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Study of Thyristor Controlled Series Compensator for the Enhancement of Power flow and Stability

Sangheetha A P, Dr.S.Padma

Abstract— One of the biggest challenges in power industry is to transmit the power with minimal losses and at the same time with good stability and controllability. Though newer technologies enable one to install modern power transmission network and associated facilities that can achieve efficient power transmission, it is not always possible to replace the older power networks with newer ones. Hence, cost-effective solutions need to be provided to improve the efficiency and minimize transmission losses. In this regard, Flexible Alternating Current Transmission System (FACTS) technology has been proven to be a promising solution in improving the power transmission capacity and controllability in already existing power networks. There are different types of FACTS controllers proposed for the regulation of power system. Those controllers are shunt controllers, series controllers and the combination of both. This work focusses on the series controller- Thyristor Controlled Series Compensator (TCSC). TCSC enhances power flow in the system and provides a continuous control of operating region. Different operating regions of TCSC are analyzed by varying the firing angle of thyristors and the impedance characteristics are visualized using the MATLAB software. TCSC is operated in both open loop and closed loop conditions. The results show that closed loop control of TCSC provides a better performance than the open loop system. The resonance region for the proposed system configuration is simulated using LABVIEW software. Transient stability analysis of the system with and without TCSC is performed. The simulation results show that TCSC is capable of increasing the power level and improving transient stability.

Index Terms— FACTS, LABVIEW, MATLAB, Series controllers, TCSC

1 Introduction

THE estimated electricity consumption increased from 43,724 GWh during 1970-71 to 7, 72,603 GWh during 2011-12. Without continuous improvements in energy efficiency, demand would have to grow much more rapidly simply to sustain economic growth. Installing power plants and transmission lines are not the immediate solutions because installation may take several years. Moreover this is not possible because of lack of space, cost etc. In this issue, FACTS technology will provide a promising solution. Installing the FACTS devices in the transmission line will improve the transmission efficiency and this will improve the stability of the system. Among the two major classes of FACTS devices, series compensation is used to regulate the power flow and shunt compensation is used to regulate the voltage profile in the system. TCSC, a series FACTS device used to enhance the power flow in the transmission line, reduces the transmission losses and improves the transient stability. This will provide wide range of compensation and also limits the fault current in case of fault in the system. In this paper, under varying load conditions, load voltage, power flow and the transient stability through the system are analysed.

2 OPERATION OF TCSC

The configuration of TCSC is shown in fig.1. Here, a Thyristor controlled reactor (TCR) is connected in parallel with a fixed capacitor to enable continuous control over the series compensation. The value of inductor can be varied by varying the firing angle of thyristors. Thus the impedance of the line can be varied depending on the load conditions. TCSC is available for application in AC lines of voltage up to 500 kV. TCSC can also be used to protect the transmission line from over-voltages. Depending on the varying load conditions, the thyristor firing angles are varied to provide the necessary impedance to the transmission network. By varying the impedance of the circuit, both the capacitive and inductive compensation can be provided. Based on the impedance provided by the TCSC, there are three different operating modes [1, 2].

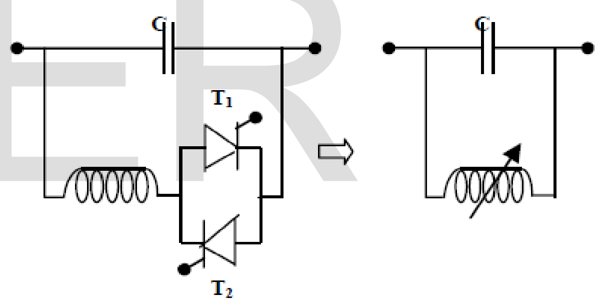

Fig. 1. Thyristor Controlled Series Compensator

i) Inductive Mode
ii) Resonance
iii) Capacitive Mode

Inductive mode is used when the load on the system decreases. Conversely, when the load on the system increases, TCSC is made to operate in the capacitive mode. Generally, capacitive

- *Sangheetha A P is currently pursuing masters degree program in electric power engineering in Sona College of Technology, Anna University, India E-mail: sangheetha.0311@gmail.com*
- *Dr.S.Padma is currently Professor in* the department of electrical and electronics engineering ,*Sona College of Technology,Anna University, India E-mail: swanisha@gmail.com*

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mode of operation is provided in the system.

