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"An Assessment of Voltage Stability based on Line Voltage Stability Indices and its Enhancement Using TCSC"

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Abstract: *The issue of voltage instability is becoming a matter of concern throughout the world. It is of absolute importance to maintain the stability of the power system or it would lead to a condition of total collapse of the system and ultimately blackout of the whole network. This paper analyses the performance of line voltage stability indices, Fast Voltage Stability index (FVSI), Line index (LQP), Reactive Power Index (VQI) and line Stability Index (L_{MN}). These indices are used to identify the most critical line and bus of the system. Under a condition of single line outage a TCSC is installed at the most critical line and its effect has been observed. An IEEE 14 bus system is used for simulation purpose.*
Keywords: *TCSC, FVSI, LQP, VQI, L_{MN}*

I. Introduction

The enlarged power demand has desired the attention of the power researchers worldwide, and has caused the power system to be operated closer to its stability limits. Any situation of power system instability if not responded to instantaneously can cause a scenario of voltage collapse in the system accompanied by a total blackout.

A power system is said to have a situation of voltage instability when a disturbance causes a progressive and uncontrollable decrease in voltage level. Power system stability is the ability of the system to maintain acceptable levels of voltage at all the buses of the system following a disturbance [1]. Several methods have been used to analyse the performance of the system stability like the PV Curves, QV Curves, Sensitivity Analysis, Modal Analysis [2]. An accurate knowledge of how close the actual system's operating point is from the voltage stability limit is essential to operators. Therefore, voltage stability index was developed for voltage stability studies. These indices provide reliable information about proximity of voltage instability in a power system. Usually, an index value varies between 0 and 1. Line voltage stability indices (LVSI) thus provide information about the system stability by determining the most severe line in the system [3]. Literatures on the indices show that several voltage stability indices have been developed for stability analysis studies [5], [6]-[9]. The value of these indices indicate the closeness of the system towards instability, if the index value is closer to 1 it shows that the system is on the verge of instability, if index value is greater than 1, the system has crossed its stability limit leading to a condition of voltage collapse which can ultimately cause blackout of the system.

Flexible AC Transmission System (FACTS) can be used to enhance the system stability [4] thereby reducing the seriousness of the system. FACT devices should be installed at the most appropriate location i.e. on the most critical line as determined by the indices. The advantage of using FACT controllers be it series or shunt is that the power flow through the line is enhanced and the voltage profile of the system is also improved [10], [11]. A TCSC is a series FACT controller which provides series compensation in the transmission line in which it is installed by modifying the value of line reactance, the advantage of using TCSC is that it can be operated in both inductive and capacitive modes by suitable selection of firing angle [12] ,[13]. Optimal location of TCSC helps in enhancing the voltages of the buses between which it is placed. This paper proposes to analyse and enhance the stability of the system using line voltage stability indices thereby reducing the severity of the system by installing a Thyristor Controlled Series Capacitor (TCSC) in the most critical transmission line.

II. Line Voltage Stability Indices (LVSI)

The line voltage stability indices play a vital role in determining the system stability. They help in determining the weakest bus and the most critical line in the system so that voltage collapse and hence total blackout of the system can be interrupted. This paper analyses the effect of some of the line indices on system stability. These can be briefly discussed as:

2.1 Fast Voltage stability index FVSI

The Fast Voltage Stability Index FVSI as proposed by Musirin et al. [5] [6] is also based on the concept of power flow through a single line. For a typical transmission line, the stability index FVSI is calculated by the following equation as:

$$\mathrm{FVSI} = \frac{4Z^2 Q_i}{V_i X} \ldots\ldots\ldots\ldots\ldots\ldots\ldots (1)$$

Where,

Z = line impedance
X = line reactance
Q_j = reactive power flow at the receiving end
V_i = sending end voltage

When the FVSI of any line approaches unity it means that the line is approaching its stability limits. The FVSI of all the lines must be lower than 1 to assure the stability of the power system.

2.2 Line stability factor LQP

Line stability index LQP as defined in [7] can be expressed as:

$$\mathrm{LQP} = 4\left(\frac{X}{V_i}\right)\left(\frac{X}{{V_i}^2}{P_i}^2 + Q_j\right) \ldots\ldots\ldots\ldots\ldots\ldots (2)$$

Where,

X = line reactance
Q_j = reactive power flow at the receiving bus
V_i = voltage at the sending bus
P_i = active power flow at the sending bus.

