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Simulation and performance evaluation of TCSC for load voltage regulation

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Abstract: Thyristor Controlled Series Compensator is a FACTS device which is majorly used to control the overloading and under loading conditions automatically. As the line current leads capacitive voltage, TCSC works in capacitive region and as the line current lags the capacitive voltage, TCSC works in inductive region. In this paper, Thyristor Controlled Series Compensator (TCSC) is connected in series with the transmission line to enhance the voltage regulation at receiving end when load is increased by emulating capacitive reactance. The mathematical modelling of TCSC is simulated using MATLAB Simulink. The theoretical background of TCSC is studied and implemented.

Keywords: TCSC, FACTS, voltage regulation, capacitive reactance.

I. INTRODUCTION

Flexible AC Transmission System (FACTS) devices play an important role in improving the performance of a power system. Dr. Narain G. Hingorani is considered the father of FACTS. FACTS controllers use thyristor switching devices to provide greater control, speed and flexibility of ac transmission systems. [6] TCSC helps in reducing system losses and improving stability of the network. The main aim of using TCSC is to enhance the power flow, maintain good system stability in power system and can also be used to maintain the receiving end voltage. [3]

World's first TCSC was installed in Kayenta substation between Glen Canyon and Shiprock, Arizona, USA in 1990's. This installation improved the power transfer capability from 300MW to 400MW[2]. TCSC s plays a major role in controlling overloading and under loading conditions. An inductive reactance is added when the load is lightly loaded and when the load is heavily loaded, TCSC offers capacitive reactance in series with line. This enhances capability to transfer power and improves the voltage regulation.

In this paper, a theoretical method to control the reactance of TCSC in order to enhance the voltage regulation is presented. Theoretical background under inductive and capacitive mode is analysed and is verified with simulation using MATLAB Simulink. Since, the objective is to enhance the voltage regulation when the load varies, TCSC controller is considered to maintain the voltage constant.

II. BASIC THEORETICAL BACKGROUND

Thyristor Controlled Series Compensator (TCSC) is variable impedance type FACTS device consisting of a series capacitor in parallel with an inductor which is in series with two anti-parallel thyristors. In other words TCSC is a combination of a capacitor and a TCR (Thyristor Controlled Reactor). An inductive part of TCSC is formed by an inductor connected in series with a back to back thyristor. The thyristors start to operate when a gate pulse is applied to thyristors of same polarity. Once the gate pulses are applied, it maintains its conduction mode until the current passing through the thyristor becomes zero.

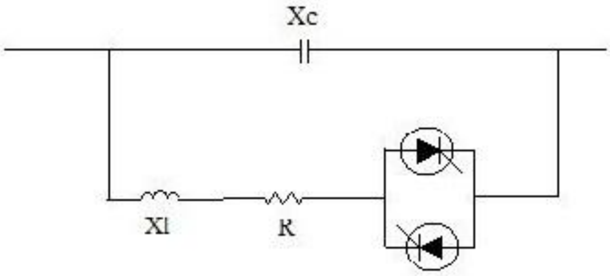

Figure 1 Basic circuit of TCSC

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Controlling the current through the inductor by varying the firing angle of the gate pulse applied to the thyristor is the main objective in TCSC. This hence changes the nature of the waveform and the average value of the current passing through series capacitor. The resulting voltage across the device also changes. Therefore the voltage and current of TCSC is controlled with respect to the change in firing angle α.

The current through the reactor is said to be maximum when the thyristors are in full conduction mode and the current in the reactor is zero when thyristors are in blocking mode. Figure 2 shows the equivalent circuit of TCSC and its capacitive and inductive mode of operation.

