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Design and Implementation of TCSC Controller for Power Flow Enhancement

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Abstract: **In the present day scenario, transmission systems are becoming more insecure with unscheduled power flows. The transmission and distribution losses are increasing day by day because of high demand. However, many high voltage transmission systems are operating below their thermal ratings due to constraints, such as voltage and stability limits. This leads to reduction of life of transmission lines and is less economical. The power flow through the transmission network is mainly limited due to line impedance and load angle of the generator. To control the real power flow through any transmission line it is needed to control the impedance of the line or load angle. This control can be achieved by Flexible Alternating Current Transmission System (FACTS) device. In this paper, Thyristor Controlled Series Capacitor is used to compensate the line reactance of transmission line and look up table based TCSC controller is proposed for power flow control. The design and hardware implementation of TCSC control is discussed in this paper. The system stability is analyzed with and without TCSC Controller. It can be achieved by introducing TCSC through a transmission line. The effective impedance of the transmission line is changed by giving series compensation to the transmission line, thus compensating line reactance. This system is tested in laboratory set up for open loop and closed loop control under different operating conditions.**

***Index Terms*— FACTS, power system stability enhancement, TCSC**

I. INTRODUCTION

Modern power systems continuously expanded and upgraded to cater the need of ever-growing power demand. It is essential to fulfill the demand with better power quality. Available transmissions lines must be powerful enough for safely transmit the increased demand. Lack of transmission facilities and over exploitation of existing resources make power system instable imminent in modern power systems. With the increased loading of transmission lines, system stability becomes an important criterion in designing of power systems. Improving transient stability and satisfactory damping of power oscillations are important issues. Lack of damping torque results in power oscillations and it may affect the stability of the entire system.

Traditionally, fixed or mechanically switched shunt and series capacitors, circuit breakers etc. were used for improving stability. Recent development in power electronics introduces the use of Flexible AC Transmission Systems (FACTS) controllers in power system. The main objectives of FACTS are to load transmission lines up to its thermal capacity and control the power flow over designated transmission routes. Typically, FACTS devices are divided into three categories: shunt-connected, series-connected and a combination of both. Thyristor Controlled Series Capacitor (TCSC) is one of the series connected FACTS device that can regulate the line impedance and improve the stability. TCSC provides capacitive compensation and modifies the reactance of the transmission lines.

The main objective of this thesis is to propose an effective method for control of real power flow by using TCSC. In this paper Thyristor Controlled Series Capacitor (TCSC), a series connected FACTS controller is adopted for stability enhancement. The modeling of TCSC for power flow and stability enhancement is discussed. The description of hardware testing of real power flow control in the scaled down laboratory model of power system with and without using TCSC is discussed. The effect of series capacitive compensation in damping of oscillation in real power is analyzed. The testing details of controller circuit of TCSC are presented in this thesis. This includes hardware the implementation of firing circuit for TCSC units.

II. SYSTEM MODELING

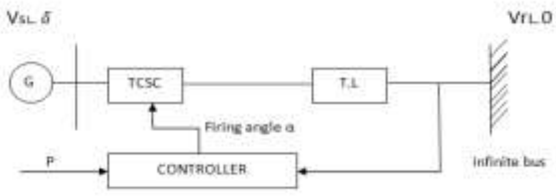

Fig.1 Single Machine Connected To Infinite Bus through TCSC Compensated Transmission Line

The system under study consists of a salient pole synchronous generator connected to infinite bus through a series connected lossless transmission line as shown in fig 1. The synchronous generator is delivering power to infinite bus through series compensated transmission line. The series compensation is provided by TCSC. The generator terminal voltage is represented as and $v_s\llcorner\delta$ the infinite bus voltage is represented as v_r .the operating load angle is δ. The controller gives the firing pulse for the TCSC to turn on.
The controller used is the arduino atmega controller. Creating oscillations in the laboratory setup and studied the effect of series compensator in damping these oscillations. Matlab/simulink model was used to analyze the effect of tcsc in the system. After this, the firing circuit using arduino controller in open loop power flow enhancement s designed and implemented. In the following discussion, the modeling of every block is discussed.

