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Performance Assessment of Thyristor Controlled Series Compensator Considering Various Circuit Parameters Using Voltage and Current Steady-State Equations on Simulink

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Abstract:. There has been a substantial increase in the demand of power in recent years. This has developed different challenges for **Abstract:** There has been a substantial increase in the demand of power in recent years. The increasing demand has caused different challenges for power engineers to increase the system's power transfer capability. Flexible AC Transmission System (FACTS) has very important part to play in such situation. It increases power capacity without expanding the installed system, which has very low initial cost as compared to installing a new power network. FACTS technology uses already installed system which undergoes minimum losses. Earlier FACTS devices were based on the Self-Commuted and Thyristor semiconductor devices which included Insulated Gate Bipolar Transistors and Integrated Gate Controlled Thyristor. With the passage of time different types of FACTs devices have been developed. TCSC (Thyristor Controlled Series Compensator) is a type of FACTS devices like. This is advanced version of TCR (Thyristor Controlled Reactor) that is enormously used in series with the long transmission lines. Lot of work has been accomplished in the field of FACTS, specially TCSC. But still there is sufficient gap to assess its performance considering stability of the system. In this paper the performance of TCSC has been analyzed by performing simulation on MATLAB/Simulink by considering impedance, firing advance angle, current and voltage equations, and power transfer of system. An overall increase in the power transfer capacity of system has been , if system is connected with TCSC. The comparison between Thyristor based Model and Phasor Model has also been done. It has been verified through simulations that Phasor Model is less accurate and neglects all transients.

Keywords: FACTS, TCSC, Power Transfer Capability Simulink, Thyristor Phasor Model

I. INTRODUCTION

The concept of FACTS (Flexible AC Transmission Systems) was first proposed by Mr Hingorani in (1988), in his paper, "Power Electronics in Electric Utilities: Role of Power Electronics in Future Power Systems". The basic idea was to achieve high level of control flexibility as it is achieved in HVDC (High Voltage Direct current).

There are widespread failures which can affect the modern power system. Complexity of large power system is also increasing. Similarly, the demand of power is increasing with the passage of time. To tackle these problems in addition to many other like voltage instability, VAR Compensation, Transient and Dynamic instability and active and reactive power control etc FACTS is proposed (Hingorani, 1988). FACTs are power electronic component based devices which enhance controllability and power transfer capability. It can make future electric transmission systems smart.

FACTS is defined by IEEE Working Group as "Alternating current transmission systems incorporating power electronic-based and other static controllers to enhance controllability and increase power transfer capability" (Hingorani, 1999). There been drastic increase in the speed of Power electronics and other static controllers. They perform great number of operations like transistor which are used in wide variety of processors. On the other hand, GTO and IGBT are power devices which lead to variety of controllers (Kimbark, 1971).

(Fig. 1) shows three different types of FACTS controllers. Part (a) represents the series controller which basically injects voltage into the transmission line with the help of series connection. The part (b) is shunt controller that injects current in parallel to the transmission line. While part (c) injects both quantities by using both types of connections.

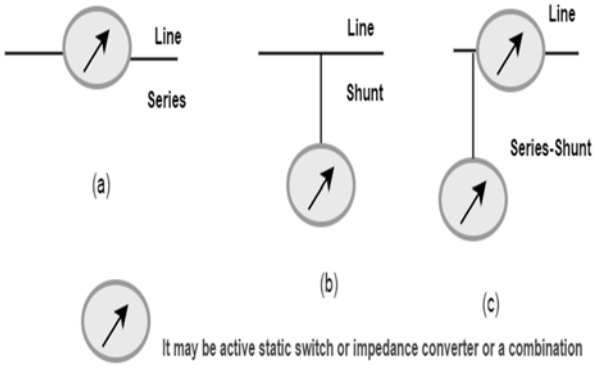


Fig.1 Series Controller, Shunt Controller, Series-Shunt Controller

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a. Thyristor Controlled Series Compensator

Power transfer between two areas can be changed by varying the overall series impedance of the system. One of the methods to increase power is to install a capacitor in series which minimizes the overall impedance, which will definitely allow more power to be transferred. The method has the limitation of slow switching times. But thyristor controlled devices on the other hand are capable to timely manage the line compensation over a continuous range in a smooth way. **(Fig. 2)** shows the Thyristor Controlled Series Compensator which uses Thyristor Controlled Reactor (TCR) in parallel with the capacitor segments. The capacitive reactance can be smoothly controlled by simply combining TCR and Series Capacitor.

