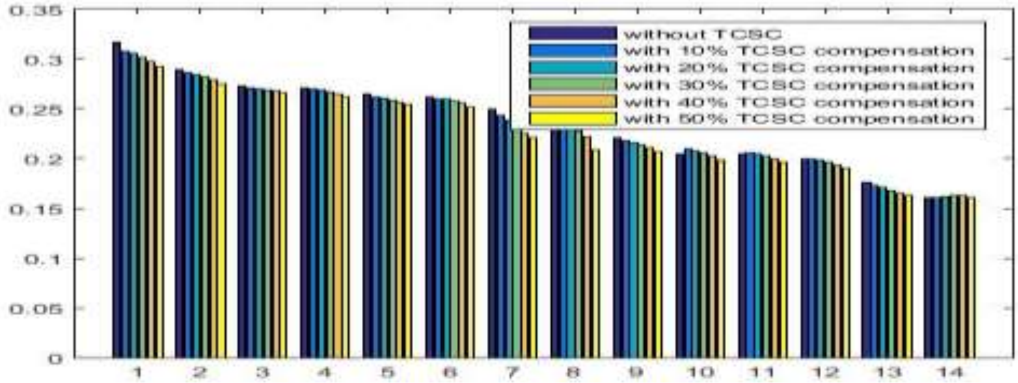

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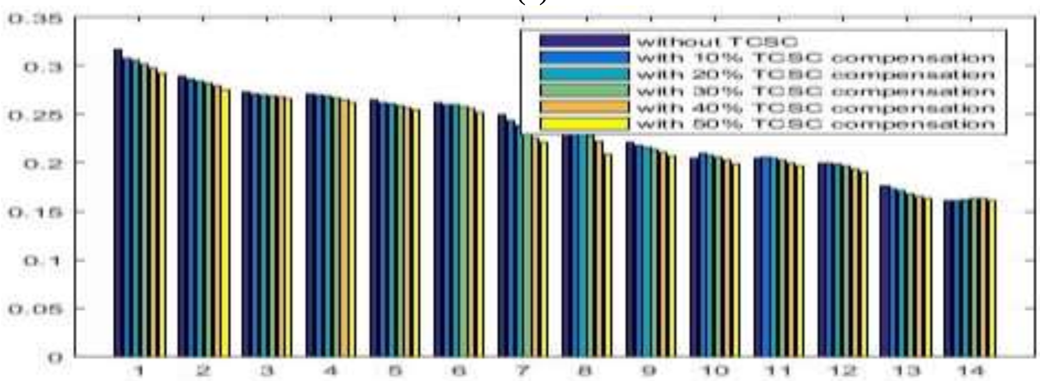

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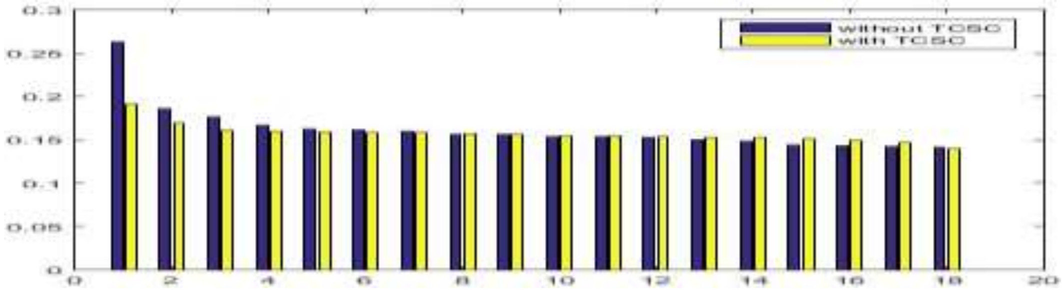
Figure 6. a) 100%, b) 120%, c) 140% and d) 160% System Loading Condition with Varying TCSC Compensation

Figure 6. (a), (b), (c) and (d) represents100%, 120%, 140%, and 160% system loading condition under various percentage compensation of TCSC. It can be observed that as the compensation is varied, the line voltage stability index also varies and the rank has been changed slightly.

Case 3. Critical Line Ranking through L_{mn} without and with TCSC under Contingency condition for system loading

In this case L_{mn} can be used to evaluate the critical branch in the system under different loading conditions with contingency. TCSC is connected in series to improve power flows in transmission line. By varying the percentage compensation of TCSC the severity of line should be decreased as shown in Figure 7.