The line that exhibits LQP value close to 1 implies that it is approaching the instability point. If LQP goes beyond 1, one of the buses connected to the line experiences a sudden voltage drop leading to system collapse.

2.3 Line stability index L_{MN}

This index also determines the stability of each line connected between two buses in an interconnected network. As long as the stability index L_{MN} remains (< 1), the system is stable. This voltage stability criterion is also based on a power transmission concept in a single line [7]. In order to prevent the system from collapse point the index value should be (< 1). The Line Stability Index L_{MN} is given by:

$$L_{MN} = \frac{4X_{ij} Q_j}{[V_i \sin(\theta - \delta)]^2} \ldots\ldots\ldots\ldots\ldots\ldots\ldots (3)$$

Where,

θ = line impedance angle
δ = angle difference between the sending end and the receiving end voltage
X = line reactance
Q_j = reactive power flow at the receiving end
V_i = sending end voltage

2.4 Reactive power index VQI

The reactive power index is based on the power flow concept through a single transmission line is given as [8], [9]:

$$\mathrm{VQI} = \frac{4\, Q_j}{B_{ij}{V_i}^2} \ldots\ldots\ldots\ldots\ldots\ldots\ldots (4)$$

Where,

Q_j = reactive power at the receiving end
B_{ij} = susceptance of line
V_i = the sending end voltage

The index value (> 1) indicates that the system is on the verge of instability. So as to prevent the system collapse its value should always be (< 1).

III. TCSC

The Thyristor Controlled Series Capacitor (TCSC) is one of the most effective Flexible AC Transmission System (FACTS) devices. It offers fast-acting reactive power compensation on high-voltage electricity transmission networks with much faster response compared to the traditional control .TCSC is one of the most important and best known series FACTS controllers [10]. It has been in use for many years to increase line power transfer as well as to enhance system stability. Installation of TCSC at the most appropriate location i.e. at the most stressed line in the system reduces the value of line stability index hence the system stability is improved. It also helps in improving the voltage profile of the system [11] [12]. The basic construction of a TCSC is shown in Fig. 1.

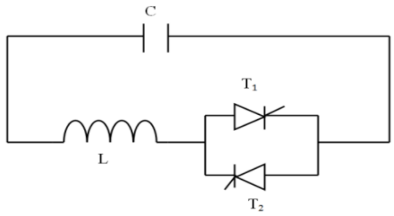

Fig 1. A schematic diagram of TCSC

It consists of three components: capacitor C, bypass inductor L and bidirectional thyristors T1 and T2. The firing angles of the thyristors are controlled to adjust the TCSC reactance in accordance with system requirements. According to the operating principle of the TCSC, it can control the active power flow for the line by compensating the transmission line reactance. A TCSC can provide both inductive and capacitive compensations [13].

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

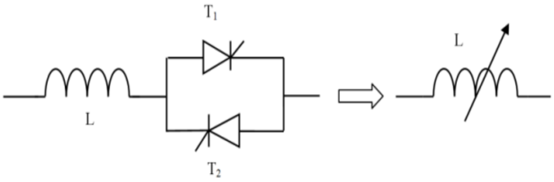

Fig 2. TCSC Inductive Mode

$$X_L(\alpha) = X_L \frac{\pi}{\pi - 2\alpha - \sin 2\alpha} \dots\dots\dots\dots (5)$$

$$X_C = \frac{1}{2\pi f C} \dots\dots\dots (6)$$

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

3.2 Capacitive Mode: The controlled reactor is connected across the series capacitor, so that the variable capacitive reactance, as shown in Fig. 3, is possible across the TCSC which modifies the transmission line impedance. Effective TCSC reactance X_{TCSC} with respect to alpha (α) can be given as:

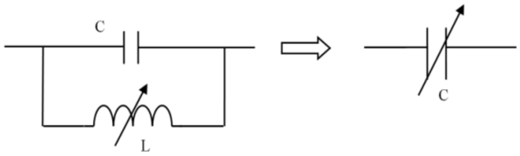

Fig 3. TCSC Capacitive Mode

$$X_{TCSC}(\alpha) = -X_C + C_1\big(2(\pi-\alpha) + \sin\big(2(\pi-\alpha)\big)\big) - C_2\cos^2(\pi-\alpha)\Big(\omega\tan\big(\omega(\pi-\alpha)\big) - \tan(\pi-\alpha)\Big) \dots\dots (6)$$

