Journal Of Engineering And Development, Vol. 15, No.4, Des 2011 ISSN 1813- 7822

Design and Simulation of Control Circuit for TCSC Based MATLAB Simulink

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Abstract:

Thyristor Control Series Compensator (TCSC) can be considered as one of the solutions for increasing power demand nowadays. This paper presents design of control system that is able to change the impedance of the TCSC by controlling thyristors firing angle (α) of three stages TCSC using constant power control strategy for thyristor control series compensators to increase the capability of reactive power compensation of the transmission line. Matlab Simulink implemented to evaluate the performance of the proposed control circuit for the duration of peak load and half load of the transmission line where the simulation shows a good results where two third of the total amount of reactive power is compensated and transmission line capacity is extended.

Key-words: Static VAR compensator, Reactive power compensator, FACTS, TCSC.

الخلاصة:

تعتبر طريقة السيطرة على معوض القدرة الخيالية المتوالي باستخدام الثنائي المسيطر عليه (thyristor) أحدى طرق حل مشاكل تزايد الطلب على الطاقة في الوقت الحالي. البحث الحالي يقدّم تصميم دائرة سيطرة للتحكم بزاوية قدح الثنائي (α) لمعوض قدرة مكون من ثلاث مراحل وذلك لغرض التحكم بممانعة معوض القدرة الخيالية وباستخدام تقنية السيطرة بالطاقة الثابتة على المعوضات المتوالية لزيادة قابلية تعويض القدرة المتفاعلة لخط النقل. استخدمت طريقة المحاكاة باستخدام برنامج (Matlab) لتقدير أداء دائرة السيطرة المقترحة لحالتين من حالات خط النقل وهي أقصى الحمل ونصف الحمل وقد أعطت المحاكاة نتائج جيدة حيث تمّ تعويض ثلثي القدرة المتفاعلة والمنقولة إلى الحمل مما أدى إلى زيادة القدرة الكلية لسعة خط النقل.

1. Introduction:

Today's power systems are highly complicated, sometimes made of thousands of buses and hundreds of generators. New power generations are primarily determined based on environmental and economic reasons, and are somewhat inexpensive and relatively easy to build and operate, especially nowadays with the availability of cheap natural gas and high performance gas turbines. On the other hand, new transmission systems are expensive and take considerable amount of time to build. Hence, in order to meet increasing power demands, utilities must rely on power export, important arrangements through existing transmission systems. While the power flow in some of these transmission lines is well below their thermal limits, certain lines are overloaded, which has the effect of deteriorating voltage profiles and decreasing system stability. This requires the review of traditional transmission methods and practices, and the creation of new concepts to allow for the use of existing transmission systems without reduction in system security [1].

Flexible AC Transmission Systems (FACTS) is a new approach to a more efficient use of existing power system resources based on the utilization of high-current high-voltage power electronic controllers [2]. FACT device is used to enhance its power transfer capability by compensating the reactive power in the transmission lines. During last decade, reactive power control was depend on mechanically controlled shunt switches controlling a capacitor and reactors which are slow in response for load variation. In recent years, development of high power semiconductors with a combination of digital electronics are being widely used for fast and efficient reactive power compensation control using thyristor controlled static VAR. First adaptation of shunt compensators of AC transmission was implemented by thyristors controlling reactor and capacitor through a transformer. Nowadays series compensation is used for long transmission lines to compensate the reactive power by altering or changing the characteristic impedance of the line. All types of static power compensators offering increasing transferred power in long lines, improving stability, damping of low frequency oscillations and control of dynamic over voltages [3,4].

2. Basic Operation of TCSC:

Figure (1) shows the circuit diagram of single phase TCSC. The system is composed of a fixed capacitor in parallel with a Thyristor Control Reactor (TCR). The switching element of the TCR consist of two anti- parallel thyristors, which alternate their switching at the supply frequency .The system is controlled by varying the firing angle of the thyristor firing pulses relative to the zero crossing of some reference waveform .The effect of such variation can be interpreted as avariation in the value of the capacitive,

inductive reactance at the fundamental frequency. In our analysis, the thyristors will be ideal, so that nonlinearities due to the thyristor turn on and turn off are neglected. Also, the line current i_s is essentially assumed sinusoidal, and take it to be the reference waveform for the synchronization of the firing pulses. A slight modification for analysis is needed if the synchronization is instead done with the capacitor voltage v_C.

