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Voltage Stability Limit Enhancement using Thyristor Controlled Series Capacitor (TCSC)

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ABSTRACT

Flexible Alternating Current Transmission System (FACTS) devices can regulate the active and reactive power control as well as adaptive to voltage magnitude control simultaneously, because of their flexibility and fast control characteristics. Placement of these devices in suitable location can lead to control in line flow and maintain bus voltages in desired level and so improve voltage stability margins. This paper presents an application of Fast Voltage Stability Index (FVSI) for identifying the critical line which is considered as the best location for Thyristor Controlled Series Capacitor for voltage stability improvement. The analysis is performed on standard IEEE 30-bus test system.

Keywords

TCSC, Voltage stability, Fast Voltage Stability Index (FVSI), Reactive power

1. INTRODUCTION

Voltage stability has become an issue of great concern for both power system planning and operation in recent years, as a result of a number of major blackouts that have been experienced in many countries due to voltage stability problems. This has been mainly due to power systems being operated closer to their stability limits because of increased demand for electricity [1, 2]. The main cause of voltage instability may be due to the shortage of reactive power in power system [3].

In recent times, Flexible Alternating Current Transmission System (FACTS) controllers have become essential for reliable operation of power system. The application of these devices is a very effective solution to prevent a voltage instability and voltage collapse due to their fast and very flexible control. Placement of FACTS devices in suitable location can lead to control in line flow and maintain bus voltages in desired level and so improve voltage stability margins. The best location for reactive power compensation for the improvement of voltage stability margin is by considering the identified “weakest buses or lines” of the system. These critical buses and lines constitute the set of candidate points for the reinforcement against voltage stability.

There are many types of voltage indices used to counted voltage stability limits and to identified weak buses or transmission lines in power system, such as sensitivity index [4], maximum loading margin index (MLM) [5], load proximity index [6, 7], impedance index [8], Fast Voltage Stability Index (FVSI) [9], Line stability index [10].

This paper presents an application of Fast Voltage Stability Index (FVSI) for identifying the most suitable locations for FACTS devices. TCSC has been incorporated to observe their effectiveness to enhance voltage stability limit. The analysis is performed on standard IEEE 30-bus test system.

This paper is organized as follows: In section 2, the structure and operation principle of TCSC is introduced. The application of Fast Voltage Stability Index (FVSI) for identifying the most suitable locations for TCSC is presented in section 3. The results obtained for the test system is given and discussed in section 4.

2. TCSC MODEL

Flexible AC Transmission Systems (FACTS) are controllable power electronic based devices in electric transmission systems which allow enhancing controllability and increasing power transfer capability. FACTS devices can basically be sub-divided into three categories:

- Shunt devices such as Static Var Compensator (SVC);
- Series devices such as Thyristor Controlled Series Capacitors (TCSC);
- Combined series-shunt controllers such as Unified Power Flow Controller(UPFC)

Series compensation wills [11]:

- Increase power transmission capability.
- Improve system stability.
- Reduce system losses.
- Improve voltage profile of the lines.
- Optimize power flow between parallel lines.

Thyristor Controlled Series Capacitors (TCSC) is a type of series compensator, can provide many benefits for a power system including controlling power flow in the line, damping power oscillations, and improving of voltage stability.

A TCSC is a capacitive reactance compensator, which consists of a series capacitor bank shunted by a thyristor controlled reactor in order to provide a smoothly variable series capacitive reactance [12]. Figure 1 shows a schematic representation of a TCSC connected in a transmission line between bus **n** and **m** of power system.

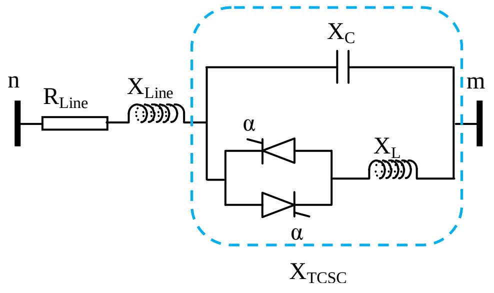

Fig 1: Transmission Line with TCSC Controller

The principle of TCSC in voltage stability enhancement is to control the transmission line impedance by adjust the TCSC reactance X_{TCSC}. The equivalent reactance of TCSC being a function of the firing angle α of the TCR, The firing angles of the thyristors are controlled to adjust the TCSC reactance according to the system control algorithm, normally in response to some system parameter variations. According to the variation of the thyristor firing angle or conduction angle, this process can be modeled as a fast switch between corresponding reactance offered to the power system. Assuming that the total current passing through the TCSC is sinusoidal, the equivalent reactance at the fundamental frequency can be represented as a variable reactance X_{TCSC}. The TCSC can be controlled to work either in the capacitive or the inductive zones avoiding steady state resonance [13], as represented in Figure 2. Thus, impedance characteristics of TCSC shows, both capacitive and inductive region are possible though varying firing angle (α):