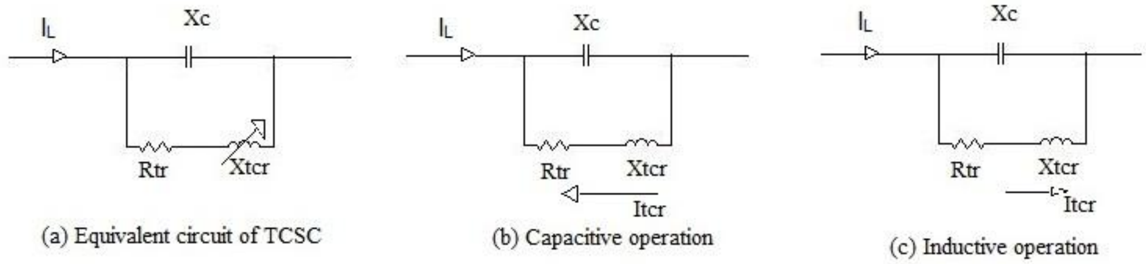

Figure 2 Operation of TCSC

Impedance of TCSC is given as

$$Z_{TCSC} = \frac{-jX_C \cdot jX_{TCR}}{j(X_{TCR} - X_C)} = \frac{-jX_C}{\left(1-\frac{X_C}{X_{TCR}}\right)} \quad \ldots\ldots(1)$$

The current flowing through the TCR can be given as

$$\hat{I}_{TCR} = \frac{-jX_C}{j(X_{TCR} - X_C)}\hat{I}_L = \frac{\hat{I}_L}{\left(1-\frac{X_{TCR}}{X_C}\right)} \quad \ldots\ldots(2)$$

The TCSC impedance is said to be purely reactive as the losses are neglected. The capacitive reactance of TCSC is obtained from Z_{TCSC} equation as

$$X_{TCSC} = \frac{X_C}{\left(1-\frac{X_C}{X_{TCSC}}\right)} \quad \ldots\ldots(3)$$

X_{TCSC} is capacitive when $X_C<X_{TCR}$. $X_{TCR}=\infty$ when the thyristors are blocked and $I_{TCR}=0$. When $X_C<X_{TCR}$, $\hat{I}_{TCR}$ is 180˚ out of phase with the line current phase, $\hat{I}_L$ i.e. , $\hat{I}_L$ is in phase with -$\hat{I}_{TCR}$.
X_{TCSC} is inductive when $X_C > X_{TCR}$ i.e., the reactance of TCSC is negative. In inductive region, , $\hat{I}_L$ and $\hat{I}_{TCR}$ are in phase. The capacitive and inductive operation of TCSC is shown in fig 2(b) and 2(c) respectively.

Keeping β=90˚-α;
where β=angle of advance; α=delay angle;
The ratio of (X_{TCSC} / X_C) is derived as

$$\frac{X_{TCSC}}{X_C} = 1 + \frac{2}{\pi}\frac{\lambda^2}{(\lambda^2-1)}\left[\frac{2\cos^2\beta}{(\lambda^2-1)}(\lambda\tan\lambda\beta - \tan\beta) - \beta - \frac{\sin 2\beta}{2}\right] \quad \ldots\ldots(4)$$

III. MODES OF OPERATION

In normal operating conditions, there are 3 modes of operation: Each mode is as shown in fig 3(a), 3(b), 3(c) respectively.

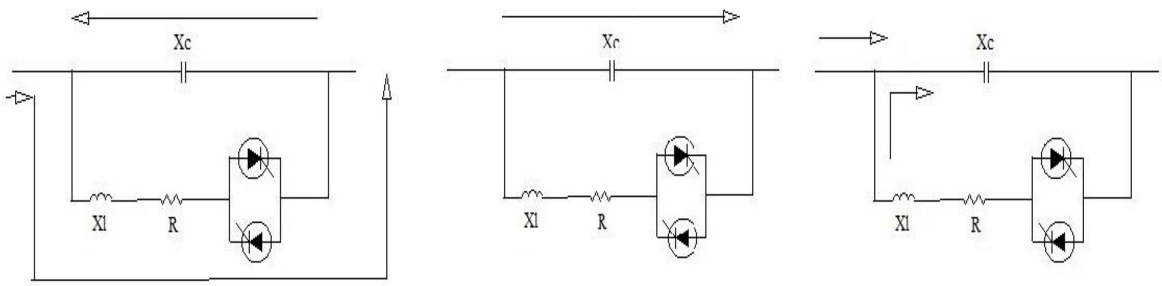

Fig 3(a)Bypassed Vernier control Fig 3(b) Inserted with Thyristor Fig 3(c) Inserted with valve blocked

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A. Bypassed mode

Bypassed mode is also known as TSR mode. This mode is used to protect capacitor against overvoltage. In this mode, the thyristor valve is gated for 180° conduction. The current flow in reactor is continuous and sinusoidal. Large amount of line current flows through reactor and thyristor valve and a small amount of current flows through capacitor. The net reactance in this mode is slightly inductive.