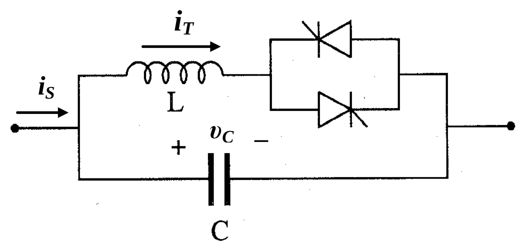


Figure (1): TCSC Circuit Diagram

The waveforms of the TCSC are shown in figure (2), with denoting the current waveform of the TCSC branch. The thyristor is turned on after a delay α relative to zero crossing of the line current i_S, and keeps conducting unit τ, where the inductor current i_T becomes zero. In steady-state, the conduction angle ($\sigma = \tau - \alpha$) becomes symmetrical with respect to the peak value of the line current, and the angle ϕ between the negative peak of the inductor current (which occurs at the zero-crossing of the capacitor voltage) and the positive peak of the line current goes to zero [5,6,7] .

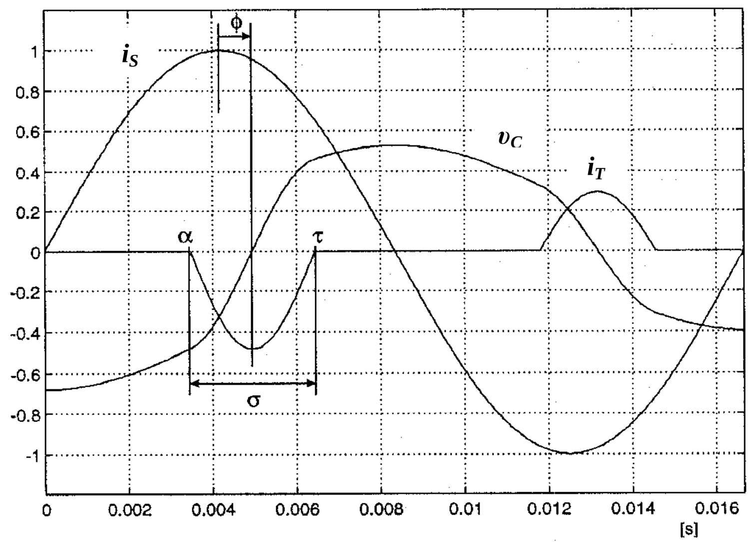


Figure (2): TCSC Waveforms

3. Circuit Analysis of TCSC:

TCSC behaves at fundamental system frequency like continuously variable reactive impedance, controllable by thyristor firing angle α and the parallel *LC* circuit determines the steady-state impedance of the TCSC. The *LC* circuit consists of a fixed series capacitor and variable inductive impedance as shown in figure (3). The following assumes that the line current $i_s(t)$ in figure (3) will be [8,9,10]:

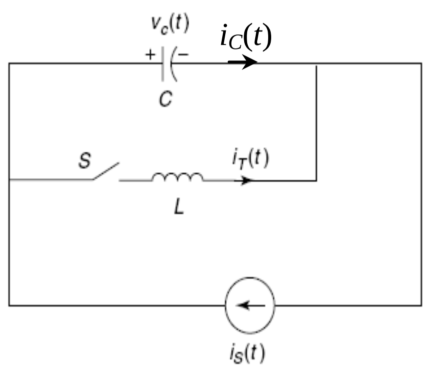


Figure (3): Variable Impedance of TCSC

$$i_S(t) = \cos(\omega t) \qquad \text{p.u.} \tag{1}$$

, and the voltage drop across the conducting thyristor valve is zero .The angle σ is define as $\sigma = \pi - \alpha$. All calculations assume steady state [6,8].

For $-\sigma \leq \omega t \leq \sigma$, the thyristor valve conducts

$$i_S(t) = i_T(t) + i_C(t)$$

$$\cos(\omega t) = i_T(t) + C\frac{\partial \upsilon_C(t)}{\partial t} = i_T(t) + LC\frac{\partial^2 i_T(t)}{\partial t^2}$$

By using Laplace transform to find TCSC impedunce, the above equation will be:

$$\frac{s}{s^2+\omega^2} = I_T(s) + LC(s^2 I_T(s) - s i_T(0^+) - i_T{}'(0^+)) \tag{2}$$

Using $\omega_o = 1/\sqrt{LC}$ in Eq. (2) and solving for I_T (s):

$$I_T(s) = \frac{s}{s^2+\omega^2}\cdot\frac{\omega_o{}^2}{s^2+\omega_o{}^2} + \frac{s}{s^2+\omega_o{}^2} i_T(0^+) + \frac{1}{s^2+\omega_o{}^2} i_T{}'(0^+))$$