- Thyristor valve bypass mode (inductive region operation) : From 90° to α_{Llim} ;
- Thyristor valve blocked mode (resonance region for inhibited operation) : Between α_{Llim} and α_{Clim} ;
- Vernier control mode (capacitive region operation) : From α_{Llim} to 180°.

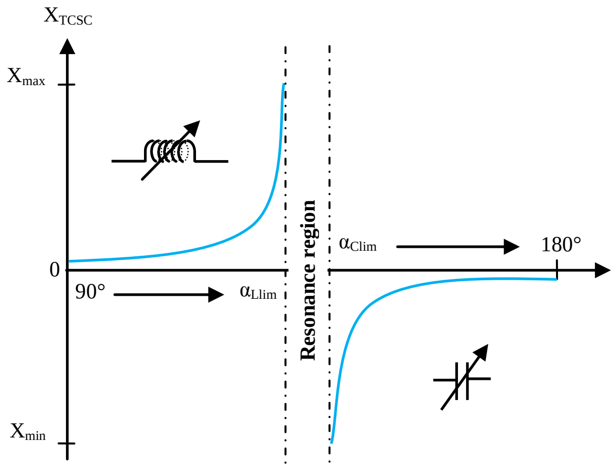

Fig 2: Impedance Vs firing angle characteristic curve

There exists a steady-state relationship between the firing angle α and the reactance X_{TCSC}. This relationship can be described by the following equation [14]:

$$X_{TCSC}(\alpha) = \frac{X_C X_l(\alpha)}{X_l(\alpha) - X_C} \tag{1}$$

Where:

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

With: $X_L = \omega L$

α is the firing angle, X_L is the reactance of the inductor and X_l is the effective reactance of the inductor at firing angle.

The effective series transmission impedance is given by:

$$X_{eff} = (1-K) X_{Line} \tag{3}$$

Where k is the degree of series compensation:

$$K = \frac{X_{TCSC}}{X_{Line}}$$

3. IDENTIFICATION OF THE WEAK LOAD BUSES

Identification of weakest bus is for objective to identify the best location for reactive power compensation for the improvement of static voltage stability margin of the system. In this study a line based voltage stability index called Fast Voltage Stability Index symbolized (FVSI) proposed by I. Musirin et al. [9] is utilized as the indicator.

The FVSI can be calculated for any of the lines of the network and depends, essentially of reactive power. The value of line index that is closed to the unity indicates that the respective line is closed to its stability limit.

The calculated FVSI can also be used to determine the weakest bus [15]. The determination of weakest bus is based on the maximum reactive power loading. The most critical bus or the weakest bus in system corresponds to the bus with smaller maximum reactive power loading.

Figure 3 illustrates a single line of interconnected network where the FVSI is derived from.

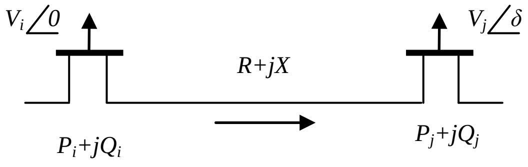

Fig 3: Model of simple branch for voltage stability research

By taking the sending bus (bus i) as the reference, the voltage of receiving end V_j can be calculated by [9]:

$$V_j^2 - \left(\frac{R}{X}\sin\delta + \cos\delta\right)V_i V_j + \left(X + \frac{R^2}{X}\right)Q_j = 0 \tag{5}$$

In (1), the condition for obtaining the real roots of V_j is that the discriminate must be set greater than or equal to 0, i.e:

$$\frac{4Z^2 Q_j X}{V_i^2 (R\sin\delta + X\cos\delta)} \le 1 \tag{6}$$

Considering the angle difference δ is very small, i.e. 0≈δ, the index is formulated as:

$$FVSI = \frac{4Z^2 Q_j}{V_i^2 X} \leq 1 \qquad (7)$$

Where: Z is the line impedance, X is the line reactance, V_i is the voltage at the sending end and Q_j is the reactive power at the receiving end.

