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Load Flow Control and Analytical Assessment of Voltage Stability Index Using Thyristor Controlled Series Capacitor (Tcsc)

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Abstract:- Voltage stability problem has become one of the major concerns in the operation of power system in recent years. The reason is that power systems all over the globe are being operated with reduced margins because of the exponentially growing demands and the associated stress on the power transmission resources aggravated by a general reluctance to invest in improvement of the electric grid infrastructure. Moreover, voltage instability has been responsible for severe network collapses world-wide and subsequently, the possible threat of voltage instability is becoming more pronounced in power utilities. In order to avoid the voltage collapse, this paper presents maximum loadability identification of a load bus in a power transmission network which is achieved by performing voltage stability study by utilizing Fast Voltage Stability Index (FVSI) as an indicator of the maximum loadability termed as Q_{max}. In this technique, reactive power loading will be increased gradually at particular load bus until the FVSI reaches close to unity. Therefore, a critical value of FVSI was set as the maximum loadability point. This value ensures the system from entering voltage-collapse region. The main purpose in the maximum loadability assessment is to plan for the maximum allowable load value to avoid voltage collapse; which is important in power system planning risk assessment index. In order to improve the system stability, Thyristor Controlled Series Capacitor (TCSC) is installed in the most severe line, which is identified from the line stability index values of all lines in a system. TCSC is a series compensated device used for voltage stability enhancement, which is to be connected in series with transmission line. It can control the transmission line impedance to improve the line transfer capability and to regulate the receiving end bus voltage. This proposed technique was applied to solve real problems in a 14 bus power grid using Power flow analysis. Power flow is very necessary for planning, operation, economic scheduling and exchange of power between utilities. Newton Raphson iterative algorithm is used for solving the power flow problems due to its ability to converge very fast with small number of iteration. Simulation of power flow solutions with and without TCSC was done using MATLAB 7.5 program. The result shows that the application of TCSC improved the voltage profile of the system and furtherly enhanced the power flow.

Keywords: TCSC, FACTS, Line Flow Index, FVSI, Criticality Index, load flow, Matlab.

I. INTRODUCTION

The voltage instability is considered as one of the critical issue in electric power system. The inherent complexity and interconnectivity forces a power system to operate closer to limits of stability, along with the added contribution to system instability by inadequate supply of reactive power which in turn leads to voltage collapse. Fast voltage stability analysis and prediction of collapse point are great challenges in power system. Many of the researchers in the recent-past focused on the effective online monitoring of status of the system and hence to solve the problem of voltage collapse. In this regard, voltage stability index of each transmission line becomes the useful measure of power system monitoring. The index could identify how far a system is from its point of collapse [1]. Performance indices to predict closeness to voltage stability boundary have been a permanent concern of researchers and power system operators, as these indices can be used online or offline to help dispatchers determine how close the system is to a possible voltage instability state [2]. Several voltage stability indices used to measure proximity to voltage collapse in off-line as well as on-line applications are detailed [3].

The voltage stability is the ability of a power system to maintain steady acceptable voltage at all buses in the system at normal and after being subjected to a disturbance. A power system becomes unstable, when voltages uncontrollably decrease due to increment of loads, decrement of power generation, outage of equipment and lines and failure of voltage control mechanism. The problem of voltage instability is mainly due to insufficient supply of the reactive power or by an excessive absorption of reactive power. As the voltage instability affects the satisfactory operation of power system, continuous monitoring of the system status is required. Stability of the power system can be identified through various stability factors. The indicator uses bus voltage and network information provided by the power flow program. Moghavvemi’s stability index, FVSI, Mohamed’s stability factor and Jasman’s stability factors are used to identify the most severe line in the system.

In this paper, Fast voltage stability index is used to calculate the stability of each line in IEEE 14 bus systems. When this index value changes from 0 to 1, the voltage stability of the system relatively decreases. If this index value is greater than 1, then the system is considered as unstable. Instability problem affects the desired operation of power system. Sometimes entire system may be collapsed. TCSC is a series compensated device used for voltage stability enhancement, which is to be connected in series with transmission line. It can control the transmission line impedance to improve the line transfer capability and to regulate the receiving end bus voltage [4-6]. In order to improve the system stability the TCSC is installed in the most severe line, which is identified from the line stability index values of all lines in a system.

II. POWER FLOW CONTROL

FACTS Technology is concerned with the management of active and reactive power to improve the performance of electrical networks. The concept of FACTS technology embraces a wide variety of tasks related to both networks and consumers problems, especially related to power quality issues, where a lot of power quality issues can be improved or enhanced with an adequate control of the power flow [7-8]. In general, the concept of power flow control is concerned with two jobs: load support and voltage compensation. Through the demand operation, the tasks are to raise the amount of the network power factor, to increase the true power from the source, to compensate voltage regulation and to decrease harmonic components resulted from large and fluctuating nonlinear loads especially in industry applications. Voltage Support is mainly important to decrease voltage changes at the terminals of a transmission path. Reactive power support in transmission networks also enhances the stability of the networks by maximizing the active power that can be transferred. It also assists to keep a substantially regulated voltage profile at all sections of power transfer, it enhances HVDC (High Voltage Direct Current) feature performance, raises transmission efficiency, sets steady-state bus normal voltage and over voltages, and can avoid serious blackouts.