, and by taking the Laplace inverse for the above equation:

$$i_T(t) = \frac{\omega_o{}^2}{\omega_o{}^2+\omega^2}\cdot\cos\omega t - \frac{\omega_o{}^2}{\omega_o{}^2+\omega^2}\cdot\cos\omega_o t + i_T(0^+)\cos\omega_o t + \frac{\sin\omega_o t}{\omega_o} i_T{}'(0^+)) \tag{3}$$

Supposing that: $\rho = \omega_o/\omega$ and $A = \omega_o^2/(\omega_o^2 - \omega^2) = \rho^2/(\rho^2-1)$, Eq. (3) will be:

$$i_T(t) = A\cdot\cos\omega t - A\cdot\cos\omega_o t + i_T(0^+)\cos\rho\omega t + \frac{\sin\rho\omega t}{\omega_o} i_T{}'(0^+)) \tag{4}$$

In the steady state, the inductor current i_T is equal to zero for $\omega t = -\sigma$ and $\omega t = \sigma$. Substituting for $t = -\omega/\sigma$ and $t = \omega/\sigma$ in Eq. (4) to get:

$$i_T(0^+) = A\frac{\cos\rho\sigma - \cos\sigma}{\cos\rho\sigma}, \qquad i_T{}'(0^+) = 0 \tag{5}$$

Subsituting for $i_T(0^+)$ and $i_T{}'(0^+)$ in Eq. (4), the inductor current will be:

$$i_T(\omega t) = A\left(\cos\omega t - \frac{\cos\sigma}{\cos\rho\sigma}\cos\rho\omega t\right) \tag{6}$$

The voltage across the capacitor is:

$$\upsilon_c(t) = L\frac{\partial i_T(t)}{\partial t} = -AX_L \sin\omega t + \frac{A\rho X_L \cos\sigma}{\cos\rho\sigma}\sin\rho\omega t \tag{7}$$

For $\sigma \le \omega t \le \pi - \sigma$, the thyristor valves does not conduct. Therefore :

$i_s(t) = C\frac{\partial \upsilon_c(t)}{\partial t}$, so: $\cos(\omega t + \sigma) = C\frac{\partial \upsilon_c(t)}{\partial t}$ and by using the Laplace transform:

$$V_C(s) = \frac{1}{sC}\frac{s\cos\sigma - \omega\sin\sigma}{\omega^2 + s^2} + \frac{1}{s}\upsilon_C(\sigma^+) \tag{8}$$

By substituting for $\upsilon_C(\sigma^+)$ and considering the angle shift, the inverse Laplace transformation yields :

$$\upsilon_C(t) = X_C(\sin\omega t - \sin\sigma) - AX_L(\sin\sigma - \rho\cos\sigma\cdot\tan\rho\sigma) \tag{9}$$

Similar calculations are done for $\pi\text{-}\sigma \le \omega t \le \pi\text{+}\sigma$ to yielding the overall analytic expressions for:

$$i_T(\omega t) = \begin{Bmatrix} A\left(\cos\omega t - \dfrac{\cos\sigma}{\cos\rho\sigma}\cos\rho\omega t\right) & for\ -\sigma \le \omega t \le \sigma \\ 0 & for\ -\sigma \le \omega t \le \pi - \sigma \\ A\left(\cos\omega t - \dfrac{\cos\sigma}{\cos\rho\sigma}\cos\rho(\omega t - \pi)\right) & for\ \pi - \sigma \le \omega t \le \pi + \sigma \end{Bmatrix} \tag{10}$$

and

$$\upsilon_C(\omega t) = \begin{Bmatrix} -AX_L\sin\omega t + \dfrac{A\rho X_L\cos\sigma}{\cos\rho\sigma}\sin\rho\omega t & for\ -\sigma \le \omega t \le \sigma \\ X_C(\sin\omega t - \sin\sigma) - AX_L(\sin\sigma - \rho\cos\sigma\tan\rho\sigma) & for\ -\sigma \le \omega t \le \pi - \sigma \\ -AX_L\sin\omega t - \dfrac{A\rho X_L\cos\sigma}{\cos\rho\sigma}\sin\rho(\omega t - \pi) & for\ \pi - \sigma \le \omega t \le \pi + \sigma \end{Bmatrix} \tag{11}$$

Fourier analysis of Eq. (11) yields the fundamental component of the capacitor voltage. Since the line current i_T is sinusoidal, it is easy to derive the TCSC fundamental impedance X_{TCSC} [5,7,8].

$$X_{TCSC} = X_C - (X_C + X_{LC})\frac{2\sigma + \sin 2\sigma}{\pi} + \frac{4X_{LC}^2\cos^2\sigma}{X_L}\left(\frac{\sigma\tan\rho\sigma - \tan\sigma}{\pi}\right) \tag{12}$$

, where $X_{LC}=(X_C\ X_L) / (X_C - X_L)$.