Modeling of TCSC

TCSC is a capacitive reactance compensator, which consists of series capacitor bank shunted by a thyristor-controlled reactor in order to provide a smoothly variable series capacitive reactance [2]. It is based on the thyristor without the gate turn-off capability [1].

The equivalent reactance of TCSC can be represented by using a variable reactance. The steady-state relationship between the firing angle α and the reactance is given by the following equation (1)

$$X_{TCSC}(\alpha) = -X_C + C_1(2(\pi-\alpha)+\sin(2(\pi-\alpha)))\text{-}C_2\cos^2(\pi-\alpha)(\varpi\tan(\varpi(\pi-\alpha))\text{-}\tan(\pi-\alpha)) \qquad (1)\ [3]$$

$$X_{LC} = \frac{X_C X_L}{X_C - X_L}, C_1 = \frac{X_C - X_L}{\pi}, C_2 = \frac{4\times X_{LC}^{\ 2}}{X_L\times\pi}, \varpi = \sqrt{\frac{X_C}{X_L}} \qquad (2)\ [3]$$

- X_C = capacitive reactance
- X_L= inductive reactance
- α = firing angle of TCSC

The range of firing angle in which TCSC is in capacitive mode of operation is obtained by implementing equation (1) in MATLAB m-file. From the impedance characteristics, the operating firing angle is determined as 100° to 180° . The optimal value of L, C is chosen by implementing equation (1) in MATAB by considering 70% as the compensation by the TCSC. Least Mean Square (LMS) algorithm is used to find optimal value of L, C.

$$P = \frac{Vs\times Vr}{Xeff}\sin\delta \qquad (3)$$

Equation (3) gives the real power flow through a transmission line.
Where X_{eff} is effective reactance, Xeff = X_{line} - X_{tcsc} (4)
X_{tcsc}=1/2πfC; capacitive reactance (5)
X_{line}=3.768; inductive reactance.
Vs = 0.8p.u, Vr = 1p.u

As the firing angle increases, TCSC reactance decreases. Real power is increasing linearly with increase in percentage compensation. After a certain value, the relation becomes nonlinear.

$$\%Compensation = \frac{Xtcsc}{Xline} \qquad (6)$$

Percentage Compensation provided by different values of capacitors is determined. The graph between real power versus firing angle (α) and real power versus percentage compensation are plotted for different values of TCSC reactance.

Modeling of transmission line

The transmission line used in the lab is the scaled down model of a 200km transmission line. The parameters are:
Resistance, R=1Ω
Inductance, L=15.6mH

Generator

A 415V, 4.5A, 3phase salient pole synchronous generator having rated power of 1.5 kVA is used as generator.

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Implementation of open loop control of real power flow using TCSC

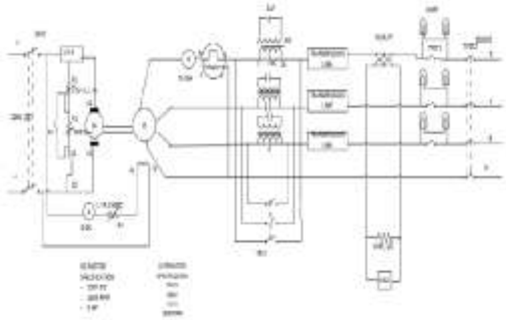


Fig2. Laboratory set up to analyze power system oscillations

Laboratory setup to analyze power oscillations with and without TCSC is shown in Fig: 2. The damping of oscillations are observed by creating a mechanical disturbance. Here TCSC is realized by connecting a capacitor to the secondary of the injecting transformer available in the laboratory. The section gives information about system description, procedures for analyzing system oscillations due to the external disturbance and the enhancement produced due to series compensation. Two different conditions were analyzed:

1. Without any FACTS devices.
2. With series capacitor compensation
Percentage compensation and Xeff are calculated for different

Capacitors, turns ratio to determine the optimal value of percentage compensation that can be provided by series capacitor. This is done by using implementing equations 1to 5 in MATLAB m-files. A 415V, 4.5A, 3phase salient pole synchronous generator having rated power of 1.5 kVA is used. The turbine modeled as a DC motor with 1500 rpm, 5 HP, 230V DC. Scaled down model of 200MVA, 220V, 250km transmission line with line impedance of 3.768Ω is used. The generator was synchronized with the infinite bus bar. After that, power flow through transmission line is adjusted. The below mentioned table give the values of percentage compensation, X_{eff} values for different values of capacitance, turns ratio.