3 IMPEDANCE CHARACTERISTICS

The above mentioned operating regions are classified based on the thyristor firing angles and it is shown in fig.2 and tabulated in table 1 [3].

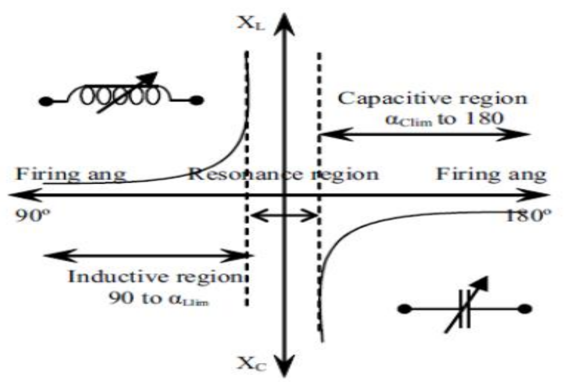

Fig. 2 Impedance Characteristics

TABLE 1
IMPEDANCE CHARACTERISTICS

RANGE OF FIRING ANGLE	OPERATING REGION
$90^o \leq \alpha \leq \alpha_{L\ lim}$	Inductive region
$\alpha_{L\ lim} \leq \alpha \leq \alpha_{C\ lim}$	Resonance region
$\alpha_{C\ lim} \leq \alpha \leq 180^o$	Capacitive region

The resultant TCSC impedance is obtained using the formula,

$$X_{tcr} = \omega L \left[\frac{\pi}{\sigma - \sin(\sigma)} \right]$$

$$X_{t\,csc} = \left[\frac{X_{tcr} . X_C}{(X_{tcr} + X_C)} \right]$$

where $\beta = \pi - \alpha$ $\sigma = 2\beta$

σ - conducting angle ; β – angle of advance ;
α – firing angle

4 SIMULATION CIRCUIT OF TCSC

The TCSC implemented in the transmission line is of 7mH and the capacitor is of 500μF. Here, the single phase system is considered with a voltage of 220 V. Line compensation is provided and it is 26% of the transmission line impedance. The firing angles given to the antiparallel thyristors are 180° out of phase with each other.

4.1 Simulation of TCSC for Resonant Point

Different operating regions and the resonance point can be determined with the help of impedance characteristics. This can be visualised with the help of TCSC specifications [4, 5]. By implementing the formulae (1) and (2) in the LABVIEW, the results are shown below which is the variation of reactance with respect to the firing angle. The result shown will vary depending on the TCSC specifications and there may be a single or multi resonant point. For the considered TCSC values, there is a single resonant point and it is in the range of 148° to 150°.

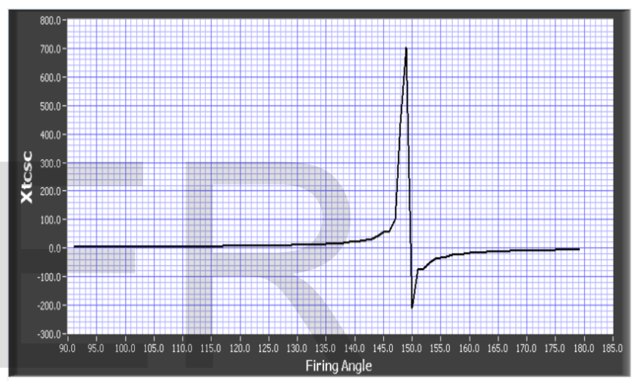

Fig. 3. Firing angle versus TCSC Reactance

α (delay angle) ranges from 90° to 180°. From fig. 3, different operating regions and the resonance points are identified and they are tabulated in table 2

TABLE 2
RESULTS FROM FIG. 3

OPERATING MODE	RANGE OF FIRING ANGLE
Inductive Mode	90^o to 148^o
Resonance Region	148^o to 150^o
Capacitive Mode	150^o to 180^o

5 SIMULINK DIAGRAM

5.1 Open Loop

The TCSC is implemented in the single phase system as shown in fig 4. By varying the firing angle of thyristors, different operating regions are analysed. Here the transmission line impedance is given by 0.01+j4.39 Ω and the load impedance is 15+1.57Ω. Firing angle to the thyristors are given with the help of pulse generators. Firing pulses are

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given in terms of pulse width and the phase delays. From the table 2, it is observed that the system will be in inductive vernier mode from 90º to 148º and from 150º to 180º capacitive mode of operation. Resonance region is between 148º to 150º. When the load on the system increases, the system will enter into the capacitive mode of operation. Similarly, when the load decreases, the system will enter in to the inductive mode

