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Simulation Aspects of Thyristor Controlled Series Compensator in Power System

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Abstract : The Thyristor controlled series compensator (TCSC) is one of the important members of FACTS family that is increasingly applied with long transmission lines by the utilities in modern power systems. It can have various roles in the operation and control of power systems, such as scheduling power flow; decreasing unsymmetrical components; reducing net loss; providing voltage support; limiting short-circuit currents; mitigating sub synchronous resonance; damping the power oscillation and enhancing transient stability control of power systems, systems and procedures are used to compensate dynamically the detrimental effect of nonlinear loads. The compensation process should be carried out without important alteration of the signal quality along with some benefits like reduction of losses in distribution lines, harmonic content minimization and power factor improvement. The dynamic behavior of industrial load requires the use of that compensator which can be adapted to the load changes. Thyristor Controlled Series Capacitor (TCSC) is an important FACTS device which has been used in power system transmission networks; these few aspects of the TCSC operation which we are simulating in ORCAD and MATLAB (i) To calculate the various resonance points in the impedance characteristics of the TCSC w.r.t. various firing angle. (ii) Contribution of the TCSC to power system operation and control system and study by implementing the TCSC in small power model of power system using ORCAD and MATLAB.

Keywords: *FACTS, Series Compensator, TCSC, Thyristor, MATLAB.*

I. INTRODUCTION

Power electronic devices, such as high voltage dc converters and static var compensators, have long established their usefulness in bulk power transmission. The scope of application of such devices has been extended considerably in recent years, as these devices provide much better transient responses, compared with their mechanical, electrical and electromechanical counterparts. The use of any such device can increase the level of power that can be transferred over a transmission corridor without endangering the system stability [1] [9]. Thyristor-controlled series capacitors (TCSC) is a type of series compensator, can provide many benefits for a power system including controlling power flow in the line, damping power oscillations, and mitigating sub synchronous resonance. Shunt compensation is ineffective in controlling the actual transmitted power as given by [2]:

$$P = \frac{V_s V_R \sin\delta}{Z_S}$$

Where Zs=Series Line Impedance, δ = Angle between the end voltages, P=Actual transmitted power, Vs= Sending end voltage, Vr= Receiving end Voltage

The variable series compensation is highly effective in both controlling power flow in line and improving stability, design, model and implement the TCSC in power system model is simulations are performed using the MATLAB. The rest of the paper is as organized section 2 Literature survey Section 3 TCSC model considering Section 4 Analysis of TCSC section 5 Experimental setup and response of the zero cross detector, response of the A/D converter, and firing pulses of the SCR i.e. output of the microcontroller, simulation analysis of the implemented TCSC circuit section 6 consists of conclusion and further scope of work.

II. LITERATURE SURVEY

- Hailian Xie and Lennart Angquist designed a new control scheme instead of traditional firing angle control scheme called as the Static Voltage Reversal Control scheme. Following that scheme the simulation results are analyzed using real time simulator [3].
- T.Venegas and C.R. Fuerete Esquivel report on large scale power flow studies. The ASC model are developed in phase coordinates and incorporated into an existing Newton Raphson power flow algorithm and analysis is done on both balanced and unbalanced power network operating conditions [4].

- Dragan Jovcic, member IEEE and G.N.Pillai presents an analytical, linear, state-space model of TCSC. First a simplified fundamental frequency model of TCSC is proposed and the model results are verified. Using the nonlinear TCSC segment, a simplified nonlinear state space model is derived where frequency of dominant TCSC complex poles shows linear dependence on the firing angle. The nonlinear element is linearised and linked with the AC network model along with TCSC model and is implemented on MATLAB and verified on EMTDC/ PSCAD in frequency and Time domain for a range of operating conditions [5] [18].
- T.Vengas and C.R. Fuerte-Esquivel develop a steady-state mathematical model of the new generation of power electronic based plant component presently emerging as a result of FACTS devices. Modeling is done in the phase domain considering the TCSC physical nature. A poly-phase power flow program based on Newton algorithm is developed in order to implement the proposed model [17].

III. TCSC MODEL CONSIDERING

This device has been traditionally modeled as a thyristor-controlled reactor in parallel with a fixed capacitor; the reactor and capacitor are represented only by their corresponding reactance.