X_L from Eq. (12) is ωL and the delay angle α is measured from the crest of the capacitor voltage or the zero crossing of the line current. As the impedance of the controllable reactor is varied from its maximum (infinity) to its minimum (ωL), the minimum capacitive compensation is increased by $X_{TCSCmin} = X_C = 1/\omega C$. Thus, the degree of series capacitive compensation is increased. When $X_C = X_L(\alpha)$, the impedance of the TCSC becomes infinite. The TCSC has two operating ranges; one is when $\alpha_{Clim} \le \alpha \le \pi/2$, where the TCSC is in capacitive mode. The other range of operation is $0 \le \alpha \le \alpha_{Llim}$, where the TCSC is in inductive mode as shown in figure (4) [8,9,11].

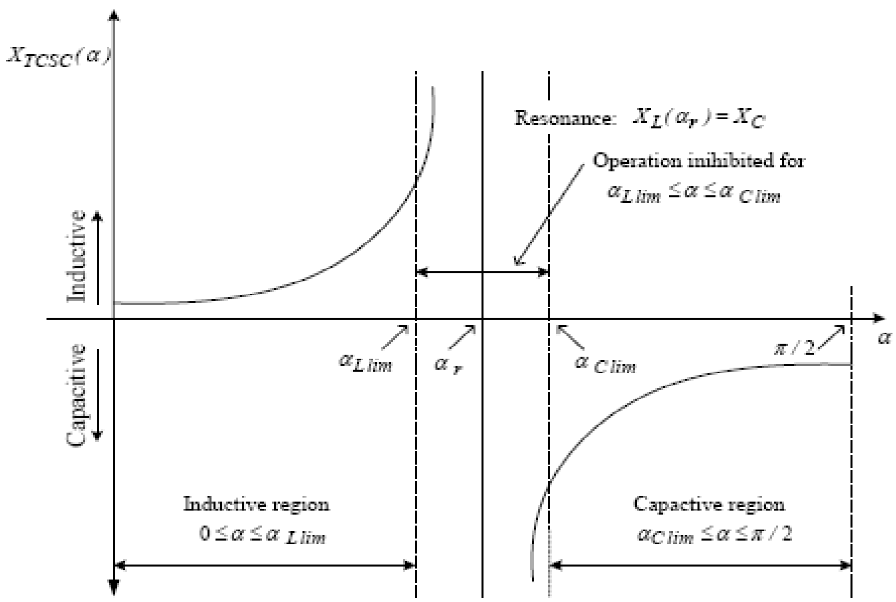


Figure (4): Changing of X_{TCSC} by Changing the Firing Angle α

In the impedance compensation mode the TCSC maintains the maximum rated compensating reactance at any line current up to its rated maximum. For this mode the TCSC thyristor controlled reactor and capacitor are chosen so that at the α_{Clim}, the maximum capacitive reactance can be maintained at and below the maximum line current rating. The two types of voltage compensation modes are capacitive and inductive. In the capacitive voltage compensation mode, the minimum delay angle α_{Clim} sets the limit for the maximum compensating voltage up and until the line current reaches such a value that the voltage across the capacitor is a maximum. The maximum voltage across the capacitor constrains the operation of the TCSC until the maximum line current is reached. For the inductive voltage compensation mode, the maximum delay angle α_{Llim} limits the voltage at low line currents and the maximum rated thyristor current at high line currents [12].