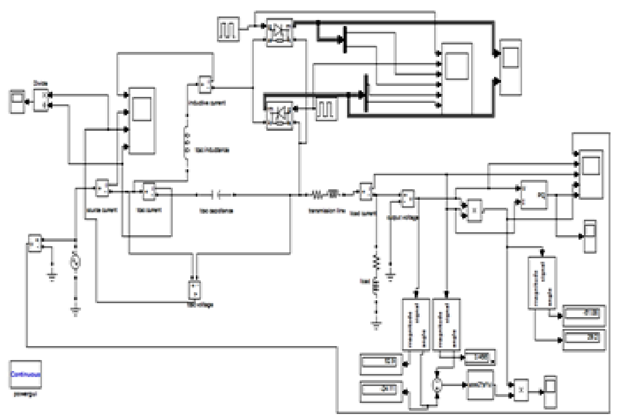

Fig. 4. Simulink Diagram of TCSC for Different Operating

of operation. For a purely inductive mode, a step input of 1 is given to the thyristors so that the thyristrors will conduct for full 180º. For a purely capacitive mode, a step input of 0 is given to the thyristors so that the capacitor alone will come into operation.

5.1.1 Capacitive Vernier mode

For capacitive vernier mode, the load is increased and the resultant voltage, current and the output voltage are checked. Normally in the uncompensated system when the load is increased, the output voltage will decrease. Here, the TCSC is implemented in the circuit and it works in the capacitive region (firing angle of above 150º). Hence, the system will operate in the rated voltage eventhough there is an increase in load. The results are given below in fig. 5, 6 and 7 for firing angle of 170º.