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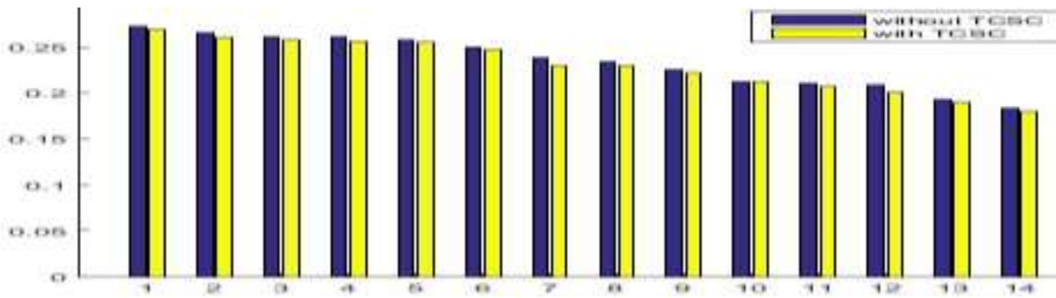

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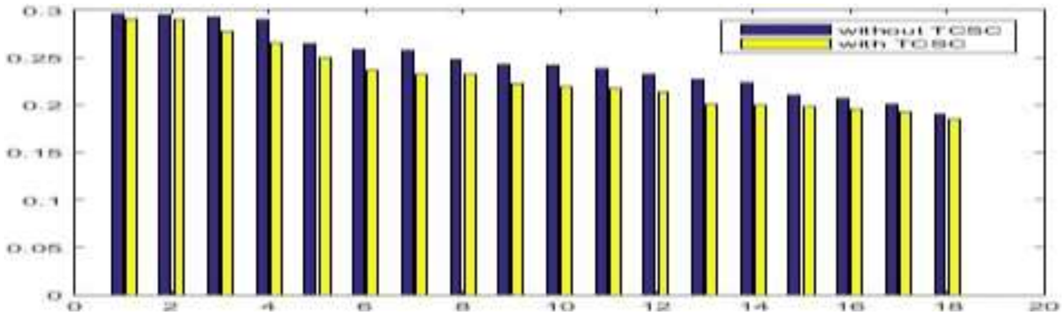

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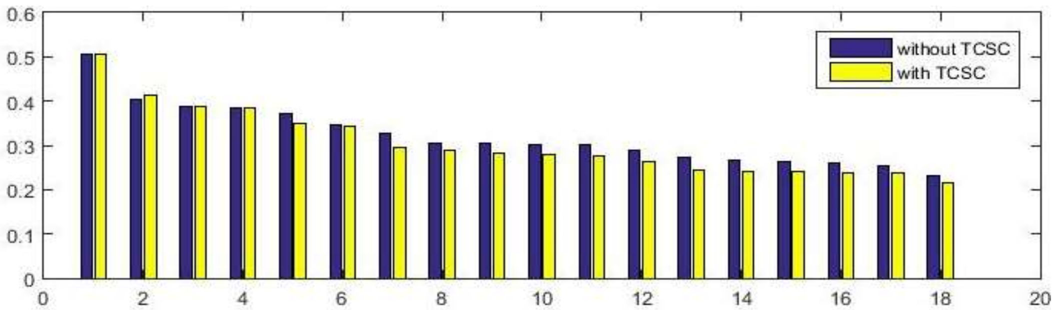

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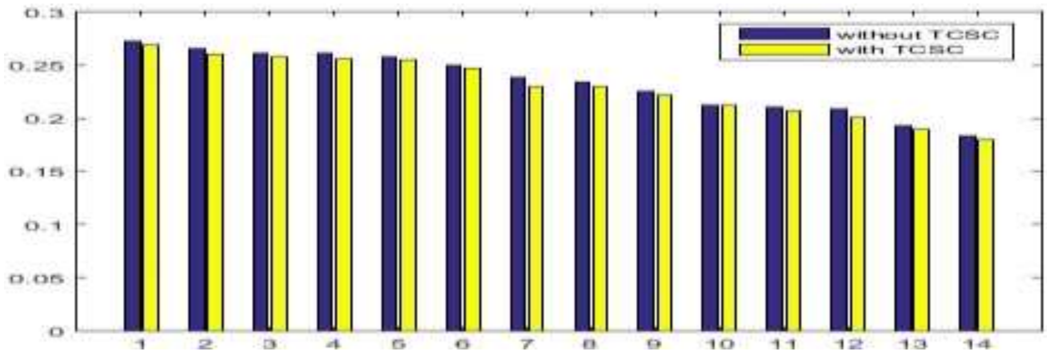
Figure 7. a) 100%, b) 120%, c) 140% and d) 160% System Loading Condition with Varying TCSC Compensation

Figure 7. (a), (b), (c) and (d) represents100%, 120%, 140%, and 160% system loading condition under various percentage compensation of TCSC. It can be observed that as the compensation is varied, the line voltage stability index also varies and the rank has been changed slightly.