Where,

$$C_1 = \frac{X_C + X_{LC}}{\pi} \dots\dots\dots\dots\dots (7)$$

$$C_2 = 4\frac{X_{LC}^2}{X_L \pi} \dots\dots\dots\dots\dots\dots . (8)$$

$$X_{LC} = \frac{X_L X_C}{X_C - X_L} \ldots\ldots\ldots\ldots\ldots (9)$$

$$\omega = \sqrt{\frac{X_C}{X_L}} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (10)$$

IV. Proposed Algorithm

- Read the system data
- Run the load flow without line outage contingency and use the results as base case
- Connect N-1 line outage contingency between any two buses and obtain load flow results
- Calculate the values of FVSI , VQI, LMN, and LQP from the equations (1) to (4)
- Rank the weakest / most critical line from the base case or line outage contingency condition having highest value of line indices
- Connect TCSC at the most critical line i.e. between load buses (neglecting the generator buses).
- Obtain the results with TCSC installed in the line for various capacitive modes of 20% to 55% compensation.
- Compare the calculated values of indices pre and post TCSC placement

V. Case Study & Results

5.1 Results of Line Voltage Stability Indices (LVSI)

The simulation was performed on an IEEE 14 bus system consisting of a slack bus, 4 generator buses, 9 load buses and 20 interconnected lines. The tests were carried out using load flow programs in MATLAB. The base case results considering all four indices i.e. FVSI, VQI, L_{MN}, LQP show that no critical line and weak buses were recognized under this condition. Single line outage was carried with one line outage at a time and results were observed. The results from table reveal that under the condition of line 1-2 outages in the 14 bus test system, line 1-5 was identified as critical. It can also be seen from table 1 that the same line was observed to be the most critical line in the system for all four indices. The value of indices being 0.8015, 0.7571, 0.8419 and 1.3136 for FVSI, VQI, L_{MN} and LQP respectively.

5.2 Installation of TCSC

A TCSC was installed in line 1-5 since it showed maximum value of line index and hence was considered as the most critical line in the system. The effect of TCSC was monitored under different cases of capacitive compensations as shown in table 2. The variations in the values of line indices for various degrees of compensation are discussed briefly:

5.2.1 Case 1: FVSI

Fig. 4 demonstrates that initially during a single line outage 1-5 the FVSI base case value is 0.8 which clearly shows that the system in on the verge of instability. Providing different degrees of capacitive compensation show that there is considerable reduction in the value of FVSI, for 20% compensation index value reduces to 0.61, 30% - 0.54, 40% - 0.48, 45% - 0.46, 50% - 0.44 and for 55% - 0.42. Thus the severity of the line is reduced.

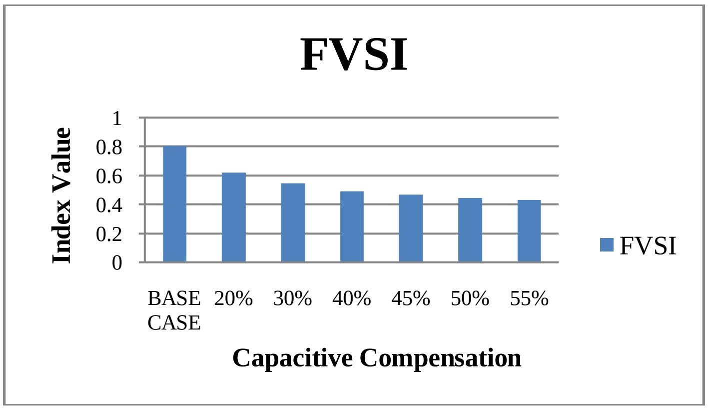

Fig. 4 FVSI variation with and without TCSC

5.2.2 Case 2: VQI

Fig. 5 illustrates that during a single line outage 1-5 the VQI base case value is found to be 0.77 which must be lowered to reduce the criticality of the system. Under different degrees of capacitive compensation with TCSC installation it is seen that there is decrement in the value of VQI, i.e. for 20% compensation index value reduces to 0.56, 30% - 0.48, 40% - 0.41, 45% - 0.38, 50% - 0.35 and for 55% - 0.33 thereby reducing the line criticality.