Series and shunt VAR compensators are able to alter the performance characteristics of electrical networks. Series compensators change the parameters of the transmission grids or distribution levels, where shunt compensators modify the impedance at the connected terminals. In both of them, the reactive power through the system can significantly improve the performance of the power system. Classically, rotating and fixed capacitors or which uses mechanical in switching or inductors are applied to VAR power compensators. Even in recent decades, static VAR compensators based on thyristor switched capacitors and thyristor controlled reactors to give or take the required reactive power are established. Additionally, the use of self commutated PWM converters by an control action allows the achievement of static compensators for generating or consuming reactive components faster than the fundamental system period. Based on the reliable high-speed power electronics, efficient analytical boxes, intelligent control Flexible AC and microcomputer devices, Flexible AC Transmission Systems (FACTS), are presented as a recent idea for the operation of power networks [9]. Inside these concepts, static VAR compensation uses fast response times and plays an important role in improving the amount of total power transfer through a transmission line, near its thermal rate, without violation in its stability boundary. These techniques arise through the power of special static VAR compensators to adapt the related parameters that control the performance of transmission systems with the reactance, current, resistances, voltage, load angle and oscillations damping . The core of FACTS technology contains high power electronics, a variety of thyristor devices, micro-electronics, communications and advanced control actions . By FACTS, operator governs the phase angle, the voltage profile at certain buses and line impedance [10-11].

Power flow is controlled and it flows by the control actions using FACTS devices, which include

- Static VAR Compensators (SVC)
- Thyristor Controlled Series Capacitors (TCSC)
- Static Compensators (STATCOM)
- Static Series Synchronous Compensators (SSSC)
- Unified Power Flow Controllers (UPFC)

III. LITERATURE REVIEW

Electric power systems throughout the world are undergoing considerable change in regard to structure, operation and regulation. Technological developments and evolving consumers' expectations are among the driving factors in the new electricity model. Competition and uncertainty in the new deregulated electric utility industry are serious concerns. Electric power utilities also face increasing uncertainty regarding the political, economic, societal and environmental constraints under which they have to operate existing systems and plan future systems. All these conditions have created new electric utility environments that require extensive justification of new facilities, optimization of system configurations, improvements in system reliability and decreases in construction and operating costs. New planning criteria with broader engineering considerations of transmission access and consistent risk assessment must be explicitly addressed. The likelihood of the occurrence of worst possible scenarios must also be recognized in the criteria and acceptable risk levels incorporated in the decision making process [12].

Assessment of power system security is necessary in order to develop measures to maintain or keep power supply stable and reliable for power system operations, when one or more elements fail. A power system is "secure" when it can withstand the loss of one or more elements and still continue operation without major problems. Since the main concern of power system Engineers is certainly to ensure continuity of service in a power system. Current electric utility operating policies (such as NERC's) require that each utility's power system must be able to withstand and recover from any "first contingency" or any single failure. Future policies may extend this to withstanding a "second contingency" or any subsequent single failure.

2.1 Voltage Stability Analysis using Line Stability Indices

The voltage stability is the ability of a power system to maintain steady acceptable voltage at all buses in the system at normal and after being subjected to a disturbance [13]. A power system becomes unstable, when voltages uncontrollably decrease due to increment of loads, decrement of power generation, outage of equipment and lines and failure of voltage control mechanism. The problem of voltage instability is mainly due to insufficient supply of the reactive power or by an excessive absorption of reactive power. As the voltage instability affects the satisfactory operation of power system, continuous monitoring of the system status is required. Stability of the power system can be identified through various stability factors.

In this paper, Fast voltage line stability factor is used to calculate the stability of each line in IEEE 14 bus systems. When this index value changes from 0 to 1, the voltage stability of the system relatively decreases. If this index value is greater than 1, then the system is considered as unstable. Instability problem affects the desired operation of power system.

Sometimes entire system may be collapsed. TCSC is a series compensated device used for voltage stability enhancement, which is to be connected in series with transmission line. It can control the transmission line impedance to improve the line transfer capability and to regulate the receiving end bus voltage. In order to improve the system stability the TCSC is installed in the most severe line, which is identified from the line stability index values of all lines in a system.

2.2 Voltage Stability Indices

Many aspects of voltage stability problems can be effectively analyzed by using static methods. These methods examine the viability of the equilibrium point represented by a specified operating condition of the power system. Static approaches like sensitivity analysis, modal analysis, P-V and Q-V methods for voltage stability assessment use a system condition or snapshot for voltage stability evaluation [14]. They usually solve power flow equations of the network with specific load increments until the point of voltage collapse is reached. These techniques allow examination of a wide range of system conditions and can provide much insight into the nature of this phenomenon by computation of the contributing factors.