Case 4. Critical Bus Ranking through VCPI without and with TCSC Under Contingency Condition for System Loading

In this case VCPI can be used to evaluate the critical branch in the system under different loading conditions with contingency. TCSC is connected in series to improve power flows in transmission line. By varying the percentage compensation of TCSC the severity of bus should be decreased as shown in Figure 8.



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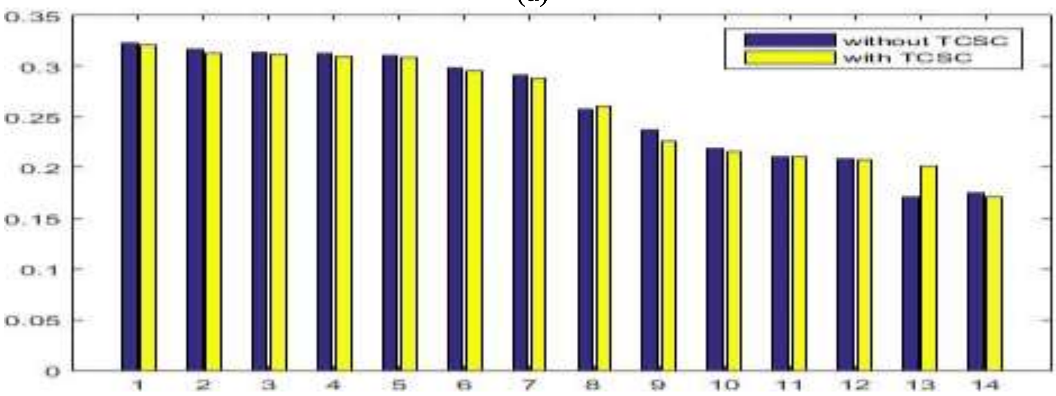

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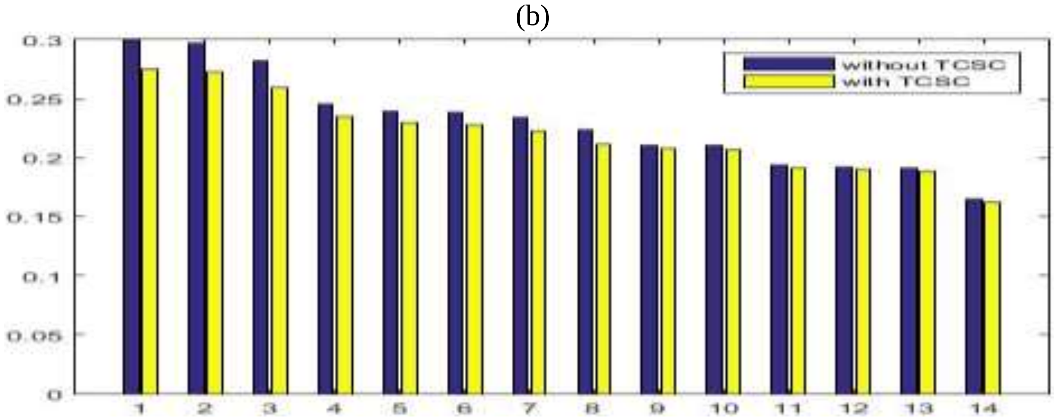