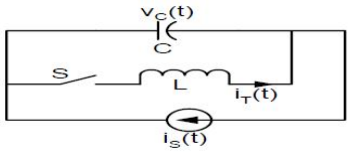


Fig: 2 A variable Inductor connected in shunt with a fixed capacitor

The steady state current of thyristor, i_T can be given by;

$$i_T(t) = \frac{k^2}{k^2-2} I_m \left(\cos\omega t - \frac{\cos\beta}{\cos k\beta} \cos\omega_r t \right); -\beta \le \omega t \le \beta \quad (1)$$

Where $k = \frac{\omega_r}{\omega} = \sqrt{\frac{X_c}{X_p}}$ (2)

In eq (1) and eq(2), I_m is the maximum current. ω is the rotor speed. k is the compensation ration. β is the angle of advance. X_c is the nominal capacitance. X_p is inductive reactance inductor which is in parallel connection with fixed capacitor.

Similarly the capacitor voltage is determined as,

$$v_c(t) = \frac{X_c I_m}{k^2-1} \left(-\sin\omega t + \frac{\cos\beta}{\cos k\beta} \sin\omega_r t \right); -\beta \le \omega t \le \beta \quad (3)$$

Here fundamental component is represented by V_{CF}. This can be obtained as:

$$V_{CF} = \frac{4}{\pi} \int_0^{\frac{\pi}{2}} v_c(t) \sin(\omega t) d(\omega t) \quad (4)$$

So, the equivalent TCSC reactance is given by;

$$X_{TCSC} = \frac{V_{CF}}{I_m} = X_C \frac{X_c^2}{X_C - X_p} \frac{2\beta + \sin(2\beta)}{\pi} + \frac{4X_c^2}{(X_C - X_p)} \frac{\cos^2\beta}{(k^2-1)} \frac{k\tan(k\beta) - \tan(\beta)}{\pi} \quad (5)$$

Here X_C is the nominal reactance of the fixed capacitor. V_{CF} is the fundamental component of the voltage of capacitor. X_p is the inductive reactance of inductor connected in parallel with fixed capacitor and β is the angle of advance.

b. Operating Regions of TCSC

TCSC Module has got series capacitor shunted with Thyristor Controlled Reactor. Here the controlling variable is impedance of the transmission line; instantaneous value of impedance is used to change the conduction level of thyristor (Mahajan, 2006). Firing angle is used to vary the conduction of thyristor which changes the impedance. It can be said that varying impedance is basically the function of firing angle. The operating regions of TCSC can be Capacitive, Inductive and Resonance as shown in **(Fig. 3).**

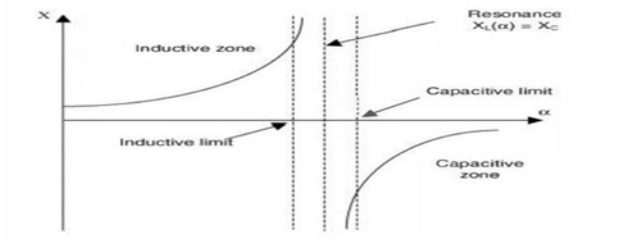


Fig. 3 Schematic Diagram of TCSC

The amount of power can be varied by selecting the appropriate operating region of TCSC. For example if the power is decreased from sending bus to receiving bus then inductive region would be used. While with this scenario the length of transmission line would be increased. This mode is rarely used (Mahajan, 2006) . If the length of transmission line is to be decreased or in other words, the magnitude of power transfer is to be increased then TCSC should be used in capacitive region. Whereas resonance region is not preferred due to stability issue.