The slow variation in reactive power loading towards its maximum point causes the traditional load flow solution to reach its non convergence point. Beyond this point, the ordinary load flow solution does not converge, which in turn forces the systems to reach the voltage stability limit prior to bifurcation in the system. The margin measured from the base case solution to the maximum convergence point in the load flow computation determines the maximum loadability at a particular bus in the system.

The condition of voltage stability in a power system can be known using voltage stability indices. These indices can either reveal the critical bus of a power system or the stability of each line connected between two buses in an interconnected network or evaluate the voltage stability margins of a system. Several methods have been proposed in this paper to assess the static security of the network. The basic formulas used to examine the system stability and the voltage collapses are briefly described in this section. The purpose of voltage stability indices is to determine the point of voltage instability, the weakest bus in the system and the critical line referred to a bus. Voltage stability indices are proposed to aiming to detect the system loadability. These indices provide reliable information about proximity of voltage instability in a power system. It is important for the operators and planners to find out the limit point of voltage instability. Therefore finding a voltage stability index has become an important task for voltage stability studies.

There are three line stability indices involved in this section to perform the voltage stability analysis. Firstly, the Fast Voltage Stability Index (FVSI) is considered for the voltage stability analysis which yields the desired simulation results. Later, the results are verified with another two line indices namely, L_{mn} and L_{QP}. These indices are briefly discussed in the following section.

2.2.1 Fast Voltage Stability Index (FVSI)

The FVSI is derived from the voltage quadratic equation at the receiving bus on a two- bus system. The general two bus system is represented is in Figure 1

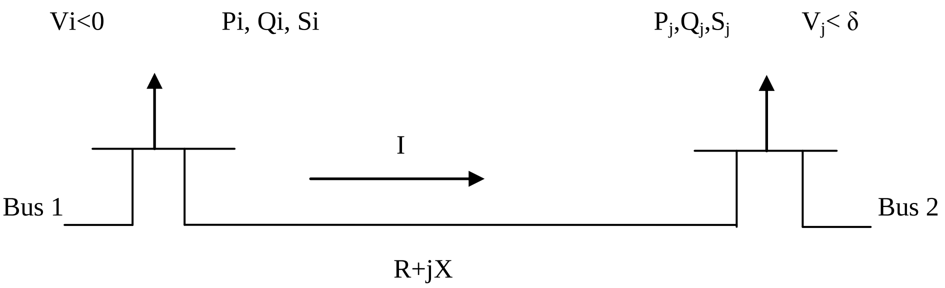

Figure 1 Single line diagram of two-bus power system

From the figure 1, the line impedance is noted as Z = R+jX with the current that flows in the line is given by,

$$I = \frac{V_i < 0 - V_j < \partial}{R + jX} \tag{1}$$

$$S_j = V_j I^* \tag{2}$$

$$I = \left(\frac{S_j}{V_j}\right) \text{ and} \tag{3}$$

$$I = \frac{P_j - JQ_i}{V_j < -\partial} \tag{4}$$

Equating (1) and (4) we obtained,

$$\frac{V_i < 0 - V_j < \partial}{R + jX} = \frac{P_j - JQ_i}{V_j < -\partial}$$

$$V_i V_j < -\partial - V_j{}^2 < 0 = (R + jX)\left(P_j - jQ_j\right) \tag{5}$$

Separating the imaginary part yields

$$V_i V_j \cos\partial - V_j{}^2 = RP_j + XQ_j \tag{6}$$

$$-V_i V_j \sin\partial - V_j{}^2 = RP_j - XQ_j \tag{7}$$

Rearranging (7) for P_j and substituting into equation (6) yields, the voltage quadratic equation at the receiving bus as

$$V_j{}^2 - \left(\frac{R}{X}\sin\partial + \cos\partial\right) V_i V_j + \left(X + \frac{R^2}{X}\right) Q_j \tag{8}$$

Setting the discriminant of the equation (8) to be greater than or equal to zero yields

$$\left[\left(\frac{R}{X}\sin\partial + \cos\partial\right) V_i\right]^2 - 4\left(X + \frac{R^2}{X}\right) Q_i \geq 0 \tag{9}$$

Rearranging (9), we obtain

$$\frac{4Z^2 Q_j X}{(V_i{}^2)(R\sin\partial + X\cos\partial)^2} \leq 1 \tag{10}$$

Since the value of ∂ is normally very minimum, then

$$R\sin\partial = 0 \text{ and } X\cos\partial = X$$

FVSI can be defined by

$$\boldsymbol{FVSI_{ij}} = \frac{4Z^2 Q_j}{V^2 X} \tag{11}$$

Where:
Z = line impedance
X = line reactance
Q_j = reactive power at receiving end
V_i = sending end voltage

The value of FVSI is evaluated which is nearly equal to 1.00 indicates that particular line is closed to its instability point which may leads to voltage collapse in the entire system. This particular line will be the most critical line of the bus and may lead to system wide instability scenario. This index can also be used to determine the weakest bus on the system. The weakest bus in the system corresponds to the bus with the smallest maximum permissible load.