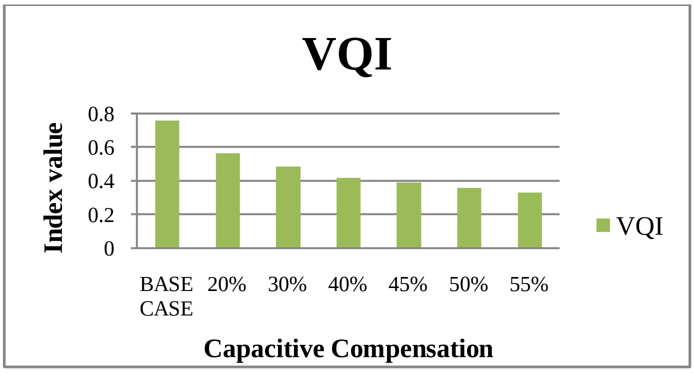

Fig. 5 VQI variation with and without TCSC

5.2.3 Case 3: L_{MN}

Fig. 6 indicates that during a single line outage 1-5 the L_{MN} base case value is 0.84 which clearly reveals that the system in close to instability. Installing TCSC and providing different degrees of capacitive compensation show that there is considerable reduction in the value of L_{MN}, i.e. for 20% compensation index value lowers to 0.57, 30% - 0.48, 40% - 0.41, 45% - 0.39, 50% - 0.36 and for 55% - 0.34. Thus the seriousness of the line is reduced.

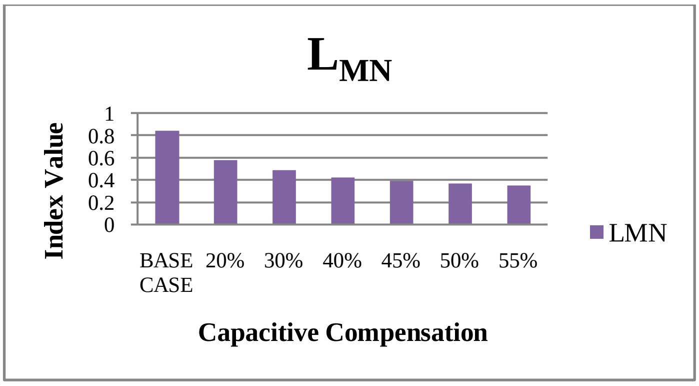

Fig. 6 L_{MN} variation with and without TCSC

5.2.4 Case 4: LQP

Fig. 7 shows that the LQP base case value which occurs during a single line outage 1-5 is 1.31 which explains that the system has crossed its stability limits with index value exceeding 1 and can consequently cause a total collapse of the entire system. TCSC installation can help to reduce the system instability by lowering the index values under different degrees of capacitive compensation, i.e. for 20% compensation index value lowers to 0.95, 30% - 0.78, 40% - 0.63, 45% - 0.56, 50% - 0.49 and for 55% - 0.43. Thus the collapse of the system can be prevented with the effective use of TCSC.

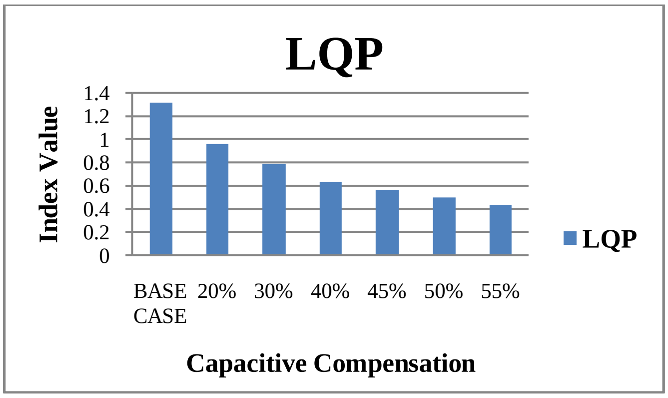

Fig. 7 LQP variation with and without TCSC

5.2.5 Voltage Profile

Figure 8 depicts the deviations in the voltages of bus 5 due to the placement of TCSC in line 1-5, it can be seen that there is an improvement in the voltage level of bus 5 from 0.993 during base case to a maximum of 0.998 during 30 and 40 % compensation, further to 0.996 and 0.995 for 50 % and 55% compensation respectively.