2. LITERATURE REVIEW

TCSC is employed in realistic power systems as a high-performance and cost-effective series FACTS for smooth and secured optimal power flow (OPF) control in transmission lines (Meikandasivam, 2013) (Duong, 2013). They focus on split TCSC and its benefits. However the mathematical assessment of TCSC with the help of Current and Voltage Equations is lacking. The series compensation is one of the most economic ways to increase the capacity of transmission lines to carry more active power, this is easily implemented by TCSC (Mathur, 2002) (Zhang, 2006). These papers give good insight about the implementation however stability of system while using TCSC is not considered. The TCSC controller can be implemented to minimize efficiently the sub-synchronous resonance (SSR) (Mathur, 2002). In addition to this, a complementary power swing damping (PSD) controller can be added to TCSC to increase the rotor angle stability of multi-machine power system (Meikandasivam, 2008).The design of TCSC-based PSD controller and power system stabilizer (PSS) is performed abundantly in

recent years to improve the small-signal stability of power systems (Eslami, 2012) (Morsali, 2013) (Morsali, 2014) (Ali, 2012). However none of the above papers assess the performance of TCSC considering Voltage and Current equations and a comparison between Thyristor-based model and Phasor based model.

While in (Mahajan, 2006), the author has explained the TCSC in great detail. But this paper is more focused on the modes of TCSC and how these modes can be used. Whereas the stability of system is not discussed. Considering that gap, in this paper, the performance of TCSC is analyzed. Transmission system is simulated with and without TCSC. System Power Transfer Capability is also analyzed. System achieves more amount of power transfer capability, decrement in impedance when connected with TCSC. The simulation results suggest the use of TCSC to achieve steady state stability in addition to increasing power transfer.
A practical example has been discussed to create the analogy with simple LC circuit, to better understand the concept of TCSC. This paper, as supplementary discusses the performance and stability which is achieved by using this compensator.

3. RESEARCH METHODOLOGY

The research has been mainly divided into two parts; mathematical analysis and Matlab Simulations TCSC connected power system.

In the first part, current and voltage equations of TCSC are mathematically discussed when it is in steady-state condition. The equivalent circuit of TCSC is considered while performing mathematical operations. In the second part, the power system is simulated on Simulink, two models of TCSC are simulated; Detailed model and Phasor Model.

TCSC Module steady state voltage and current equations can be determined from the assessment of parallel circuit of inductor and capacitor having variable inductance. If it is assumed that current loop is trapped in the reactor-capacitor circuit, the external circuit can be represented by a sinusoidal current source. In these situations, the equivalent electric circuit of TCSC module connected in a power system can be schematically represented by **(Fig. 4).**

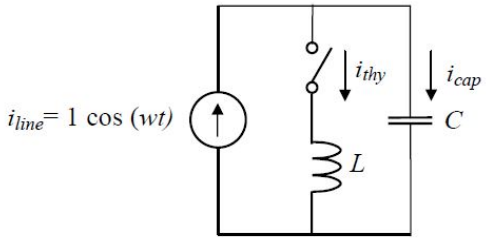


Fig.4 Equivalent Electric Circuit of TCSC Module

In Fig. 4, Kirchhoff's current law to the circuit is applied. The resultant equation is then represented in Laplace domain.

$$\cos\sigma_a \frac{s}{s^2+w^2} + \sin\sigma_a \frac{w}{s^2+w^2} = I_{thy}(s) + I_{cap}(s) \quad (6)$$

The voltage across the TCSC inductive and capacitive reactance becomes equivalent to each other. The expression in Laplace domain can be written as,

$$s\,L\,I_{thy}(s) = \frac{I_{cap}(s)}{s\,C} + \frac{V^{+}_{cap}}{s} \quad (7)$$

In the above equation, V^{+}_{cap} is the voltage across the capacitor when thyristor is at "On Condition". A mathematical expression for the current flowing in thyristor, in time domain, can be obtained by substituting $I_{cap}(s)$ from equation 7 into equation 6. Solving for I_{thy} gives,

$$\begin{aligned} i_{thy} &= A\cos(wt) + \\ &\left(-A\cos(\sigma_a)\cos(k\sigma_a) - B\sin(\sigma_a)\sin(k\sigma_a) + DV^{+}_{cap}\sin(k\sigma_a)\right) \\ V^{+}_{cap} &= \frac{B}{D}\sin(\sigma_a) - \frac{A}{D}\cos(\sigma_a)\tan(k\sigma_a) \\ &\left(A\cos(\sigma_a)\sin(k\sigma_a) - B\sin(\sigma_a)\cos(k\sigma_a) + DV^{+}_{cap}\cos(k\sigma_a)\right)\sin(w_0 t) \end{aligned} \quad (8)$$