2.2.2 Line Stability Index (L_{mn})

A voltage stability criterion is derived on the basis of power transmission concept in a single line [15]. This index is derived based on a two machine model of the power system connected by a single transmission as shown in Figure 2. In the derivation that followed, the discriminant of the voltage quadratic equation is set to be greater than or equal to zero to achieve stability.

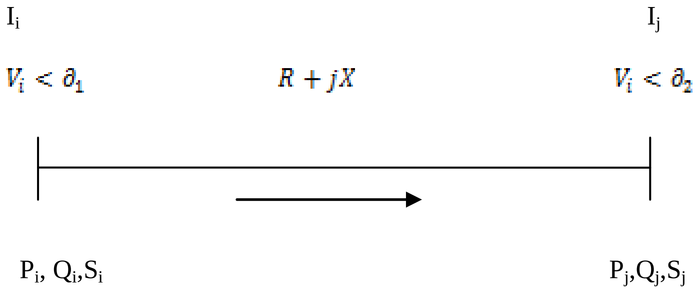

Figure 2 One line diagram of two bus system

The power flow at the receiving and sending end of the system shown in Fig 2 can be expressed as

$$S_j = \frac{|v_i||v_j|}{z} < (\theta - \delta_1 + \delta_2) - \frac{|v_j|^2}{z} < \theta \qquad (12)$$

$$\frac{|v_j|^2}{z} < \theta - \frac{|v_i||v_j|}{z} < (\theta + \delta_1 - \delta_2) \qquad (13)$$

From these power equations one can separate real and reactive power

$$P_j = \frac{|v_i||v_j|}{z} cos(\theta - \delta_1 + \delta_2) - \frac{v_j{}^2}{z} cos\theta \qquad (14)$$

$$Q_j = \frac{|v_i||v_j|}{z} sin(\theta - \delta_1 + \delta_2) - \frac{v_j{}^2}{z} sin\theta \qquad (15)$$

Putting $\delta_1 - \delta_2 = \delta$ in the above equation and solving for V_j

$$V_j = \frac{V_i \sin(\theta - \delta) \pm [(V_i \sin(\theta - \delta))^2 4ZQ_j]^{\frac{1}{2}}}{2sin\theta} \qquad (16)$$

Now for $Zsin\theta = X$, we have

$$V_j = \frac{V_i \sin(\theta - \delta) \pm [(V_i \sin(\theta - \delta))^2 4XQ_j]^{\frac{1}{2}}}{2sin\theta} \qquad (17)$$

To obtain real values of V_j in terms of Q_j, the equation must have real roots. Thus the following conditions, which can be used as a stability criterion, need to be satisfied.

$$V_i \sin(\theta - \delta))^2 4XQ_j \geq 0 \quad \text{or} \qquad (18)$$

$$\frac{4XQ_j}{[V_i \sin(\theta - \delta)]^2} \leq 1 \qquad (19)$$

$$L_{mn} = \frac{4XQ_j}{[V_i \sin(\theta - \delta)]^2} \leq 1 \qquad (20)$$

Where: Z = impedance

X = line reactance

Q_j = reactive power at receiving end

V_i = sending end voltage

θ = line impedance angle
δ = the angle difference between the supply voltage and the receiving voltage.

L_{mn} is termed as the stability index of that line. The stability criterion is used to find the stability index for each line connected between two buses in an interconnected network. As long as the stability index L_{mn} remains less than 1.00, the system is stable and when this index exceeds the value 1.00, the whole system loses its stability and voltage collapse occurs. Based on this line stability index, voltage collapse can be accurately predicted.

2.2.3 Line Stability Index (L_{QP})

A line stability index is derived based on the power transmission concept in a single line. The formulation begins with the current equation in a power system with the help of Figure 1.

The power equation for the system shown in Figure 1 can be derived as

$$\frac{X}{V_i^2}Q_j^2 - Q_j + \left(\frac{X}{V_i^2}P_i^2 + Q_j\right) \qquad (21)$$

The line stability index is obtained by setting the discriminant of the reactive power roots at bus i to be greater than or equal to zero, thus defining the line stability index L_{QP} as

$$L_{QP} = 4\left(\frac{X}{V_i^2}\right)\left(\frac{X}{V_i^2}P_i^2 + Q_j\right) \qquad (22)$$

Where: X = line reactance
Q_j = reactive power at receiving end
V_i = sending end voltage
P_i = sending end real power

Operating at secure and stable conditions requires the value of L_{QP} index to be maintained less than 1.00. An accurate knowledge of how close the actual system's operating point from the voltage stability limit is crucial to operators. Therefore, finding a voltage stability index has become an important task for many voltage stability studies. These indices provide reliable information about proximity of voltage instability in a power system.