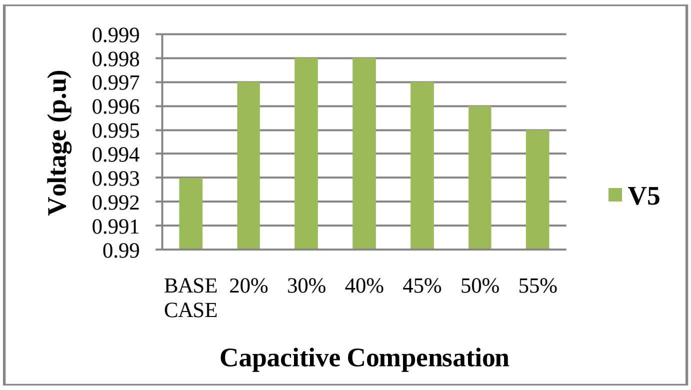

Fig.8 Voltage profile of bus 5

VI. Conclusion

The line voltage stability indices aid in determining the closeness of the system towards instability. The values of these indices are convenient in indentifying the most critical line in the system. A TCSC is installed in the most severe line and as a result enhanced values of line voltage stability indices are obtained. Thus, the severity of the line is reduced. As a result the voltage profile of the system is also enhanced.

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Appendix

Table 1 Line indices under single line outage condition

FROM BUS	TO BUS	FVSI BASE CASE	FVSI 1-2 OUTAGE	VQI BASE CASE	VQI 1-2 OUTAGE	LMN BASE CASE	LMN 1-2 OUTAGE	LQP BASE CASE	LQP 1-2 OUTAGE
1	2	0.0637	0.0000	0.0585	0.0067	0.0608	0.0075	0.0667	0.0067
1	5	0.0256	0.8015	0.0242	0.7571	0.0244	0.8419	0.0982	1.3136
2	3	0.0113	0.0532	0.0107	0.0503	0.0108	0.0514	0.0706	0.0588
2	4	0.0194	0.1844	0.0175	0.1664	0.0184	0.1858	0.0365	0.1664
2	5	0.0178	0.2836	0.0161	0.2562	0.0171	0.3003	0.0231	0.2564
3	4	0.0384	0.1694	0.0333	0.1469	0.0398	0.1849	0.0339	0.1490
4	5	0.0261	0.1067	0.0237	0.0970	0.0266	0.1118	0.0239	0.0978
4	7	0.0919	0.1272	0.0919	0.1272	0.0921	0.1275	0.0927	0.1276
4	9	0.0371	0.0658	0.0371	0.0658	0.0374	0.0661	0.0476	0.0700
5	6	0.0779	0.0458	0.0779	0.0458	0.0786	0.0464	0.0904	0.0798
6	11	0.0293	0.0333	0.0238	0.0271	0.0290	0.0328	0.0238	0.0271
6	12	0.0259	0.0257	0.0210	0.0209	0.0255	0.0254	0.0210	0.0210
6	13	0.0389	0.0404	0.0309	0.0321	0.7089	0.7226	0.0309	0.0321
7	8	0.1101	0.1437	0.1101	0.1437	0.1101	0.1437	0.1101	0.1437
7	9	0.0195	0.0236	0.0195	0.0236	0.0195	0.0236	0.0197	0.0237
9	10	0.0145	0.0134	0.0127	0.0117	0.0145	0.0134	0.0127	0.0117
9	14	0.0399	0.0388	0.0327	0.0318	0.0392	0.0383	0.0328	0.0318
10	11	0.0134	0.0175	0.0113	0.0148	0.0135	0.0177	0.0113	0.0148
12	13	0.0120	0.0116	0.0054	0.0052	0.0119	0.0116	0.0054	0.0052
13	14	0.0255	0.0280	0.0206	0.0225	0.0252	0.0274	0.0206	0.0227

Table 2 Line index values with TCSC compensation

LINE 1-5 UNDER 1-2 LINE OUTAGE				
	FVSI	VQI	LMN	LQP
BASE CASE	0.8015	0.7571	0.8419	1.3136
20%	0.6157	0.5639	0.5769	0.9574
30%	0.5448	0.4865	0.4881	0.7859
40%	0.4870	0.4188	0.4196	0.6334
45%	0.4638	0.3885	0.3923	0.5638
50%	0.4440	0.3596	0.3689	0.4981
55%	0.4284	0.3321	0.3479	0.4363