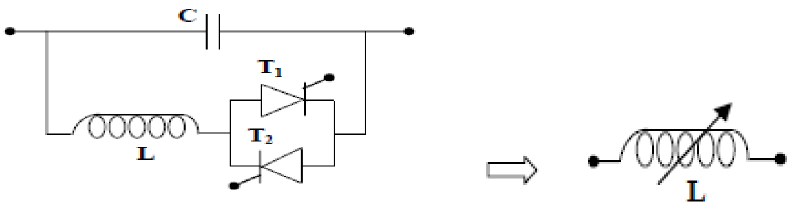

Fig. 1 Equivalent Circuit of TCSC

3.1 Modes of operation of TCSC

There are three modes of operation of TCSC depending upon the firing angle of the pulses fed to the thyristor [8].

- Thyristor blocked mode
- Thyristor by passed mode
- Vernier operating mode

3.1.1 Thyristor blocked Operating Mode:

When the thyristor valve is not triggered and the thyristors are kept in non conducting state, the TCSC is operating in blocking mode. In this mode, the TCSC performs like a fixed series capacitor.

3.1.2 Thyristor bypass Operating mode:

In bypass mode the thyristor valve is triggered continuously and the valve stays conducting all the time; so the TCSC behaves like a parallel connection of the series capacitor with the inductor, Ls in the thyristor valve branch. In this mode, the resulting voltage in the steady state across the TCSC is inductive and the valve current is somewhat bigger than the line current due to the current generation in the capacitor bank. For practical TCSC's with ratio (X_L/X_C) between 0.1 to 0.3 ranges, the capacitor voltage at a given line current is much lower in bypass than in blocking mode. Therefore, the bypass mode is utilized as a means to reduce the capacitor stress during faults [6] [15].

3.1.3 Vernier Operating Mode:

In Vernier control the TCSC dynamics are varied continuously by controlling the firing angle. The firing angle is possible from 0^o to 90^o for each half cycle when it is generated from the zero crossing of the line current hence divided into two parts [8] [10];

Capacitive Boost mode: In capacitive boost mode a trigger pulse is supplied to the thyristor having forward voltage just before the capacitor voltage crosses the zero line, so a capacitor discharge current pulse will circulate through the parallel inductive branch. The discharge current pulse adds to the line current through the capacitor and causes a capacitor voltage that adds to the voltage caused by the line current. The capacitor peak voltage thus will be increased in proportion to the charge that passes through the thyristor branch. The fundamental voltage also increases almost proportionally to the charge. From the system point of view, this mode inserts capacitors to the line up to nearly three times the fixed capacitor. This is the normal operating mode of TCSC [7] [9].

Inductive Boost Mode: In inductive boost mode the circulating current in the TCSC thyristor branch is bigger than the line current. In this mode, large thyristor currents result and further the capacitor voltage waveform is very much distorted from its sinusoidal shape. The peak voltage appears close to the turn on. The poor waveform and the high valve stress make the inductive boost mode less attractive for steady state operation. This mode increases the inductance of the line, so it is in contrast to the advantages associated with the application of TCSC [7] [19].

3.2 Practical TCSC circuit:

Practical TCSC circuit has various protection elements including MOV, circuit breaker in series with an inductor. TCSC module with different protective elements is as shown below.

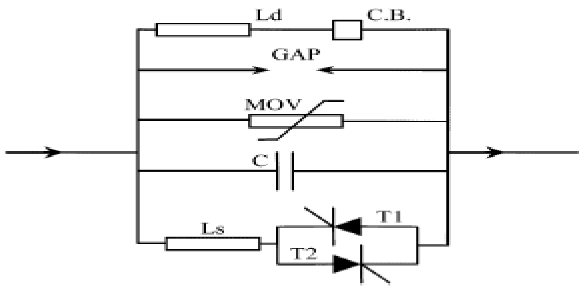

Fig. 2 Practical circuit of TCSC

Basically, it comprises a series capacitor, in parallel with a Thyristor Controlled Reactor (TCR), Ls. A Metal Oxide Varistor (MOV), essentially a nonlinear resistor, is connected across the series capacitor to prevent the occurrence of high capacitor over voltages. Not only does the MOV limit the voltage across the capacitor, but it allows the capacitor to remain in the circuit even during fault conditions and helps improve the transient stability. A circuit breaker is also installed across the TCSC module to bypass it if a severe fault or equipment malfunction occurs. A current limiting inductor, Ld is incorporated in the circuit to restrict both the magnitude and the frequency of the capacitor current during the capacitor bypass operation [11] [13].