4. Power Transfer Capability of Transmission Line:

The power transfer between two ends of uncompensated transmission line is given by [8].

$$P = \frac{V_S \cdot V_R}{X_L} \sin \delta \qquad (13)$$

, where V_S and V_R are sending end and receiving end voltages, respectively, X_L is transmission line reactance (losses is neglected) and δ is power angle. The compensating effect results from the voltage drop across the series impedance of TCSC caused by line current as shown in figure (1). The power transfer through transmission line with series compensated by using TCSC is [8]:

$$P = \frac{V_S . V_R}{X_L + X_{TCSC}(\alpha)} \sin \delta \qquad (14)$$

5. Control Strategies:

There are two types of control (either closed-loop or open-loop) can be used to control over TCSC. Open-loop control is used to generate an output according to a predefined transfer function and no response measuring is required, while closed-loop control is implies the classical feedback system as in figure (5). For the proposed study, the second type is employed and both of load current and voltage are traced as a feedback, where the ratio of compensator current to the voltage error determines the slope of voltage/current characteristic. The system stability and response are determined by total loop gain and time constants.

Conventionally, reactive power compensator controllers are based on one of the following modes; Constant Current (CC) Mode, Constant Angle (CA) Mode and Constant Power Mode (CP) [13].

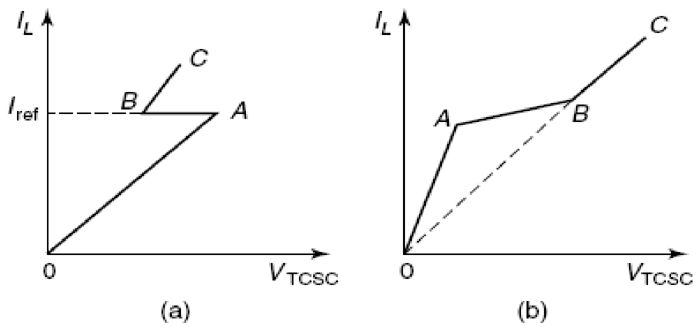


Figure (5): TCSC Control Characteristics
(a) Constant Current Mode (b) Constant Angle Mode

Steady-state control characteristic of CC mode is divided into three regions OA, AB and BC. Regions OA and BC are represent the minimum and the maximum TCSC reactance limits while region AB represent the control range in which TCSC reactance is varied through firing angle α to maintain a constant specified line current.

CP Mode is a combination of employing inner current closed loop and voltage control loop; CP mode is offering an effective method for damping oscillation that may occur during rapid load changing [7,13].

6. Proposed Control System:

The proposed firing control circuit shown in figure (6) is employing a constant power mode strategy that depending on measuring load side power factor and consumed power. This circuit is designed to ensure fast compensation response which is an important factor to enhance the dynamic response of the system. In the previous literatures [7,14], the minimum time response obtained is (4 up to 35) Sec which is extremely long period to achieve compensation.

Thyristors firing angle in any controlled rectifier based on generating gate signal in a certain time during source voltage period. For this work, control circuit will synchronize the firing angle by sensing the source voltage and compromise it as a phase reference using zero-crossing detector, while the tuning of the firing angle degree α is depending on three factors consumed load power, power factor and control circuit response slop “control circuit characteristic “which can be adjusted by the gains (K_1) and (K_2).

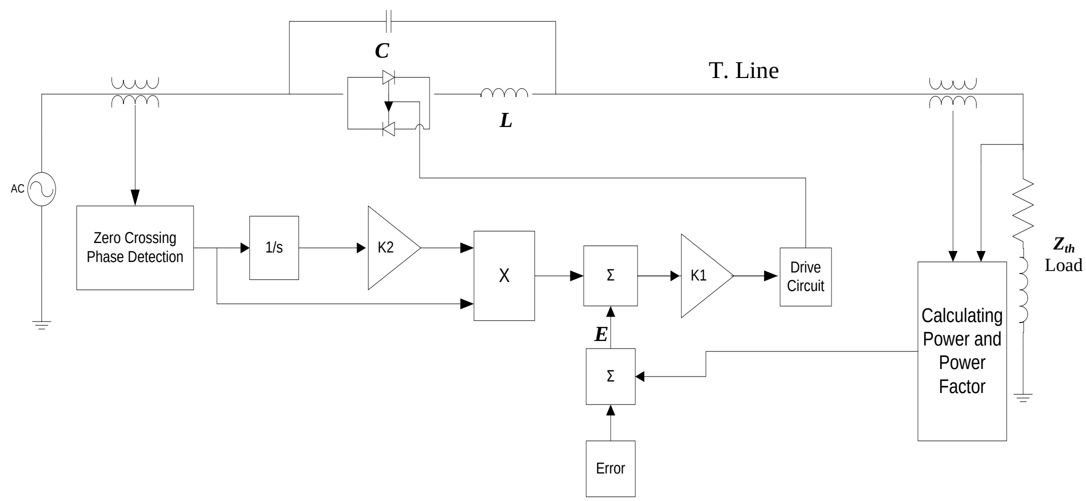


Figure (6): Control Circuit

The output of the control circuit can be found by:

$$Vo = K_1\left(\left[\frac{\frac{1}{s}}{\frac{-1}{s}}\right]\frac{K_2}{s}\times\left[\frac{\frac{1}{s}}{\frac{-1}{s}}\right]+E\right)\cdot Vi \tag{15}$$

, where Vo: is the output of the control circuit
Vi: input reference signal (as a time step input)
E: summation of error and power calculation
K_1: overall gain
K_2: integrator gain.