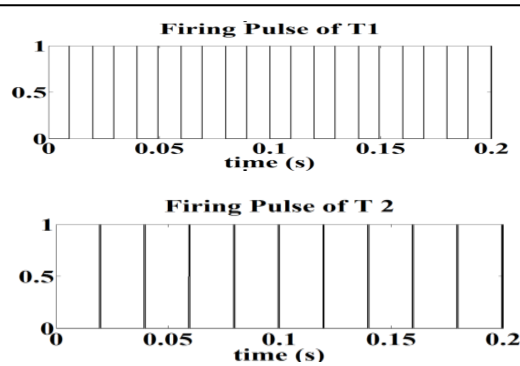

Fig. 5 Firing pulses to thyristors 1 and 2

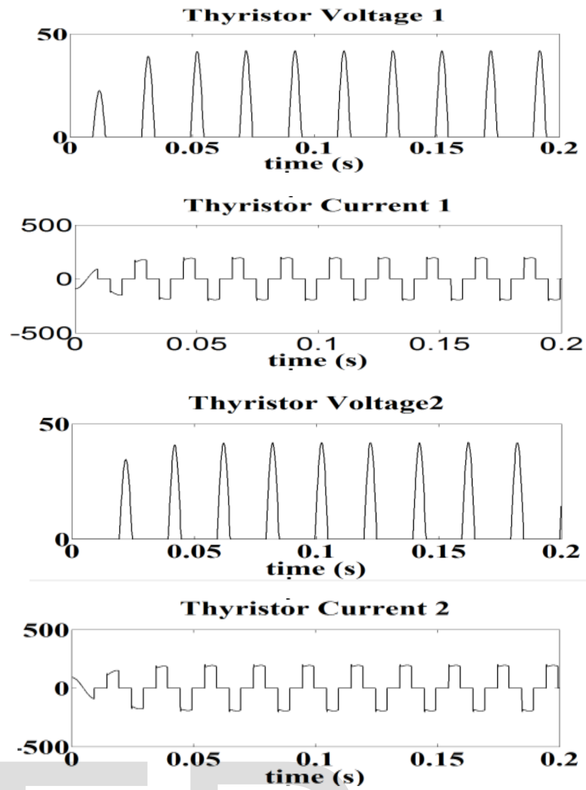

Fig. 6. Voltage and current of Thyristors 1 and 2

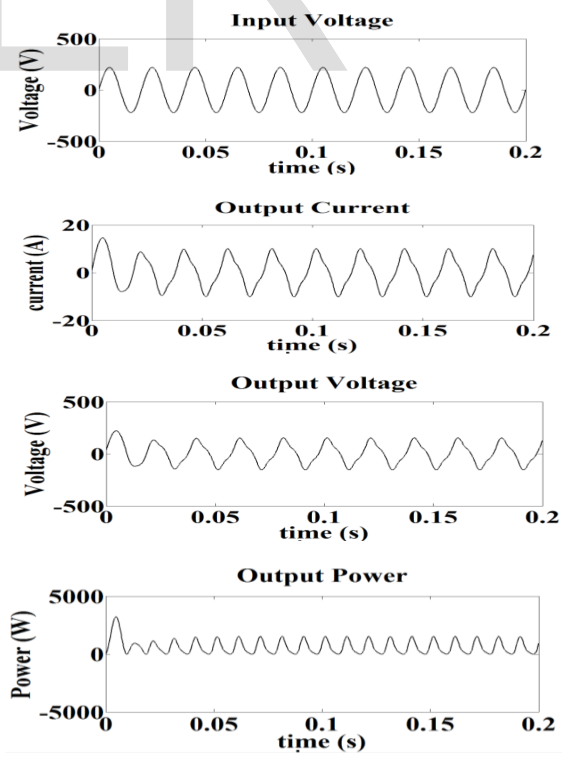

Fig. 7.Supply voltage,output current, voltage and power

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When the load increases, the TCSC can be made to operate in the capacitive vernier mode. This can be done by varying the phase delays given to the pulse generators, thereby the power flow increases and it will satisfy the load. Likewise, when the load decreases the TCSC can be switched to inductive vernier mode to maintain the stability. Thus, the TCSC can be operated during the varying load conditions and thus maintaining the stability. Also the power flow in the line can be increased with the help of TCSC [5].

5.1.2 Comparison of Output Voltage and Power for various firing angles

Here, the load is changed, making it inductive R=15Ω, L=55mH. The output voltage and power are tabulated in Table 3.

TABLE 3
COMPARISON OF OUTPUT VOLTAGE AND POWER FOR VARIOUS FIRING ANGLES

Type of circuit	**Output voltage(V)**	**Output Power(W)**
Simple circuit	175	1025
Purely capacitive	220	1800
160^o	195	1270
170^o	222	1900

The simulation results show that the power flow increases when the thyristor controlled series compensator is installed in the transmission line. In the uncompensated line, if the load increases, the output voltage and the power decrease which is given by 175V and 1025W. To operate the system in the rated voltage, TCSC is installed in the system. Because of the increase in load, the TCSC is made to operate in the capacitive mode. Now, in the purely capacitive mode the system will operate in the rated voltage of 220V and the power flow in the system also increases to 1800W which is 75% more than the uncompensated line. When the firing angle is 160°, the output voltage and the power is given by 195V and 1270W repectively. The power flow increases to 1900W when the firing angle is 170°.

6 Closed Loop Mode

6.1 Control circuit

In the control circuit, a feedback filter, PI controller, lead lag compensator, PLL circuit and delay filters are used. PI controller and the PLL having the integral gain of 0.7, 300 and the proportional gain of 0.006s, 30s. Here a second order filter is used which synchronises the thyristor firing angle with line current angle. Thyristor firirngs are discrete in time whereas the system considered is a continuous time model. To accommodate this, a delay filter having the time delay of T_{d1} (1/220s) is introduced. An additional phase lag of T_{d2} (1/1400s) is introduced for the sysnchronisation of the voltage phase angle with the thyristor firing angle. The control circuit is shown in the fig 8 [6 and 7].

The resultant firing angle is converted to pulses which are out of phase with each other. These pulses are given to the thyristors gate circuit.

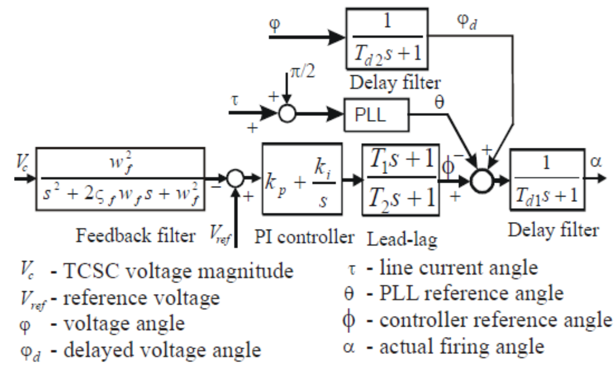

Fig.8. Controller Model

7 Comparison of Open Loop and Closed Loop Modes

The output voltage for both open and the closed loop are shown below in fig 9. For a load of resistance 25Ω and the inductance of 0.85H, output voltage in both the open loop and the closed loop are analysed.