Where σ_a is known as firing advance angle of thyristor. The relationship between σ_a and α is given as under [14, 15] DSC capacitor voltage, V^{+}_{cap}, is at such a level that the coefficient of the sinusoidal term, $\sin(w_o t)$, is equal to zero. In this instant of time the capacitor's voltage is [9],

$$V^{+}_{cap} = \frac{B}{D}\sin(\sigma_a) - \frac{A}{D}\cos(\sigma_a)\tan(k\sigma_a) \quad (9)$$

4. SIMULATIONS AND RESULTS

The simulations have been performed on Simulink (Matlab). Two separate models of TCSC have been simulated, TCSC detailed model and TCSC (Phasor). In this simulation, 500kV long transmission line is used along with TCSC. The prime focus of using TCSC apart from impedance minimization is to improve the power transfer. During the first period of 0.5 seconds of simulation, TCSC is disconnected from the system, while the power for this interval remains at 110MW. The TCSC contains a fixed capacitor and a parallel Thyristor Controlled Reactor in each phase. Nominal compensation is achieved by using only capacitors with firing angle of 90 degree, which is 75%. Natural oscillatory frequency of TCSC is 163Hz, which is 2.7 times the fundamental frequency.

There are two modes of TCSC, in which it can be operated; Capacitive Mode and Inductive Mode. However, Capacitive is mostly used. In simulation, the firing angle is restricted from 49 degree to 69 degree, as the resonance of TCSC is nearly 58 degree. The resonance of overall system when it contains line impedance is around 67 degree. On 69-90 degree, capacitive mode is achieved. TCSC has got minimum impedance at 90 degree **(Fig. 5).**

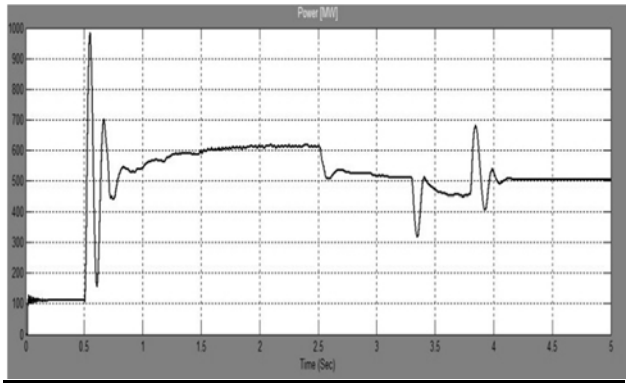


Fig. 5 Power in Mega Watt against Time

For this interval from start up and up to 0.5 sec, the power level is around 110MW. As soon as simulation reaches 0.5 sec, the system starts regulating impedance to 128 ohms **(Fig.6)** as a result this increases power transfer level to 610MW (Steady-State). The result also depicts that there are very low switching disturbances as the system starts with 90 degree as in **(Fig. 7).**

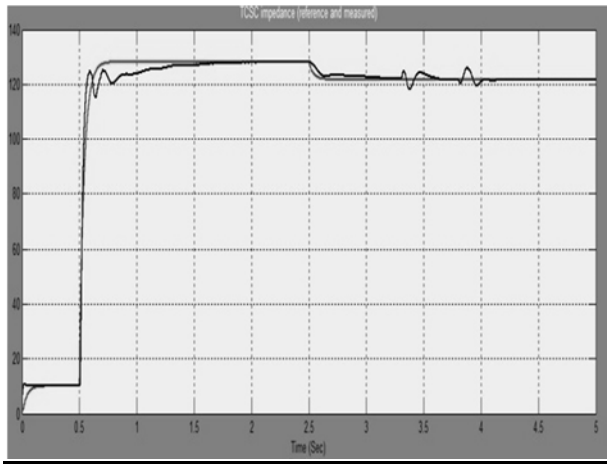


Fig. 6 TCSC Impedance (reference & Measured)

In Fig. 6, TCSC Impedance is shown with respect to change in time. System is simulated for total time of 5s. Signal in red color shows the reference impedance while black shows the actual measured impedance of TCSC. System starts regulating impedance as it reaches to 0.5 sec. Impedance of around 128 ohms is achieved which takes power level approximately 490MW-830MW. A total of 5% variation in reference impedance is applied when the system reaches at 2.5s. The simulation depicts that TCSC uses tracking of the reference impedance when it is near 500ms. However when it is at 3.3s, 4% decrement in the source voltage is incorporated. After which it comes back to 1p.u.