The output voltage of the control circuit is depending on input voltage as a time step signal and the calculation of consumed power and power factor can be represented by (E). In each practical control circuit (hardware unit), there is an adjustable error weight added to each measuring part used to reduce measuring error. In the proposed control circuit there is one error weight added to the summation of the measuring results rather than two (one for each measuring part). Usually this weight is equal to zero in simulation while practically, it has value.
The feedback (power and power factor) is based on measuring both of voltage and current as magnitude and phase angle then multiplying the magnitude by sine or cosine of the phase angle to find real and reactive power as in figure (7).

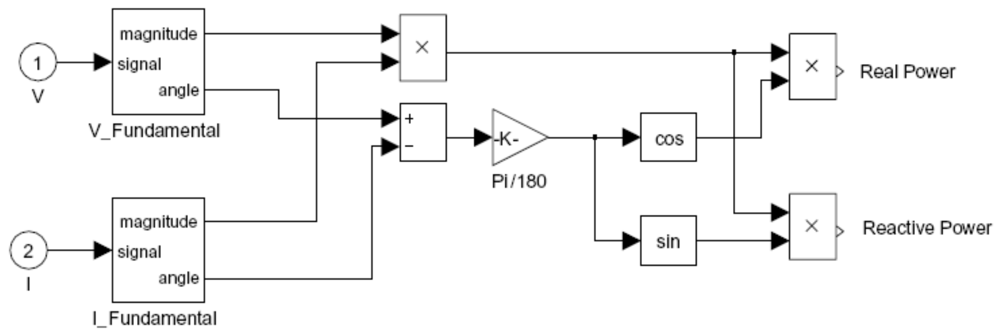


Figure (7): Measuring of Real and Reactive Power

The gain represented by (pi /180) is used to convert the degree angle to radian while the load voltage angle is taken as a reference to measure the load current angle. By measuring real and reactive power by the circuit shown in figure 7, the power factor can be easily determined from both of active and reactive load consumed power.

According to the calculated previous values, the control circuit will estimate the required compensating power and transform it to generate thyristors firing angle

7. Simulation Results:

To assess the effectiveness of the proposed control circuit, two different load conditions of 400kV, 50Hz transmission line system is simulated and the following results are obtained.

(A) Figures from (8-a) to (8-f) are showing the results for the 1st case of 250MW, 140MVAR load. Figure (8-d) shows that the received reactive power at load side of the transmission line is about 140x10^{6} VAR while the transmitted reactive power along the transmission line is only 43X10^{6} VAR as in figure (8-b) and approximately other two third amounts has been compensated from the TCSC. Despite the fact that using TCSC will increase the total power loss of the line due to the effective series resistance in the capacitor and inductor, as in figure (8-a) and figure (8-c) where the real transmitted power is 255X10^{6} Watt while the received is 250X10^{6} Watt. Figure (8-e) shows the thyristors get signal with the reference source voltage. Figure (8-f) shows the voltage across the reactor during system starting.

(B) Figures from (9-a) to (9-f) are showing the results for the 2nd case of 145MW, 120MVAR load. Figure (9-d) shows the received reactive power at load side of transmission line about 120X10^{6} VAR while the reactive transmitted power along the transmission line is 40X10^{6} VAR only as in figure (9-b) and other two third has been compensated from the TCSC. The real transmitted power for this case is $150X10^6$ Watt while the received is $145X10^6$ Watt due to same mentioned above reason as shown in figure (9-a) and figure (9-c). Figure (9-e) shows the thyristors get signal with the reference source voltage and figure (9-f) shows the voltage across the reactor during system starting.

It can be seen from figures (8) and (9) that the time required for the control circuit to start compensation and to arrive to steady state is about (0.6 Sec) which is very short time if it compared with other previous works that required (4 to 35) Sec. This will ensure improving to the dynamic performance of the system as shown in both simulated cases.