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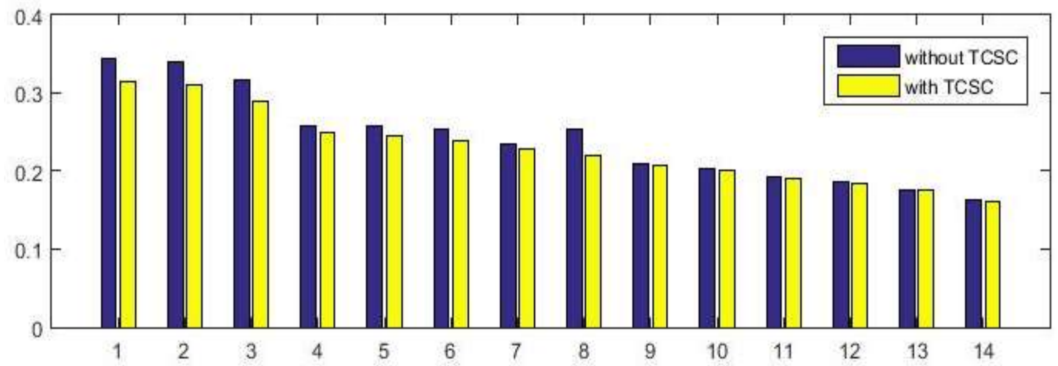

(d)

Figure 8. a) 100%, b) 120%, c) 140% and d) 160% System Loading Condition with Varying TCSC Compensation

Figure 8. (a), (b), (c) and (d) represents100%, 120%, 140%, and 160% system loading condition under various percentage compensation of TCSC. It can be observed that as the compensation is varied, the line voltage stability index also varies and the rank has been changed slightly.

6. Conclusion

Voltage stability indices like VCPI and L_{mn} have been used to identify the critical bus and critical branch in the system. When the system is voltage stable, these indices are near to zero and move near to 1 as the system gradually moving near to the critical point. These voltage stability indices are calculated and compare with different loading scenarios. Voltage stability problem is examined in the interpretation of maximum lodability limit and different loading margins. After incorporating TCSC the system voltage stability has been acceptably enhanced.

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Authors

Baleboina Guru Mohan was born at Akkalareddy palli, Porumamilla, Cuddapah (A.P), India in 1993. He received his B.Tech in Electrical and Electronics Engineering from JNTUA in 2015. He is a PG Scholar in the department of Electrical and Electronics Engineering at Sree Vidyanikethan Engineering College, Tirupathi (India).

His area of research includes voltage stability studies, security analysis.

Suresh Babu Daram was born at Vijayawada (A.P), India in 1985. He received his B.Tech in Electrical & Electronics engineering from JNTU in 2006 and M.Tech degree in Power Systems Engg from ANU, in 2009. He is a Research Scholar in the department of Electrical & Electronics Engineering at the Visvesvaraya Technological University Belgaum (India).

He was Assistant Professor in the Dept. of Electrical & Electronics at GGITM Bhopal from 2009-2015. Currently he is Asst. Prof in Dept. of Electrical & Electronics, Sree Vidyanikethan Engineering College, Tirupati (A.P), India. He has published 32 national/ International journal / conference papers. His research interests include energy management systems, power system optimization, and voltage instability studies incorporating FACTS controllers and security analysis.

Mr. Suresh is a member of IEEE, AMIE (India), IAENG, CSTA, IACSIT, IRED and Student Member-ASTM.

P. S. Venkataramu was born in India on June 20, 1961. He received his Graduation in Electrical Engineering from the Institute of Engineers (India), M. Tech degree in Power Systems from Mysore University (India) and Ph.D. in 2007 from Visvesvaraya Technological University, Belgaum (India).

He was employed as an Electrical Engineer in the Goa state Electricity Department and worked for 15 years in various capacities.

He was primarily involved in carrying power system operational and planning studies for the regional grid system. He was also a visiting faculty in the Goa college of Engineering. From 1997 to 2007, he worked as a faculty in various positions at School of Electrical Sciences, Vellore Institute of Technology, Vellore, India. From 2007 to 2015 he was a Professor in Electrical Engineering Department and Principal of Gyan Ganga Institute of Technology and Management, Bhopal (India). Currently he is Director -Internal Quality at REVA University, Bangalore. He has several national and international publications. His research interest includes AI application to power system and distribution system automation.

Dr. P. S. Venkataramu is a Fellow of the institution of engineers (India), Indian society for technical education, and System society of India.

M. S. Nagaraj completed his B.E degree in Electrical & Electronics in the year 1986 from Government BDT College of Engineering, Davangere. Master of Technology & Doctoral degree in Power System from National Institute of Engineering, Mysore in the year 1991 & 2007 respectively.

He has teaching experience of 25 years in Under Graduate College. At present he is working as Professor & Head in the department of Electrical & Electronics Engg, BIET, Davangere. He has published more than 30 papers in national/ International journal / conference papers. His research interest includes AI application to power system.

Dr. M. S. Nagaraj is a member of Indian Society for Technical Education and Institution of Engineers (India).