IV. TCSC IMPLEMENTATION ON HARDWARE

4.1 Design of Power circuit:

The power circuit of TCSC is designed with the small model of the power system .The main power supply is treated as the transmitting end generator's output with zero phase angle and 220 volts rms .From transformers secondary we can get twelve volts output to regulate it to +5 volts using center tapped full wave rectifier and regulator 7805 which is required for energizing zero cross detector, for the Vcc of microcontroller, for biasing of the transistor used as drivers and for opto-isolator but here we used it only for the opto isolator circuit and for other circuit another transformer is being used [14].

4.2 Design of Transmission line model:

Further after the generator there exists the transmission lines and here transmission lines are replaced by their pre calculated values of line inductance and resistances .Here value of line inductor assumed is 14mH and value of resistance is 4ohms.After transmission line TCSC is implemented in the middle of the circuit and again at the receiving end there is transmission line of the same rating. Resistances are taken with minimum of 5W power rating and inductors are designed in the lab by own [12].

4.3 Design of Inductors:

The inductor is designed around the soft ferrite E core. Soft ferrite core can operate in the power range of 200W-500W at a frequency of 100KHz.Two E cores are joined together with an air gap between the legs. Use of a gapped core can reduce the effect of permeability and result in high saturation level because the air gap can withstand much higher field strengths. Insulated copper wire is wound around the inner legs of the core. The inductance is directly proportional to the square of the number of turns of the winding and corresponding area of the core and inversely proportional to the length of the air gap as given below [15]:

4.4 Zero crossing detector circuit:

It is essential to synchronize the firing thyristor pulses with line current and voltage. An Op-Amp base voltage digitizer circuit is used for generating a square pulse synchronized with the input voltage. Output of zero cross detector is fed to the first pin of micro controller. The microcontroller is programmed to sense the rising

edge of the square wave. This rising edge will occur after every ten milliseconds for a line frequency of 50Hz. In this way α is generated by delaying the trigger pulses to thyristor firing pulses [16].
Here the firing pulses of the power semiconductor devices are synchronized with the line voltage because such procedure reduces the signals harmonic content .Therefore, a signal whose waveform coincides with that of the line voltage is required.

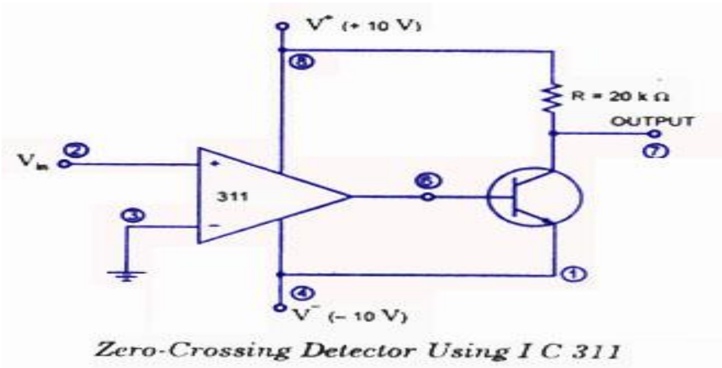

Fig.3 Zero Crossing Detector

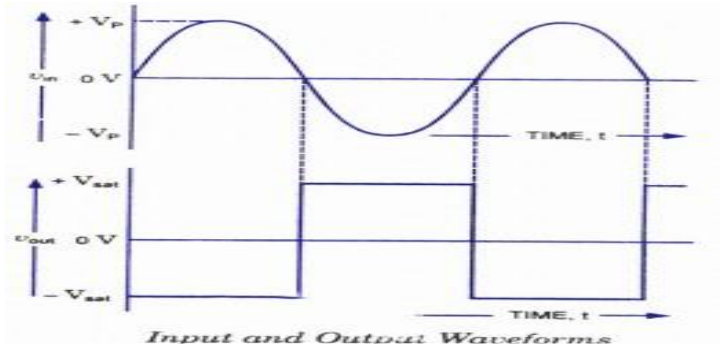

Fig. 4 Output waveform of the zero cross detector:

4.5 TCSC Hardware Implementation:

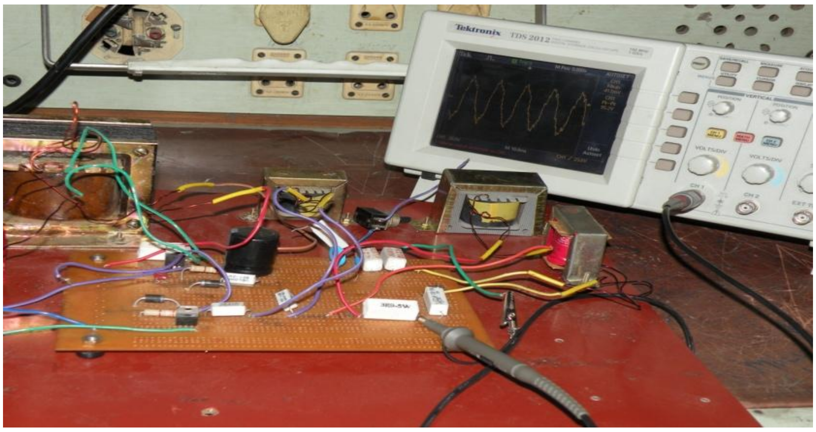

Fig. 5 Hardware implementation of TCSC

Fig. 5 shows the hardware implementation of TCSC Inductor required for the implementation of TCSC should be of 7mH value. TCSC inductor undertaken in practical design, Line inductance of value 14mH on both transmission as well as receiving end and load inductance of 5mH is also incorporated. In spite of using iron core stamping or winding to make the core, Ferrite core winding is used as the core of the reactor of the TCSC; the coil of TCSC was made up of 80 turns of 20AWG copper wire. Similarly line inductances and load inductance are designed with 20AWG wire on the ferrite core with approximately 60 turns and 40 turns respectively. Estimate the resistance Rt and the inductance Lt of the winding. The estimated parameters are: Rt =4 ohms & Lt =7mH So overall designing is accomplished by winding the 20 AWG wire across the former the ferrite core chosen was of E-25 size so former for that was made with the hard card board by cutting, folding and pasting it in the shape of former. After getting wound value of the inductance is measured on the inductance meter and if there were any ups or downs the no of turns were decreased or increased accordingly. Similar way other inductors were designed. Similarly capacitance and load resistance and load inductance is estimated. In this case the estimated parameters are R_t=0.01ohms; C_t=500uF; L-load=5mH; R-load=15ohm.

4.6 Microcontroller based control circuit:

In this stage an 89_C52 microcontroller is used. The microcontrollers detects the zero crossings of the square signal coming out of the signal conditioning stage, and delivers a firing pulse with a delay time proportional to the desired firing angle using even input bits. Each thyristor has a separate pulse and the firing angle has an accuracy of one electrical degree. The input port of the microcontroller is set for the condition of zero cross detector and the required delay is fed through the helical potentiometer through which analog I/P is given and the microcontroller inside A/D converter will convert those analog output into digital and hence delay is defined w.r.t. the high level of zero cross detector .The output port of Microcontroller will provide the trigger pulse only if zero cross detector o/p is high and the delay is defined w.r.t. the high output of the zero cross detector. Fig 6.