3.1 Static Representation of TCSC

TCSC is a capacitive reactance compensator which consists of a series capacitor bank shunted by a Thyristor Controlled Reactor (TCR) in order to provide a continuous variable series capacitive reactance. In principle, all series controllers inject voltage in series with the line. As long as the voltage is in phase quadrature with the line current, the series controllers either supplies or consumes variable reactive power. Figure 3 shows a TCSC in series with a transmission line. Inserting TCSC in a line modifies the equivalent reactance of that line, and the active power flow in that line can be varied.

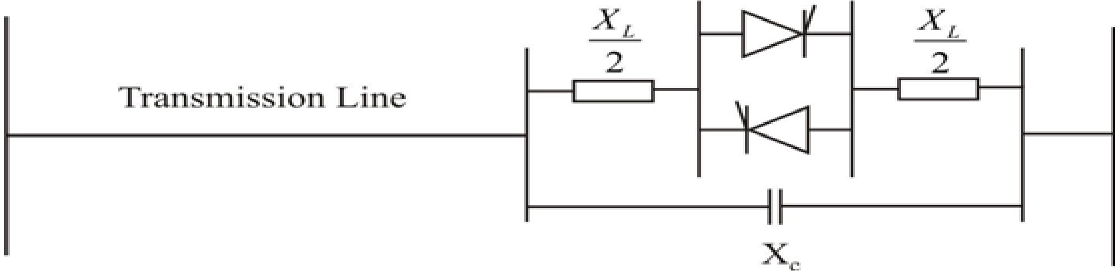

Figure 3 Thyristor controlled series compensator (TCSC)

Based on the principle of TCSC, the effect of TCSC on power system may be simulated by placing a controllable reactance Xc in the concerned transmission line. Figure 4 shows the model of network with TCSC.

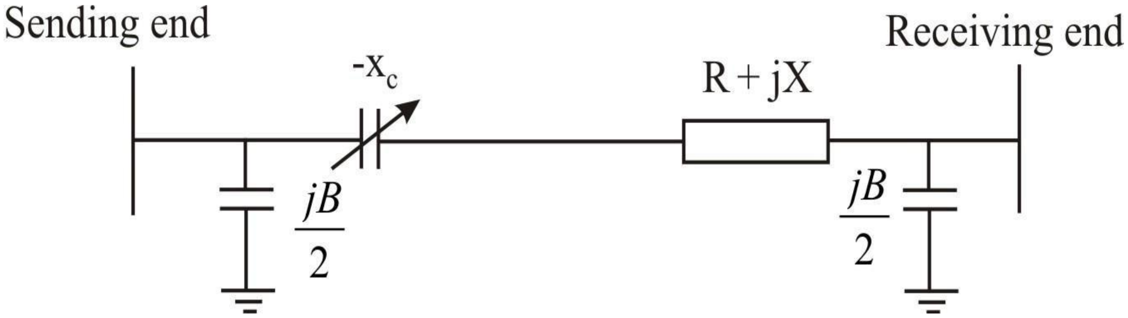

Figure 4 Equivalent circuit of TCSC

The main benefits of TCSCs are increased energy transfer, dampening of power oscillations, dampening of sub synchronous resonances, and control of line power flow. Effective operation of TCSC depends on its location and rating.

3.3.1 Analysis of the TCSC Equivalent Circuit :

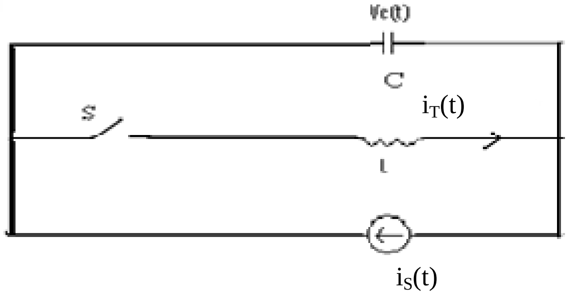

Fig 5 analysis of the TCSC equivalent circuit

The analysis of TCSC operation in the vernier-control mode is performed based on the simplified TCSC circuit as shown in Fig. 5

$i_S(t)$ = Transmission line current which is modeled as an external current source and assumed to be sinusoidal current.
$i_T(t)$ = Thyristor-valve current
u = switching variable
when u =1, thyristor is conducting i.e. switch S is closed
when u = 0, thyristor is blocked i.e switch S is open
C = Fixed capacitor used in parallel with TCR circuit
L = Inductance used in series with Thyristor bidirectional switch
$V_c(t)$ = voltage across the capacitor C
The current through the fixed capacitor C is expressed as

$$C\frac{dv_c}{dt} = i_S(t) - i_T(t)\cdot u \tag{23}$$

The current through thyristor is given by

$$L\frac{di_T}{dt} = v_C \cdot u \tag{24}$$

Let the line current $i_S(t)$ be represented by

$$i_S(t) = I_m \cos wt \tag{25}$$

In equidistant firing-pulse control, for balanced TCSC operation, the thyristors are switched on twice in each cycle of the line current at instants t_1 and t_3 and these are given by