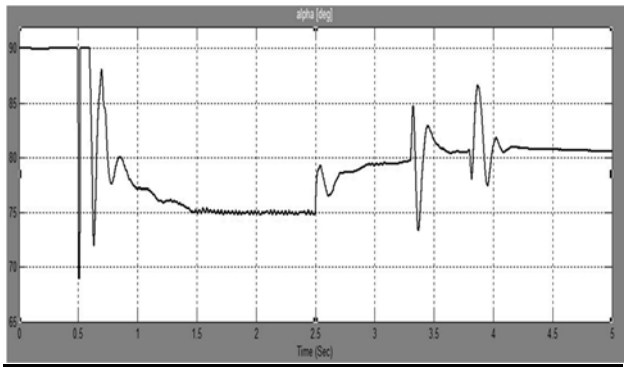


Fig.7 TCSC Firing Angle against Time

In Fig. 7, the system starts with firing angle of 90 degree for the time of 0.5 sec. As soon as the TCSC is connected with the system, the firing angle is decreased by an enormous value and becomes steady after 1.5 seconds with firing angle of 75 degree. There are some reasonable variations, however they are the range of 65-80 deg, which are acceptable as for as power transfer is to be increased.

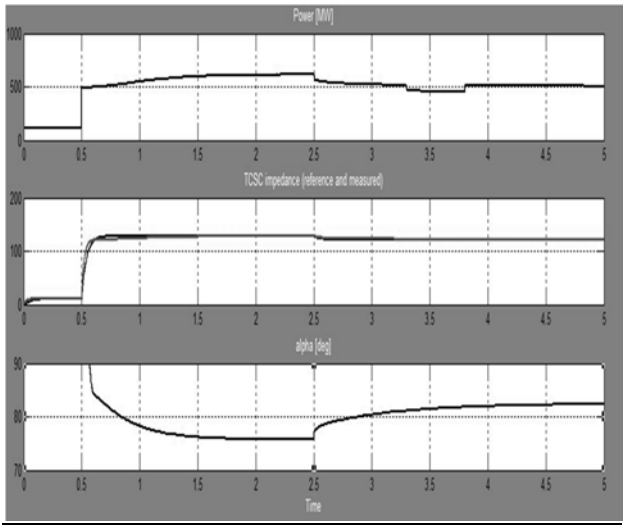


Fig. 8 TCSC (Power, Impedance & alpha) using Phasor Model.

In **(Fig. 8),** the TCSC Phase Model has been used. This uses impedances which are equal at the mean frequency. It neglects all transients, due to this; it is not as accurate as TCSC thyristor-based tests system. But Even though its importance cannot be lessened as it is

quite simple and requires less time for simulation. A variation of 5% in the reference impedance is used when the simulation reaches 2.5s.

The results indicate that system incorporates following the impedance when the settling time is near 500ms. Voltage source decreases by 4% as soon as simulation reaches 3.5s. After this it returns to 1 p.u at around 3.8s. It is observed that the errors are overcome by TCSC and the TCSC impedance remains unchanged. The TCSC response time is around 200ms-300ms. The transient response is inaccurate when phasor model is used. Therefore there is need to use thyristor based model in order to study these transients.

5. CONCLUSION

In this paper, thyristor Controlled Series Compensator is mathematically discussed. Voltage and Current Equations are also proved when circuit is in steady-state condition. Two important models of TCSC (detailed model and phasor model) are simulated. Three important variables are analyzed with the help of simulations on Simulink are assessed keeping the performance of the system in account. Power transfer capability, impedance and firing angle are main variables which play a very important role in the performance of TCSC. The effects of changing these parameters are noticed from system responses.
It is clearly observed that there is increase of 500 MW in power transfer capacity as soon as, it is connected with TCSC.

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