B. Inserted with Thyristor Valve Blocked mode

In this mode as the gate pulse is blocked, no current flows through the thyristor valve. Since no current flows through the thyristor, the value of TCSC is same as that of fixed capacitor. This mode is also known as waiting mode and this mode is usually avoided.

C. Inserted with Vernier Control mode

In this mode, the thyristor are made to conduct for part of the cycle by gating the thyristor valves in the region ($\alpha_{min} < \alpha < 90^{\circ}$). As the conduction angle increases from zero, the effective value of TCSC in capacitive region also increases. Value of α_{min} is chosen such that it is above the value of α corresponding to parallel resonance of capacitor and TCR at fundamental frequency.

IV. STUDY SYSTEM

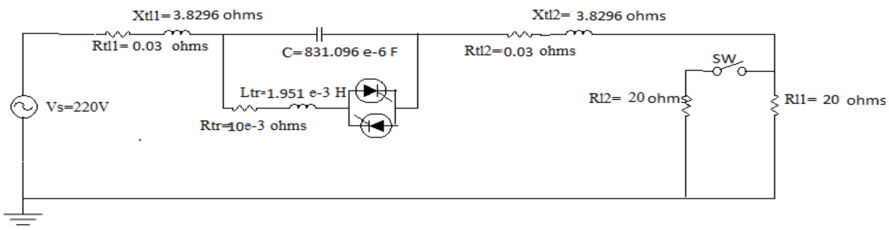

Figure 4 Circuit of TCSC in transmission line

Fig 4 represents the studied system, in which TCSC is connected in series to the transmission line.

While selecting the parameters for capacitor and inductor in TCSC, reactance of an inductor (X_L) should be less than the reactance of capacitor (X_C). λ should be less than 3.

$$\lambda = \frac{\omega_r}{\omega} = \sqrt{\frac{X_C}{X_L}} \quad \text{......(5)}$$

Hence keeping $\lambda = 2.5$,
we get [5]
$X_L = 0.6128\Omega$
$X_C = 3.83\Omega$

Differential equation for Fig 4 is obtained as

$$\frac{di_s}{dt} = \frac{\omega_b}{X_{TL}}[V_m - V_C - (R_{TL} + R_L)i_s] \quad \text{......(6)}$$

$$\frac{dV_C}{dt} = \frac{[i_s - i_{TR}]}{C} \quad \text{......(7)}$$

$$\frac{di_{TR}}{dt} = \frac{\omega_b(V_c - R_{TR}.i_s)}{X_{TL}} \quad \text{......(8)}$$

System Data:

R_{TL} =0.06Ω	X_{TL}=7.659Ω	L_{TL}=24.38mH
C=831.096μ F	X_C =3.83Ω	L_{TR}=1.951mH
X_{TR}=0.6128Ω	R_{TR} =10e-3Ω	R_{L1}=20Ω and R_{L2} =20Ω

When overloading occurs, the receiving end voltage decreases. If the receiving end voltage is below the set value, TCSC is made to operate in capacitive region and the voltage is regulated. By varying the firing angle in capacitive region, the voltage at the receiving end can be kept constant.

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V. SIMULATION RESULTS

In TCSC, the line current and the voltage across capacitor are in quadrature. If the line voltage leads the capacitor voltage, TCSC is working in capacitive mode and when the capacitive voltage leads the line current, inductive operation takes place. The waveforms for capacitive and inductive region are shown in Fig 5 and 6 respectively.