Table 1 Percentage Compensation and XEFF

Capacitors	k=80	k=40	k=26.6
1uf	Comp=13.9% Xeff=3.27	Comp=52.79% Xeff=1.77	Comp=119.39% Xeff=-0.73
2uf	Comp=6.59% Xeff=3.52	Comp=26.39% Xeff=2.77	Comp=59.69% Xeff=1.51
4uF	Comp=3.29% Xeff=3.64	Comp=13.19% Xeff=3.27	Comp=29.84% Xeff=2.64

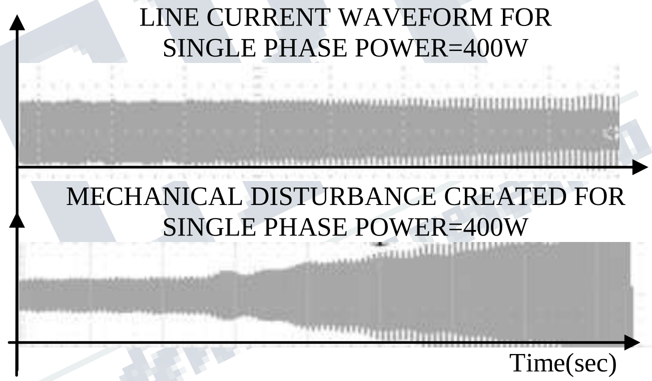
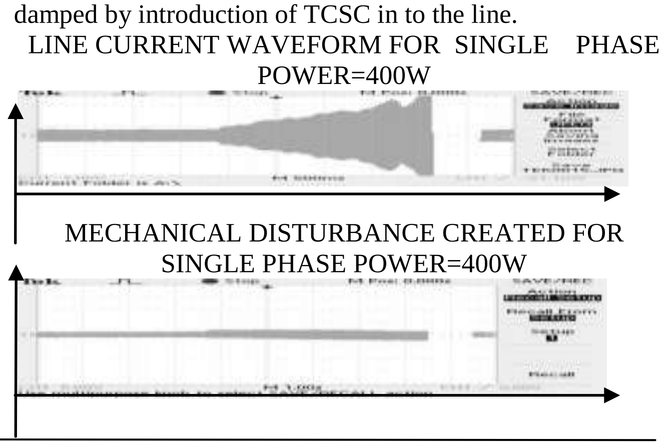


Fig3 Power oscillation when mechanical disturbance is introduced without any device

From the table 1, it is clear that the percentage compensation is inversely proportional to capacitance. From fig3, it is inferred that the oscillations in the power are created with mechanical disturbance. These oscillations are damped by introduction of TCSC in to the line.



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Time(sec)

Fig4 Power oscillation when mechanical disturbance is introduced with TCSC

The above graphs in fig 3 are drawn to the different scale. The damping of oscillations is effectively done by TCSC device. These graphs are observed for different values of capacitance and turns ratio of injecting transformer and rise of amplitude in line current, settling time of oscillations were tabulated.

Table 2 without compensation

Power (W)	Change in amplitude of Line current	Time (s)
200W	3.5	5.28
300W	3.51	5.12
400W	3.9	2.96

Turns ratio: 26.6, 2uF, 60% Compensation

Table 3 Amplitude of variation of power system oscillations for various operating power

Power (W)	Change in amplitude of Line current	Time (s)
200W	2.8	4.6
300W	3.1	2.8
400W	3.52	2.08

The results obtained shows the comparison of power flow in the transmission lines for different levels of power transfer corresponding to different turns ratio of injecting transformer. The amplitude of line current is reduced with increase in compensation. The damping of oscillations is faster with the introduction of series compensation. It is observed that load angle variation is very less compared to variation produced without any compensation.