Figures (8-f) and (9-f) shows the changing of the firing angle α during the transient time to reduce the capacitive characteristic of the series connected capacitor during system starting. This angle is synchronized to source voltage and firing the thyristor as soon as the reference waveform cross the zero as shown in figures (8-e) and (9-e).

8. Conclusions:

As seen from both simulated cases, there is same rate of total reactive power is compensated which is two of the third of load required VAR. This insures the successes of employing constant power mode strategy, as well as the ability of the control circuit to estimate the load required reactive power by determining a certain firing angle during the reference voltage period to fire the thyristors.

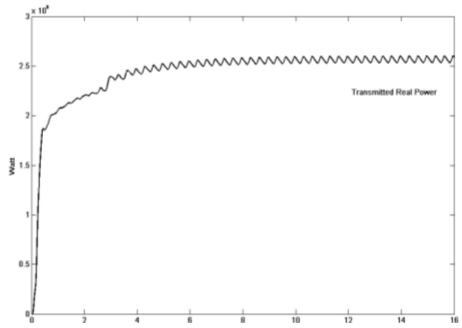
During both simulated cases, the load parameters have changed which leads to system transient response changing. The control circuit is kept same ratio of performance during load changing by changing the TCSC impedance.

Although the TCSC will increase the total power losses of the transmission line but the gaining of increasing the transmission line capacity is much higher.

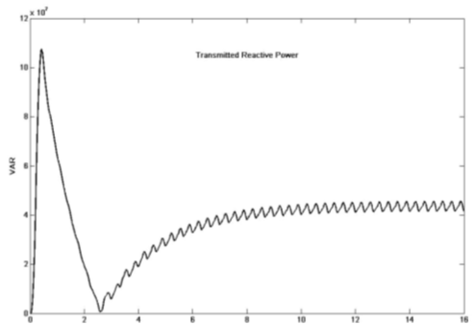
The designed control circuit offers a very high dynamic response which will increase the stability of the transmission line during fast load changing as well as keeping accurate value of compensation due to continuous variation on firing angle that will keep continuous linear change in impedance and that could not be offer in parallel compensation.

The proposed design has simplicity and fast response (due to series compensation). This simplicity offers low magnetic interference (due to low component number) between power stage and control circuit which can indicates more reliability.

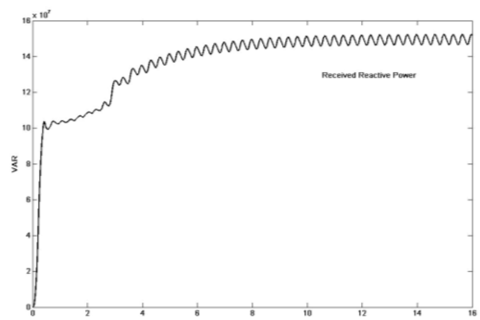
According to simulation results, the control circuit fulfills all the requirements that taken into consideration which mean that the design is carried out successfully.



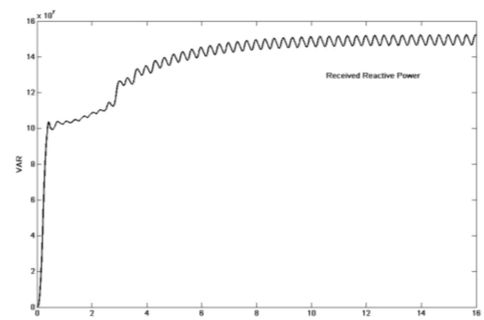
Time (Sec) x 10 $^{-1}$
(a) Transmitted Real Power (Watt)



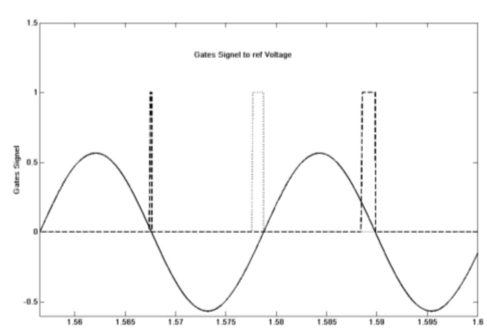
Time (Sec) x 10 $^{-1}$
(b) Transmitted Reactive Power (VAR)