The value of the index which is closed to unity indicates that the respective line is closed to its stability limit.

For identifying the weak bus the following steps are implemented [16]:

1. Run the load flow program for the base case;
2. Evaluate the FVSI value for every line in the system;
3. Gradually increase the reactive power loading at a chosen load bus until the load flow solution fails to give results for the maximum computable FVSI;
4. Extract the stability index that has the highest value;
5. Choose another load bus and repeat steps 3, 4;
6. Extract the maximum reactive power loading for the maximum computable FVSI for every load bus. The maximum reactive power loading is referred to as the maximum loadability of a particular bus;

Sort the maximum loadability obtained from step 6 in ascending order. The smallest maximum loadability is ranked the highest, implying the weakest bus in the system.

4. RESULTS AND DISCUSSION

The simulation work conducted on the IEEE 30-bus Test system, which consists of six generators (bus 1 is a slack bus 2, 5, 8, 11 and 13 are PV buses), 24 loads and 41 lines, (6-9, 6-10, 4-12 and 28-27) in which four lines are with the tap changing transformers. The line parameters and loads are taken from [17]. Simulation results have been obtained by using MATLAB software package.

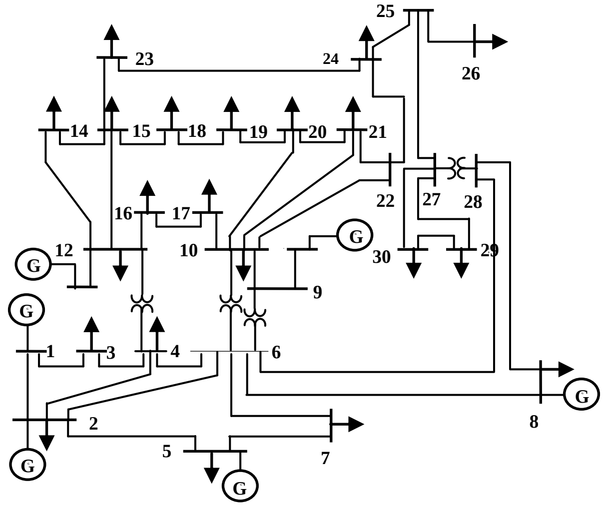

Fig 4: Single line diagram of the IEEE 30-bus system

4.1 Best Location of TCSC Device

At first, Newton-Raphson load flow analysis is done to obtain the initial bus voltages and line flows, the margin of reactive power for IEEE 30-bus test system is given in Figure 5. It shows that buses 26, 29 and 30 have the lowest margin of reactive power.

To define the appropriate placement of TCSC, the Fast Voltage Stability Index (FVSI) is computed and ranked, and the most ten severe lines according to FVSI values are recorded in Table 1. The bus 26, 29 and bus 30 are considered as the best location to provide desired reactive power support.

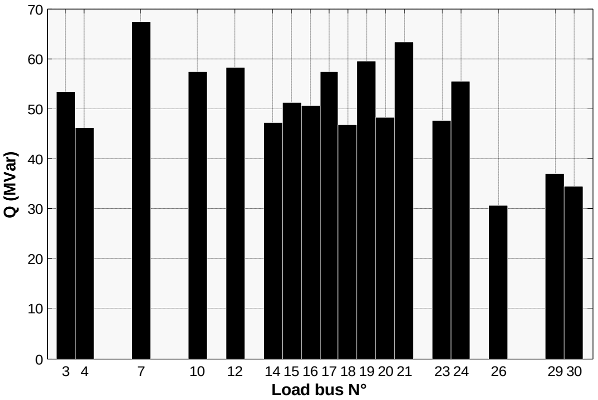

Fig 5: Margin of reactive power for IEEE 30-bus test system

Table 1: The highest ranked lines according to FVSI

Lines (From - To)	FVSI
25-26	**0.9479**
27-30	**0.9452**
27-29	**0.8944**
29-30	0.6972
28-27	0.5528
14-15	0.4388
24-25	0.3659
15-23	0.3602
15-18	0.3574
25-27	0.3518

To define the most critical line the reactive power demand (Q_d) in the test system was increased gradually at the following observed busses (bus 26, 29 and 30). Figure 6 gives the idea of most critical line in the system with respect to a bus. The line connected between buses 25 and 26 is most critical with variation in reactive power loading at bus 26 as its FVSI value is close to 1. So, the weakest line 25-26 is chosen to place TCSC device. Figure 7 shows the FVSI Index and Bus voltage versus reactive power demand for Bus 26. It can be seen that as reactive power demand is increased, the FVSI would rise eventually to a value close to 1. However the bus voltage value reduces gradually as reactive power demand increases.