$$t_1 = -\frac{\beta}{w}$$

$t_3 = \dfrac{\pi - \beta}{w}$, where β is the angle of advance (before the forward voltage becomes zero) or,

$$\beta = \pi - \alpha; \qquad 0 < \beta < \beta_{\max}$$

where α is the firing angle of the thyristor. This angle is generated using a reference signal that can be in phase with the capacitor voltage. The thyristor switch S turns off at the instants t_2 and t_4, defined as

$$t_2 = t_1 + \frac{\sigma}{w}$$

$$t_4 = t_3 + \frac{\sigma}{w}$$

where σ is the conduction angle, which is assumed to be the same in both the positive and the negative cycle of conduction. Also,

$$\sigma = 2\beta$$

Solving the TCSC equations (23)-(25) results in the steady state thyristor current i_T, as

$$i_T(t) = \frac{\varpi^2}{\varpi^2 - 2} I_m \left[\cos wt - \frac{\cos\beta}{\cos\varpi\beta}\cos w_r t\right]; \; -\beta \le wt \le \beta \tag{26}$$

where ϖ is the omega and w_r is called resonance frequency and is given by

$$w_r = \frac{1}{\sqrt{LC}} \quad \text{and} \quad \varpi = \frac{w_r}{w} = \left(\frac{X_C}{X_L}\right)^{1/2}$$

where X_C and X_L are capacitive reactance and inductive reactance respectively.The steady state capacitor voltage at the instant $wt = -\beta$ is expressed as

$$v_{C1} = \frac{\mathrm{Im} X_C}{\varpi^2 - 1}\left(\sin\beta - \varpi\cos\beta\tan\varpi\beta\right) \tag{26}$$

At $wt = \beta, i_T = 0$, the capacitor voltage is given by

$$v_C(wt = \beta) = v_{C2} = -v_{C1} \tag{27}$$

Finally the capacitor voltage is given by

$$v_C(t) = \frac{\mathrm{Im} X_C}{\varpi^2 - 1}\left(-\sin wt + \varpi\frac{\cos\beta}{\cos\varpi\beta}\sin w_r t\right); \quad -\beta \le wt \le \beta \tag{28}$$

$$v_C(t) = v_{C2} + \mathrm{Im} X_C(\sin wt - \sin\beta); \qquad \beta < wt < \pi - \beta \tag{2.29}$$

Because the non-sinusoidal capacitor voltage, v_c, has odd symmetry about the axis wt = 0, the fundamental component, V_{CF}, is obtained as

$$V_{CF} = \frac{4}{\pi}\int_0^{\pi/2} v_C(t)\sin wt \, d(wt) \tag{30}$$

The equivalent TCSC reactance is computed as the ratio of V_{CF} to I_m :

$$\begin{aligned} X_{TCSC} &= \frac{V_{CF}}{I_m} = X_C - \frac{X_C^2}{(X_C - X_L)}\frac{2\beta + \sin 2\beta}{\pi} \\ &\quad + \frac{4X_C^2}{(X_C - X_L)}\frac{\cos^2\beta}{(\varpi^2 - 1)}\frac{(\varpi\tan\varpi\beta - \tan\beta)}{\pi} \end{aligned} \tag{31}$$

If we apply $\beta = \pi - \alpha$, in equation (6.16) the reactance of TCSC becomes as :

$$\begin{aligned} X_{TCSC} &= -X_C + C_1\{2(\pi - \alpha) + \sin[2(\pi - \alpha)]\} \\ &\quad - C_2\cos^2(\pi - \alpha)\{\varpi\tan[\varpi(\pi - \alpha)] - \tan(\pi - \alpha)\} \end{aligned} \tag{32}$$

where

$$C_1 = \frac{X_C + X_{LC}}{\pi}, C_2 = \frac{4X_{LC}^2}{X_L\pi}, X_{LC} = \frac{X_C X_L}{X_C - X_L}, \varpi = \left(\frac{X_C}{X_L}\right)^{1/2}$$

From the equation (32) it is clear that the reactance of TCSC is dependent on the firing angle of thyristor and this reactance varies from inductive region to capacitive region between firing angle 90^0 to 180^0 and at around 140^0 there is a condition of resonance.

3.2 Physical model of TCSC :

Compensation means injecting reactive power for improving the power system operation by keeping the bus voltages close to nominal values, reducing line currents and network losses. It also contributes to the voltage stability enhancement. The basic idea behind series capacitive compensation is to reduce the overall effective series reactance of the transmission from the sending end to the receiving end.

The TCSC consists of the series-compensating capacitor shunted by a thyristor-controlled reactor (TCR). The impedance of the reactor X_L is sufficiently smaller than that of the capacitor impedance Xc is taken. By varying the delay angle or firing angle(α) of TCR, the inductive impedance of TCR can be varied. Thus TCSC can provide variable capacitance by means of canceling the effective capacitance by the TCR. Therefore, the steady state impedance of TCSC is simply that of the parallel LC circuit, consisting of fixed capacitive impedance Xc and variable inductive impedance X_L [16]. The power transmission over a transmission line with reactance X is given as

$$P = \frac{v^2}{x}\sin\delta \tag{33}$$

Series compensation is basically used to decrease the reactance of transmission lines carrying power over long distance, as shown by the simple equivalent of Figure 6.