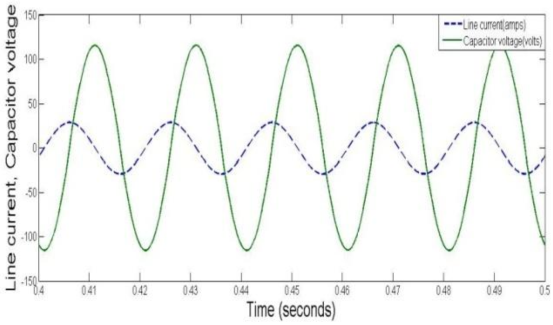

Figure 5 Capacitve mode of operation

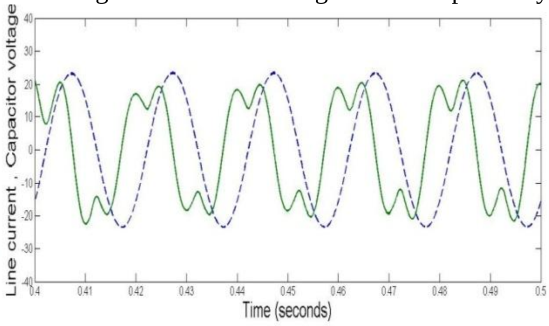

Figure 6 Inductive mode of operation

A. Simulink model

A PLL is used to generate a saw tooth for every half cycle of sinusoidal wave. The output of this is summed with the firing angle and a pulse is generated every time the saw tooth wave and the firing angle coincide. SR flipflop is used as a switch. When saw tooth and firing angle coincides, a pulse is generated which is given to S and the pulses obtained from zero crossing of inductor current is given to R. Q output is used to obtain thyristor current and Q! Output is used to obtain voltage across the switch. Differential equations are obtained using matlab simulink and is shown in Fig 8. An AC input voltage of 220V is applied. The circuit is made to work for a load of 20Ω and an output voltage of 205V is obtained. As the load is increased, the receiving end voltage starts to decrease. The receiving end voltage is regulated by operating the TCSC in capacitive mode and by varying the firing angle 2.