Change in power for different values of capacitors and turns ratio of injecting transformer and a graph had been plotted

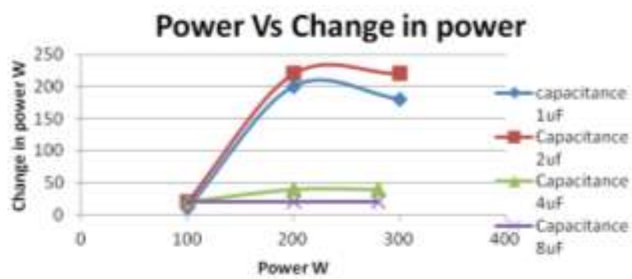

Fig 4: Real power flow vs. Change in power

The change in power for different values of real power flow is almost constant for 4uF and 8uF whereas 1uF and 2uF produces maximum power variation in the line. Hence, in this paper 1uF and 2uF capacitors are considered as capacitance values for TCSC.

Design and Implementation of open loop control of real power

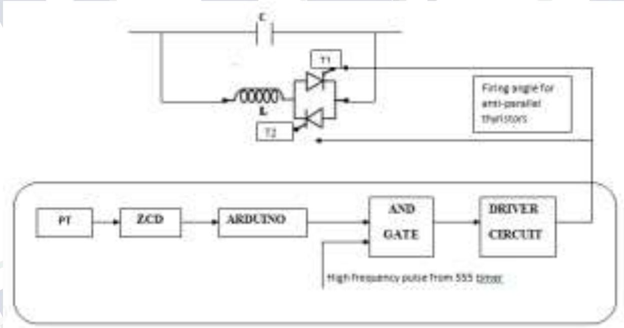

Fig 5: TCSC module controller section for open loop operation

The above figure shows a TCSC module which is controlled by Arduino controller for open loop operation. System voltage is sensed using Potential Transformer (PT). The voltage waveform from PT is given as input to the Zero Crossing Detector (ZCD) circuit. The output of ZCD is given as input to the Arduino board for synchronization with firing circuit. Arduino produces triggering pulses with a delay angle (with reference to the ZCD input) given manually in the code. The triggering pulses are ANDed with high frequency pulse from 555 timer to obtain high frequency triggering pulses. The advantage of these pulses is to reduce the switching losses of thyristors. These pulses are given to the anti-parallel thyristors in the TCSC connected in series with the transmission line.

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In order to provide supply to the ZCD, Thyristor driver, AND Gate etc. a DC power supply of voltages 5V, 9V, 12V,15V,-5V and -15V are designed. Driver circuits often take on additional functions, which include isolating the control circuit and the power circuit, detecting malfunctions, storing and reporting failures to the control system, serving as a precaution against failure, analyzing sensor signals, and creating auxiliary voltages.

The anti parallel thyristors used in this paper is TYN616

Specifications of Thyristor TYN616**:**
IGT: Continuous gate current for thyristor triggering =25mA
IL: Minimum current required for latching =60mA
VGT: Gate voltage for triggering Thyristor =1.3 V

Fig 6: Flow chart for open loop operation

The above figure represents the algorithm for open loop contol of real power flow.The ZCD output is taken as the reference and the triggering pulses are generated with a delay. In open loop, the delay is manuallay entered by the user.

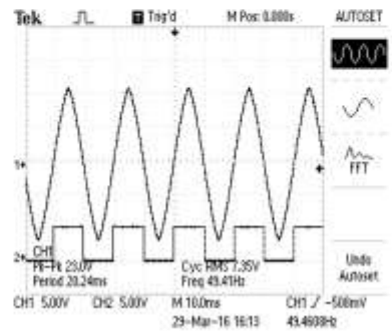

Fig 7 Input and output waveforms of ZCD

The pulse sarts at the zero crossing of the input sinusoidal pulse. This is Anded with 555 timer to get high frequency pulse as shown below

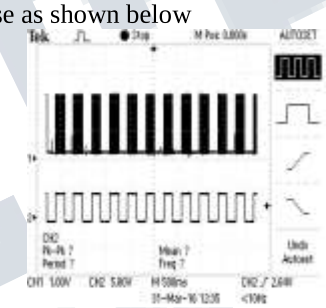

Fig 8 Input and Output of AND using NAND gate

Finally, the driver circuit generates a pulse of magnitude of 8.2v and this is given to anti parallel thyristors.