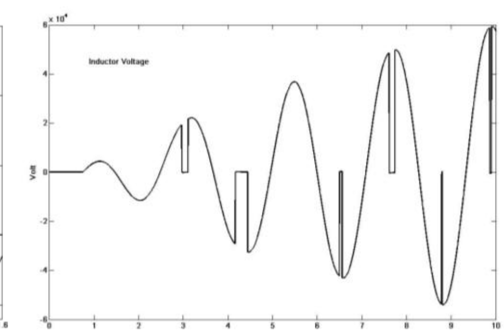
Time (Sec) x 10 $^{-1}$
(c) Received Real Power (Watt)



Time (Sec) x 10 $^{-1}$
(d) Received Reactive Power (VAR)

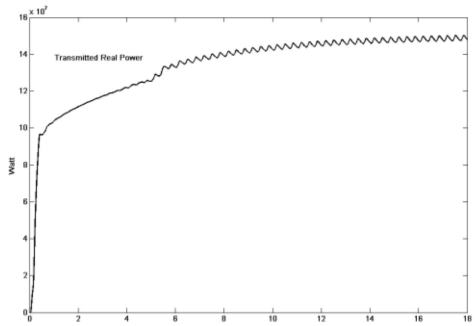


Time (Sec)
(e) Thyristor Gate Signal to Source Voltage

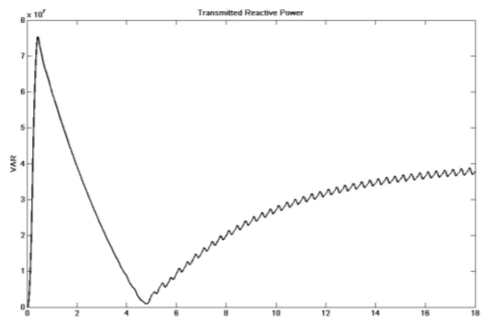


Time (Sec) x 10 $^{-2}$
(f) Voltage across the Reactor (volt)

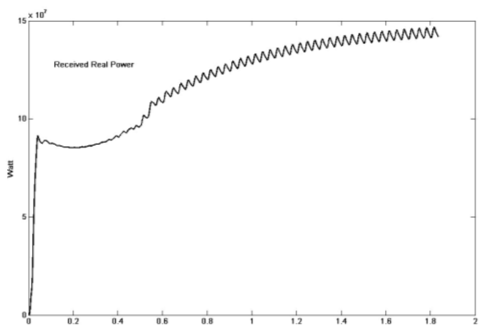
Figure (8)



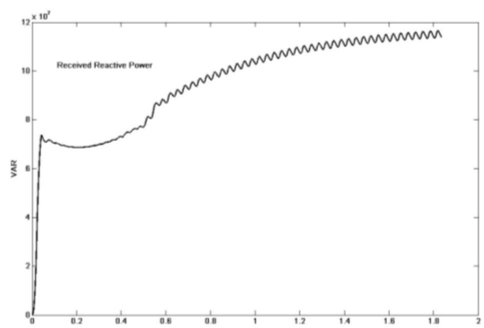
Time (Sec) x 10 $^{-1}$
(a) Transmitted Real Power (Watt)



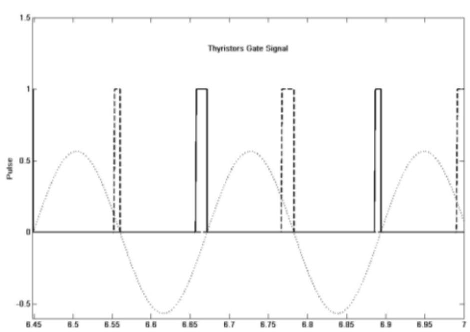
Time (Sec) x 10 $^{-1}$
(b) Transmitted Reactive Power (VAR)



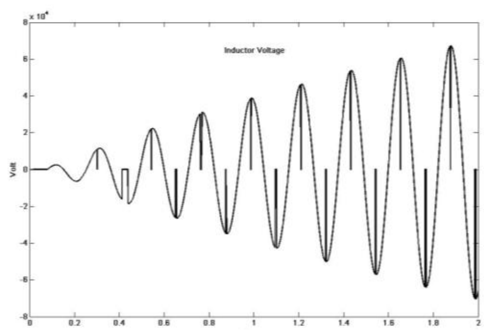
Time (Sec)
(c)Received Real Power (Watt)



Time (Sec)
(d) Received Reactive Power (VAR)



Time (Sec) x 10 $^{-1}$
(e) Thyristor Gate Signal to Source Voltage



Time (Sec) x 10 $^{-1}$
(f) Voltage across the Reactor (Volt)

Figure (9)

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