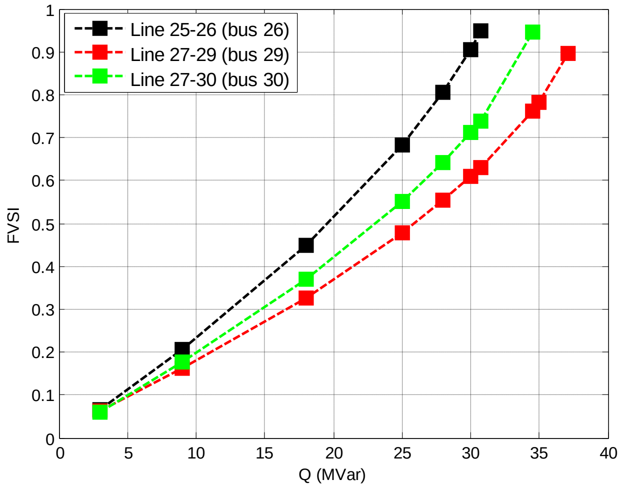

Fig 6: FVSI profiles computed with load varies at bus 26, 29 and 30

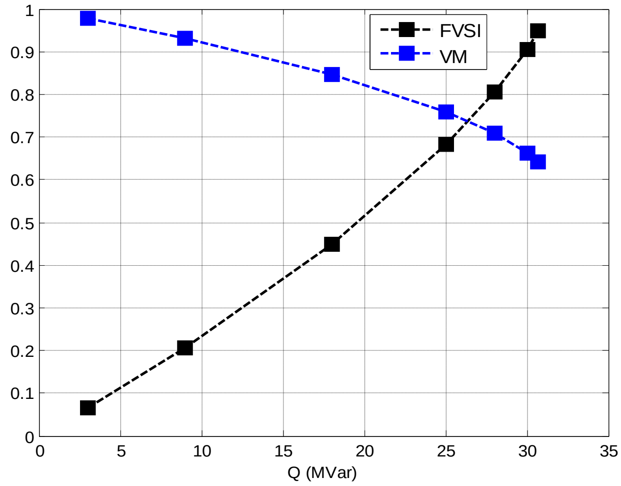

Fig 7: FVSI Index and Bus voltage versus Reactive Power Demand for Bus 26

The results above validates the expected result, whereby high reactive power demand will tend to cause a drop in bus voltage and also increase the branch load level, which in turn is represented by the FVSI characteristic.

4.2 Effect of TCSC Device

To explore the effect of the TCSC device on voltage stability, a TCSC can be connected in the weakest line 25 – 26, with a compensation level of 70%.

Figure 8 and Figure 9 shows the FVSI value variations, and the voltage magnitudes of bus 26 without and in presence of TCSC versus reactive power demand increases at the same bus. From the results, it is clearly shown that the system voltage magnitudes have been improved, Fast Voltage Stability Index (FVSI) values are reduced with inclusion of TCSC in weakest line. It is observed that at Q = 30.7 MVAr, FVSI value is reduced from 0.9479 to 0.7001. At the same time voltage profile is improved from 0.643 p.u to 0.828 p.u.