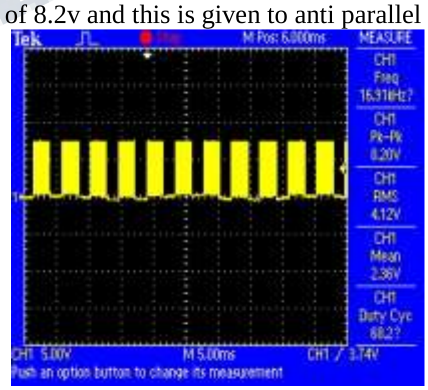

Fig 9: Output of driver circuit

This controller circuit is connected to TCSC in the laboratory set up discussed in section II. Table 4 shows the effect of series capacitive compensation with delay angle.

Table 4 Open loop control for 300W real power

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Delay(ms)	Power increase in line1 (W)	Line current amplitude with TCSC(V)	Voltage amplitude without TCSC(V)
6 (108°)	420	2.08	1.36
7 (130°)	430	2.16	1.36
8 (144°)	440	2.24	1.36

Here it is observed the power in both the lines is equal when the switch is closed. The line having TCSC has a higher power flow than the other while the switch is open i.e. when TCSC is introduced in the line. The power is observed for different firing angles. As the delay increases power flow in the line having TCSC also increases due to reduction in inductive effect and thereby increases the capacitive effect. The reactance in the line decreases resulting in increased power flow. Delay is manually varied, as it is open loop control.

IV. IMPLEMENTATION OF LOOK UP TABLE BASED CONTROL OF TCSC

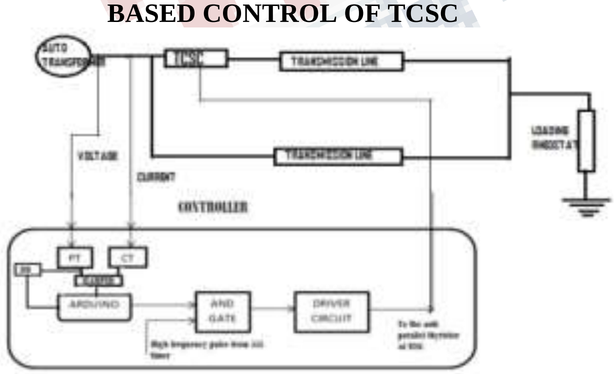

Fig 10 Hardware implementation circuit for look up table based control of real power

The real power flow can be controlled by varying firing angle to anti-parallel thyristors. The real power flowing through the transmission line is calculated by sensing current and voltage through current transducer and potential transformer. These signals are sent to the Arduino Uno controller to implement the control algorithm. As Arduino is a unipolar device, the sensed current and voltage are clamped using IC741. Look up table is formed from certain observations made in open loop control of real power flow. For a particular value of existing power (200W and 300W) in the system, the look-up table gives the delay angle for the triggering pulses of the thyristors. This look up table is implemented using Arduino controller.

Table 5 Look up table for implemented in Arduino controller

Real power (W)	Input power compensation(W)	Firing angle (ms)
200	200-240	6
200	240-260	7
200	260-280	8
300	400-420	6
300	420-430	7
300	430-440	8

The Arduino controller gives firing angle to the thyristors based on the look up table. The power compensation is taken through serial monitor i.e., by the user and provides firing angle based on look up table. The values of RMS voltage, RMS current, input power compensation provided by the user and delay provided are displayed on serial monitor in Arduino through serial print function. It is found that the Arduino controller generates the triggering pulses corresponding to any change in load. It is thus concluded that the look-up table based control circuit of TCSC is operating satisfactorily for the single phase system with two parallel transmission lines, out of which one is connected with TCSC in series.

V. CONCLUSION

A laboratory setup has been developed and implemented for analyzing the stability of power system. A transient disturbance is provided to the system and stability control is achieved by providing series capacitive compensation. A detailed comparison is done for different operating conditions. The results obtained in hardware are compared with the simulation analysis done in MATLAB/ SIMULINK and satisfactory results are obtained. The power system considered in this project is a single machine connected through a transmission line to an infinite bus. It can be designed by using a multi machine power system for better system response. Genetic Algorithm (GA), Particle Swam Optimization (PSO) or any other AI techniques can be used to develop the control algorithm for TCSC and it can be operated in real time adaptive mode.

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