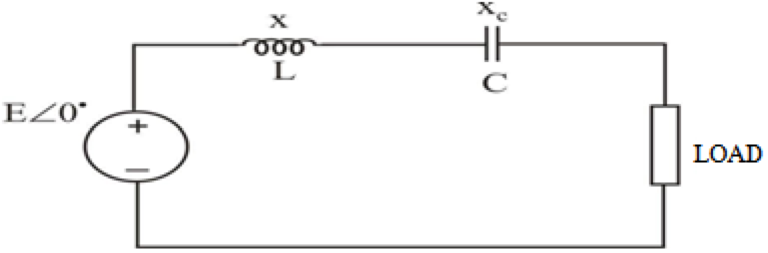

Figure 6 Series compensation

The effective transmission impedance X_{eff} with the series capacitive compensation is given by:
$X_{eff} = X - X_C$
$X_{eff} = (1-k)\,X$
where ‘k’ is the degree of series compensation, i.e.,
$k = X_C/X$; $0 \leq K \leq 1$
Usually, ‘k’ is in the range of 0.3 – 0.8.
Replacing X by X_{eff} in power equation (23), it is clearly seen that the maximum deliverable power is increased, while the voltage under maximum power is left unchanged.

The effective impedance of the TCSC is given by

$$X_T(\alpha)=\frac{X_c X_L(\alpha)}{X_L(\alpha)-Xc} \qquad (34)$$

where $X_L(\alpha)$ is the variable impedance of TCR which can be taken from the impedance of compensator

equation that is;

$$Z_L(\alpha)=\left.1\middle/Y_L\right.(\alpha)=\frac{V}{I_{LF}}=\frac{wL}{\left(1-\frac{2}{\pi}\alpha-\frac{1}{\pi}\sin 2\alpha\right)} \qquad (35)$$

$$X_L(\alpha)=X_L\frac{\pi}{\pi-2\alpha-\sin 2\alpha} \qquad \text{for } X_L \leq X_L(\alpha)\leq\infty \qquad (36)$$

where $X_L=\omega L$ and α is the delay angle measured from the crest of the capacitor voltage or the zero crossing of the line current. The TCSC behaves as a tunable parallel LC-circuit to the line current. As the impedance of the controlled reactor $X_L(\alpha)$ is varied from its maximum (infinity) toward its minimum (ωL) i.e. when α varies from 90^0 to 0^0, then TCSC increases its minimum capacitive impedance $X_{T(\min)}=X_c=\left.1\middle/\omega C\right.$, until parallel resonance occurs at $X_c=X_L(\alpha)$ and $X_T(\alpha)$ approaches to it maximum value $X_{T(max)}$=infinite. If we decrease $X_L(\alpha)$ further, the $X_T(\alpha)$ becomes inductive and approaches to its minimum value of $X_{T(min)}=XcX_L/(X_L-Xc)$ at $\alpha=0^0$. i.e the effect of capacitor is bypassed by TCR. Angle α has two limiting values (1) one for inductive $\alpha_{L(lim)}$ and (2) one for capacitive $\alpha_{C(lim).}$
The TCSC has two operating ranges around its internal circuit resonance :

(1) one is the $\alpha_{C(\lim)}\leq\alpha\leq\left.\pi\middle/2\right.$ range, where $X_T(\alpha)$ is capacitive

(2) the other is the $0\leq\alpha\leq\alpha_{L(\lim)}$ range, where $X_T(\alpha)$ is inductive.

3.2.1 Modes of Operation

The TCSC has three fundamental modes of operation as follows :

(a) Thyristor-blocked mode : In this mode of operation, the current through the TCR is zero and the TCSC function as a capacitive reactance X_c .

(b) Thyristor-bypassed mode: In this mode, the thyristor valves are fired with no delay and the TCSC has small inductive impedance.

(c) Thyristor- phase controlled mode : In this mode the value of the firing angle determines the direction of the current through the TCR and the capacitor, enabling the TCSC to work as either a capacitive or an inductive reactance. In this mode, the thyristor firing mechanism is controlled to vary the amount of effective reactance connected to the system .

3.3 Voltage Stability Analysis

There are certain irregularities or uniqueness in the system behaviour towards the onset of voltage instability. The index based instability measure captures this unique system behaviour in terms of a number and interprets them to give the notion of distance to instability. Two main factors are responsible for the voltage instability, namely, the shortage of reactive power supply and the overload of active power. The former can be caused either by the inability of sources to produce enough reactive power or by the inability of lines to transmit enough reactive power. Later, when the system becomes increasingly stressed and the line losses start to grow rapidly in the vicinity of voltage instability. A power system is composed of many power transmission paths. In the power transmission path analysis, the voltage stability degree of the power system can be represented by the voltage stability of the most vulnerable power transmission path. The process of this analysis can be summarized as the following steps.