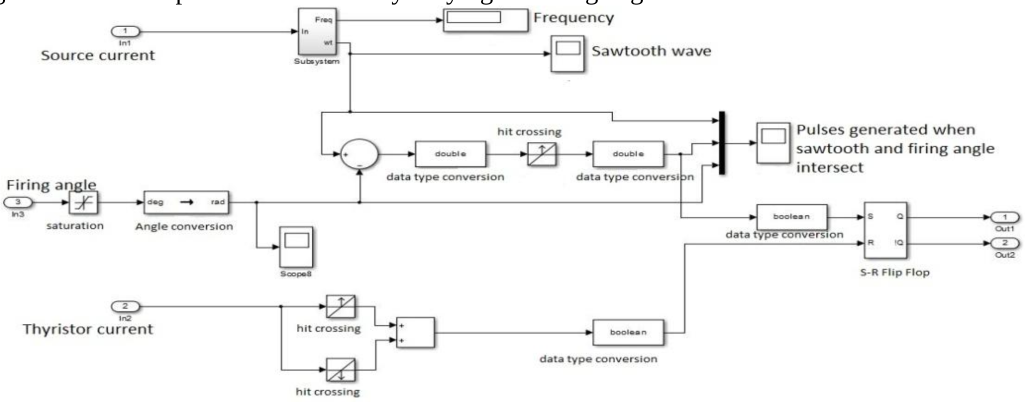

Figure 7 Generation of firing instants

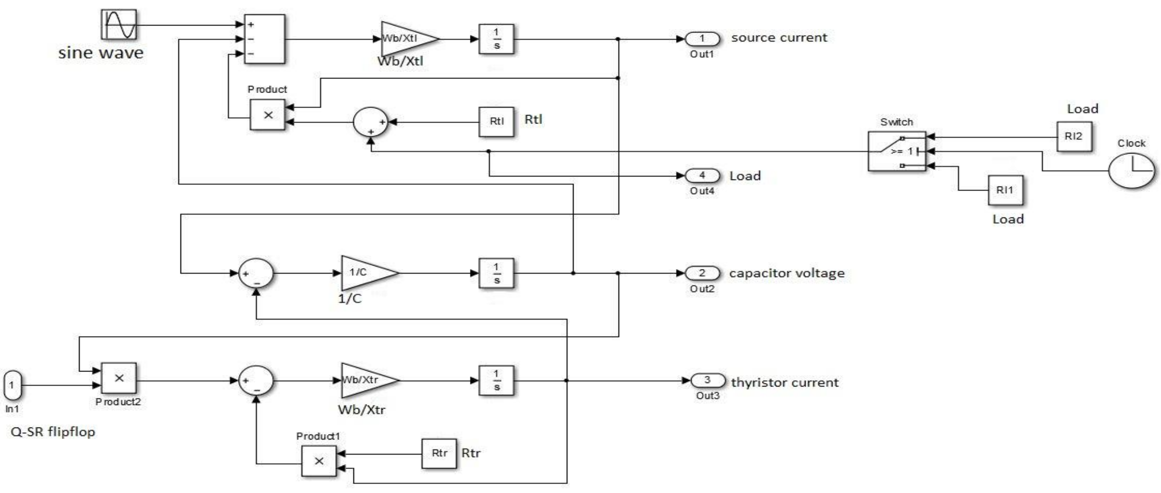

Figure 8 Simulation model of TCSC

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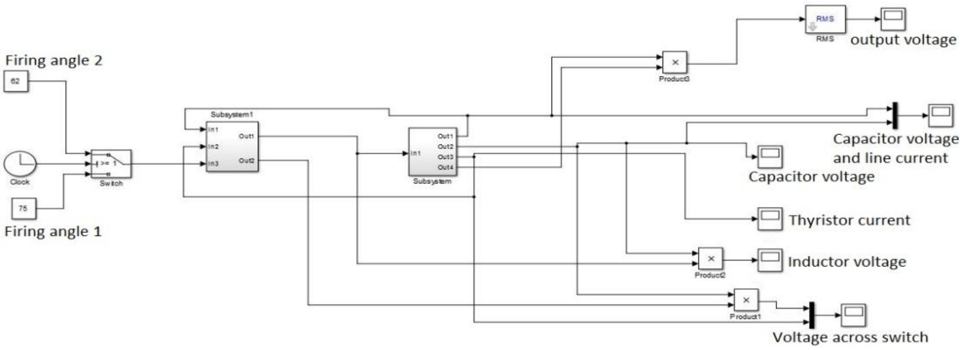

Figure 9 Simulink modeling of TCSC connected in transmission line

B. Reactance characteristics of TCSC

The graph of X_{TCSC} / X_C v/s β is obtained. The effective reactance of TCSC operates in 3 regions: inductive region, resonance region and capacitive region. When the firing angle α is in the range, $0 \leq \beta \leq \beta_{Clim}$, the TCSC operates in capacitive mode and as value of β reaches β_{Clim}, due to the increase in capacitive reactance, the effective reactance of TCSC increases. Similarly when β is operating in the range between, $\beta_{Lmin} \leq \beta \leq \pi/2$, the TCSC operates in Inductive region and the effective reactance of TCSC decreases as the advance angle decreases from π/2. The region between, $\beta_{Clim} \leq \beta \leq \beta_{Llim}$ is strictly avoided since there is a high probability of resonance between this region. In this region, $X_C = X_L(\alpha)$ and hence parallel resonance takes place. There will be a large circulating current between the inductor and capacitor due to the energy of oscillation. Since the impedance is maximum in this region, the circuit current is limited. The graph is as shown in Fig. 10