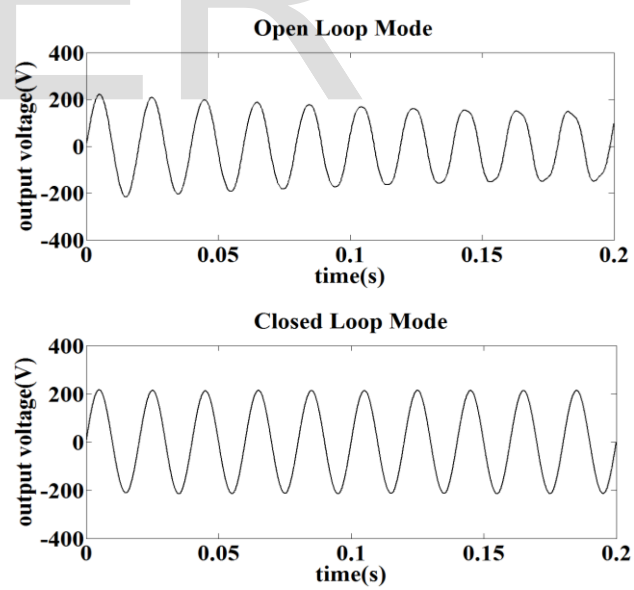

Fig. 9. Output Voltage of both open and closed loop mode

In the open loop the output voltage is about 156 V and in the closed loop system the output voltage increases and the rated voltage of 220 V is maintained. Thus, the closed loop system will provide the better results than the open loop system.

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8 Transient Stability Analysis

The transient stability analysis of the system is studied by creating a disturbance in the system. If the oscillations persist in the system for a long period of time, then the system will enter into unstable state. To reduce the time period of oscillations, series compensation is provided in circuit [8, 9 and 10].

In the given single phase transmission system, the transient stability is analysed by creating a line fault. This is done by introducing the fault block in series with the transmission line. The results are compared for (i) uncompensated line, (ii) line equipped with TCSC at firing angle of 160º, (iii) line equipped with TCSC at firing angle of 170º and (iv) line with TCSC in purely capacitive mode and shown in figs. 10, 11, 12 and 13 respectively.