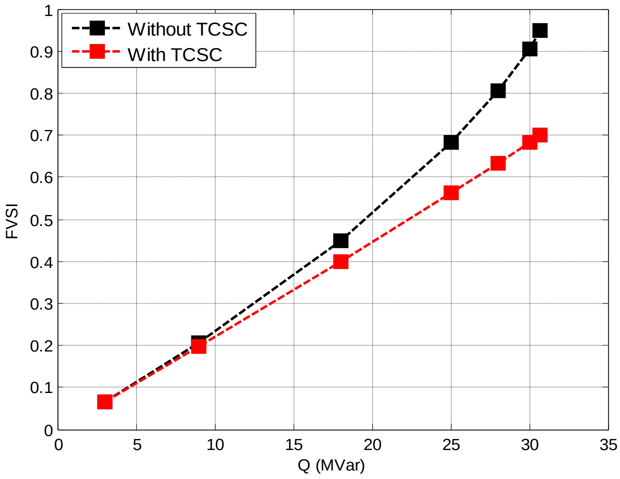

Fig 8: FVSI Index versus Reactive Power Demand for Bus 26 with and without TCSC

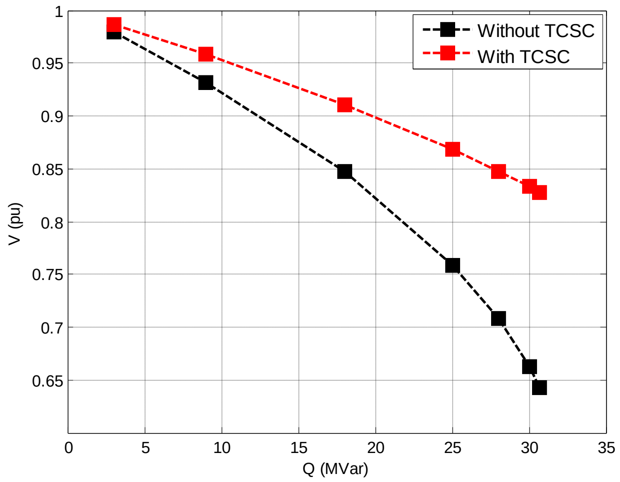

Fig 9: Voltage profile versus Reactive Power Demand for Bus 26 with and without TCSC

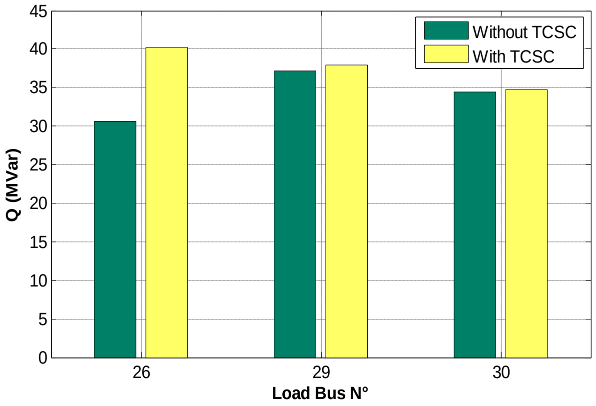

Fig 10: Maximum permissible reactive load on bus 26, 29 and 30 with and without TCSC

Figure 10 shows the Maximum permissible reactive load on bus 26, 29 and 30 with TCSC between buses 25 and 26 and without TCSC. It is observed that at bus 26 the maximum reactive power value is increased from 30.7 MVar to 40.2 MVar with TCSC. Figure 11 shows the voltage values of each bus of IEEE 30-bus system without and with insertion of TCSC. It is clearly shown that the system voltage magnitudes have been improved in several buses with the insertion of TCSC.

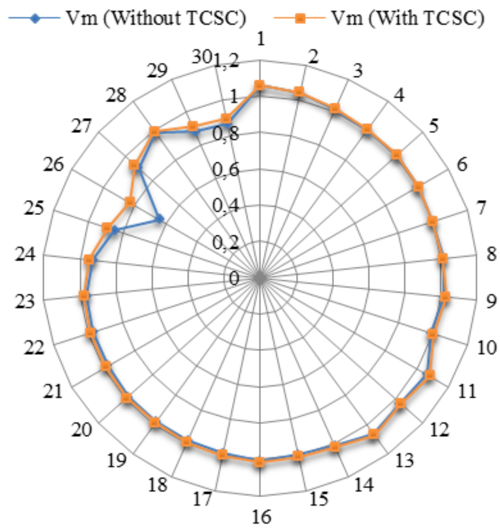

Fig 11: Voltage magnitude of buses before and after placing TCSC

5. CONCLUSION

In this paper, voltage stability assessment of the standard IEEE 30-bus test system with base case and with Thyristor Controlled Series Capacitor (TCSC) is studied. Suitable location of TCSC for voltage stability limit improvement based on identification of weakest bus using Fast Voltage Stability Index (FVSI) method is demonstrated.

Fast Voltage Stability Index determine the distance between the operating point and collapse point in terms of reactive power loading at the load bus.

From the results, it is concluded that the system performs better when TCSC is connected. TCSC would help to reduce the FVSI index hence reducing probability of Voltage Instability, improving voltage profiles and increasing the maximum permissible reactive load.

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