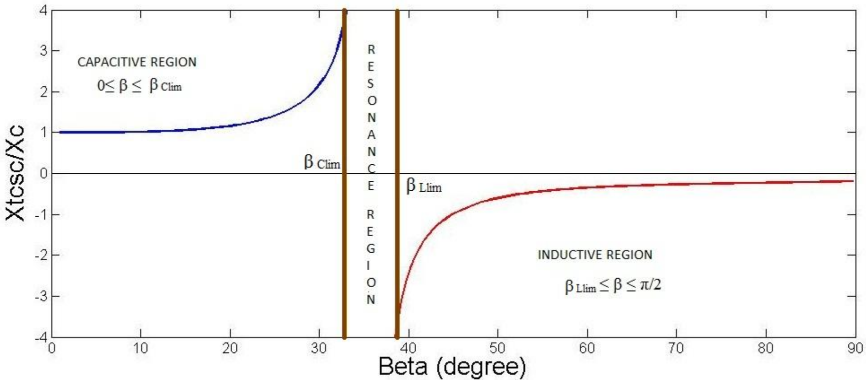

Figure 10 Variation of (X_{TCSC} / X_C)

From equation 4, β is directly proportional to X_{TCSC}/X_C. It is also evident from the above graph that as β increases, the ratio of X_{TCSC}/X_C also increases. As overloading occurs the voltage drops in receiving end voltage. By varying the firing angle, ratio of X_{TCSC}/X_C can be increased which in turn increases the receiving end voltage.

VI. RESULT

It is observed that the receiving end voltage drops as the load increases. By varying β in the range $0<\beta<\beta_{lim}$, the capacitive reactance of TCSC increases which in turn increases the effective total TCSC reactance. The increase in TCSC reactance enhances the load voltage regulation.

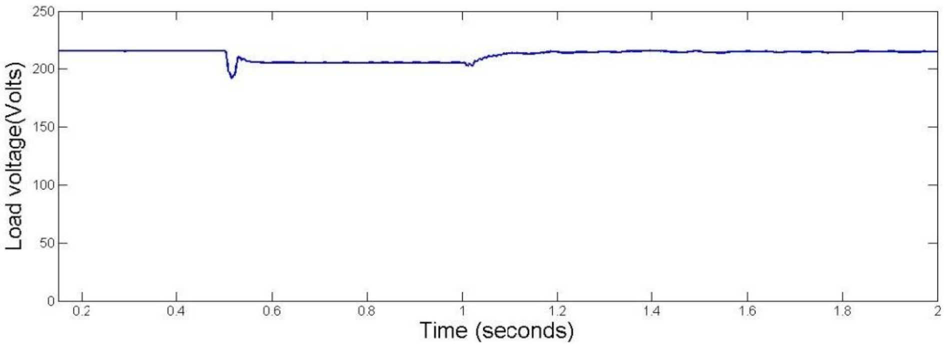

Figure 11 Variation of load voltage

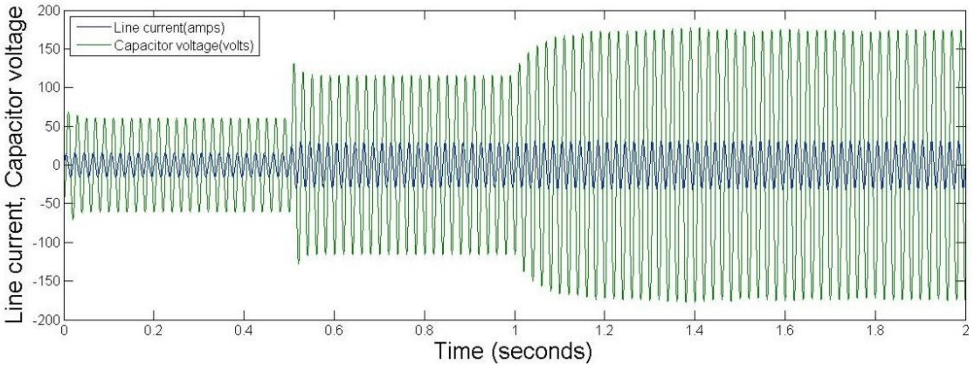

Figure 12 Line current and Capacitor voltage variation

VII. CONCLUSION

This paper presents the performance evaluation of TCSC to enhance the load voltage regulation. The results demonstrate the effectiveness of the proposed approach to keep the receiving end voltage constant under varying load condition.

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