8.1 Case 1-For an Uncompensated System

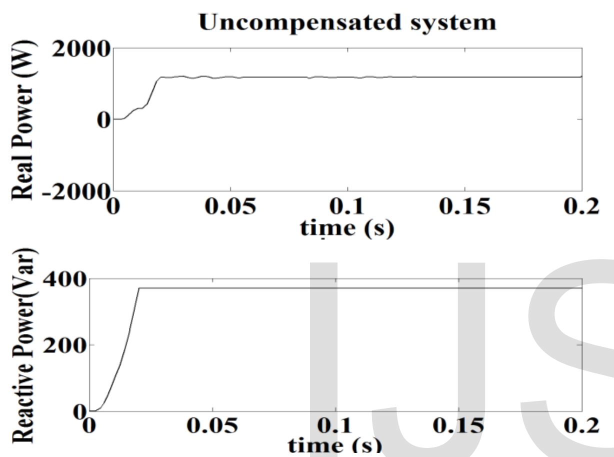


Fig. 10. Power Oscillation Diagram for an Uncompensated system

The time period for damping of oscillations for an uncompensated system is 0.18s

8.2 Case 2-For a Firing angle of 160º

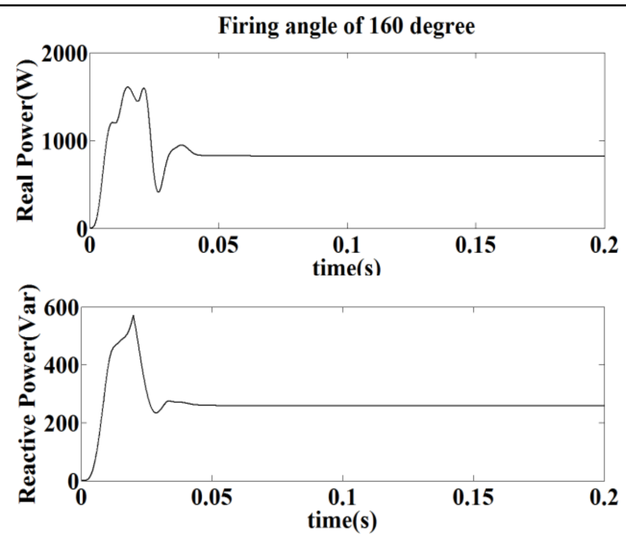


Fig. 11. Power Oscillation Diagram at 160º

The time period for damping of oscillations for a firing angle of 160º is 0.04s

8.3 Case 3- For an Firing angle of 170º

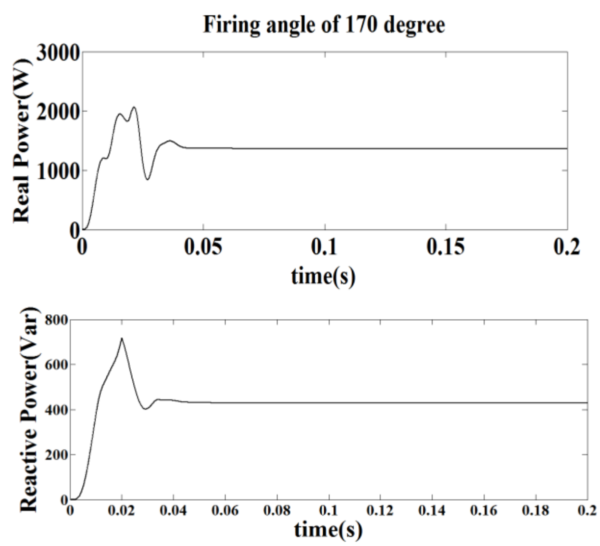
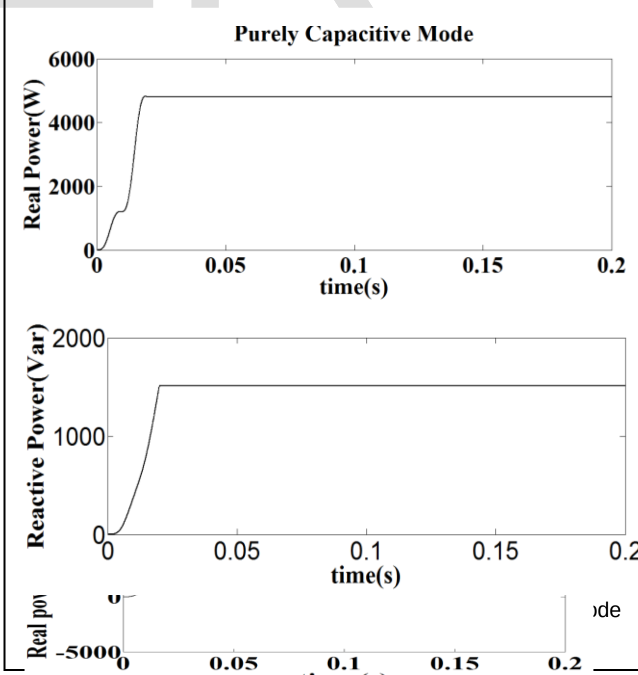


Fig. 12. Power Oscillation Diagram at 170º

The time period for damping of oscillations for a firing angle of 170º is 0.03s

8.4 Case 4- For a Purely Capacitive Mode



The time period for damping of oscillations for a purely capacitive mode is 0.01s

The results obtained are tabulated in table 4.

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. TABLE 4
TRANSIENT STABILITY ANALYSIS

Case	Firing angle (degrees)	Time (seconds)
1	Uncompensated line	0.14
2	160^o (with TCSC)	0.04
3	170^o (with TCSC)	0.02
4	Purely capacitive	0.01

From table 4, it is inferred that the oscillation will be damped in a short period of time when the TCSC is installed in the transmission line. Thus, with the help of TCSC, transient stability of the system can be improved [11].

9 CONCLUSION

Operating regions and resonance points of TCSC are analyzed with the help of LABVIEW. Under varying load conditions, power flow, output voltage and transient stability are analyzed with the help of MATLAB. It is shown that the power flow through the line can be increased and the given system can be made to operate in the rated voltage during varying load conditions. From the open loop and closed loop mode analysis, the results show that closed loop mode will give better results than the open loop system. From the transient stability analysis, we can conclude that the transient stability can be enhanced when the TCSC is implemented in the system.

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