1. Run the load flow program for the base case.
2. Evaluate the index value for every line in the system.
3. Gradually increase the loading at a chosen load bus until the load flow solution fails to give results. Calculate index values for every load variation.
4. Extract the line which has the highest index value. This line is called as the most critical line with respect to that bus.
5. Choose the next load bus and repeat the above steps for finding the critical line with respect to that bus.
6. Obtain the voltage at the maximum computable index prior to the divergence of the load flow. This determines the critical voltage of a particular bus.
7. Extract the maximum loading for the maximum computable index for every test bus. The maximum loading is referred to as the maximum load ability of a particular bus.
8. Sort the maximum load ability obtained from the step 7 in an ascending order. The smallest maximum load ability is ranked the highest implying the weakest bus in the system.

The loading pattern is chosen so that each time the load is changed in only one particular bus, keeping the load at other buses fixed at base case. Several combinations of real and reactive load pattern are selected to accomplish the voltage stability analysis.

IV. TEST RESULTS AND DISCUSSION

4.1.1 Stability Analysis without TCSC

The proposed approach has been tested on IEEE 14 systems using Newton Raphson load flow program written in MATLAB 7.5. In this case, by using equation (7), the line stability index is found for each line of IEEE 14 bus system without any disturbance and contingency. From the values of line stability index obtained for IEEE 14 bus system, the first five severe lines are identified in the descending order of line stability index values as mentioned in Table 1. It is observed that the line 2-3 has the highest stability index value when compared to the other lines. Hence, line 2-3 is considered as the most severe line in the system.

Table 1 Line stability index for IEEE 14 bus system without TCSC

Bus		Line stability index
From	**To**	
2	**3**	**0.3190**
7	8	0.1543
4	9	0.1463
5	6	0.1383
1	2	0.1195

4.1.2 Stability Analysis with TCSC

A TCSC with reactance of 0.05 p.u is installed on the lines one by one as mentioned and the results are reported for IEEE 14 bus systems in Table 2

Table 2 Line stability index values of IEEE 14 bus system with TCSC

Bus		Line stability index with TCSC in line				
From	**To**	**2-3**	**7-8**	**4-9**	**5-6**	**1-2**
2	3	0.3123	**0.0536**	0.3192	0.3176	0.3211
7	8	0.1537	**0.1122**	0.1539	0.1566	0.1542
4	9	0.1462	**0.1429**	0.1331	0.1462	0.1463
5	6	0.1372	**0.0805**	0.1387	0.0925	0.1389
1	2	0.1396	**0.0783**	0.1194	0.1209	0.2170
12	13	0.0929	**0.0929**	0.0929	0.0930	0.0929
13	14	0.0797	**0.0796**	0.0797	0.0801	0.0797
9	14	0.0623	**0.0613**	0.0623	0.0623	0.0623
6	13	0.0337	**0.0338**	0.0337	0.0338	0.0337
3	4	0.0330	**0.0292**	0.0326	0.0325	0.0327
2	4	0.0298	**0.0300**	0.0300	0.0299	0.0303
7	9	0.0263	**0.0258**	0.0263	0.0263	0.0263
9	10	0.0207	**0.0204**	0.0208	0.0208	0.0208
6	12	0.0179	**0.0179**	0.0179	0.0179	0.0179
6	11	0.0155	**0.0155**	0.0155	0.0155	0.0155
10	11	0.0151	**0.0149**	0.0151	0.0151	0.0151
1	5	0.0145	**0.0149**	0.0145	0.0145	0.0141
2	5	0.0118	**0.0118**	0.0118	0.0118	0.0120
4	5	0.0029	**0.0029**	0.0029	0.0029	0.0029
4	7	0.0000	**0.0000**	0.0000	0.0000	0.0000

For IEEE 14 bus system with TCSC in line 7-8, it is found that more number of lines have the least value of stability index, when compared with TCSC in other lines. Hence, the line 7-8 is the most optimal placement for inserting TCSC.

V. CONCLUSION

In this paper, a simple, fast acting power electronic controller which can provide current and power flow control in the transmission line by varying its firing angle is well discussed. This is a computationally feasible approach to monitor the power system voltage stability. This proposed method does not involve complex and sophisticated matrix computation. The voltage stability analysis process is carried out using line stability index which is also capable of determining the critical line.

The optimal placement of Thyristor-Controlled Series Capacitor TCSC to improve the system voltage stability is identified easily. By placing the TCSC in the optimal location, the stability of system is found improved. Thus TCSC can be used as a series capacitor to reduce the overall transmission line reactance. Depending on the enhancement of power transfer desired at that time, without affecting other system-performance criteria, series compensation can be varied by TCSC. Thus TCSC is one of the important FACTS controller, which increases the overall power transfer capacity in the transmission line. Moreover, this approach is also capable of identifying the most stressed line in power system networks which acquaints the power system operators to decide the remedial actions in case of contingencies.

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