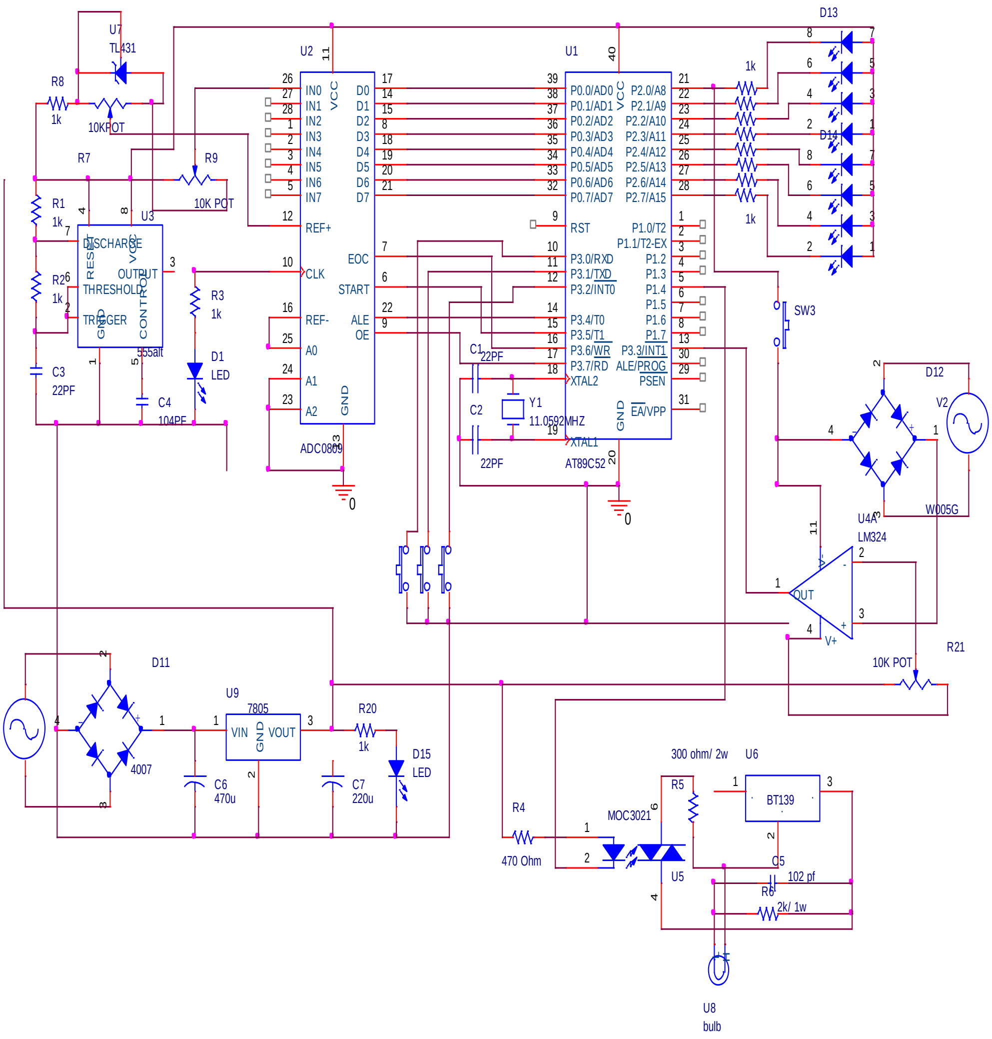

Fig. 6 Circuit diagram of the controller part of TCSC

The input port of the microcontroller is set for the condition of zero cross detector and the required delay is fed through the helical potentiometer through which analog I/P is given and the microcontroller inside A/D converter will convert those analog input into digital and hence delay is defined w.r.t. the high level of zero cross detector .The output port of Microcontroller will provide the trigger pulse only if zero cross detector o/p is high and the delay is defined w.r.t. the high output of the ZCD [20].

V. SIMULATION OF TCSC FOR SINGLE RESONANT POINT

5.1 Impedance Characteristics Curve:

With the given parameters of a TCSC, the steady-state mapping relationship between the firing angle and fundamental frequency reactance can be analyzed by writing the equation for the given TCSC circuit in the m.file of the MATLAB [17] [18] .These programs are written in simple language. Relationship between reactance and firing angle is different for the various values of the inductance and capacitance and also resonant points may be one or more depending upon the various values of capacitor inductance combination. If the frequency of supply is 50Hz then for a given values of capacitor=500_{uf} and inductor=7.1_{mH} as taken in the provided software and hardware circuit, also one reference example is also considered for the evaluation of its reactance this circuit used in Kayanta substation in USA having inductance value 6.9_{mH} and capacitance of 177_{uF} we can have various frequency responses

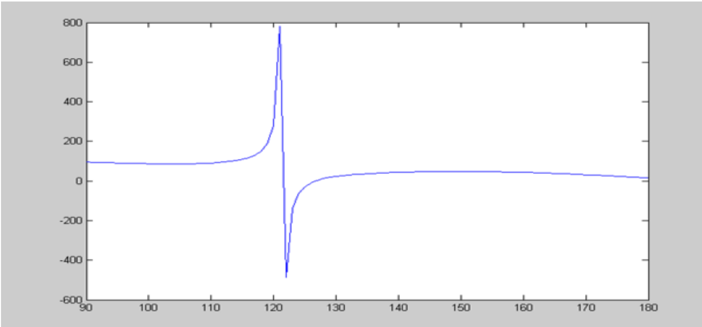

Fig. 7 Firing angle verses reactance curve L=7.1_{mH}, C=500_{uF}

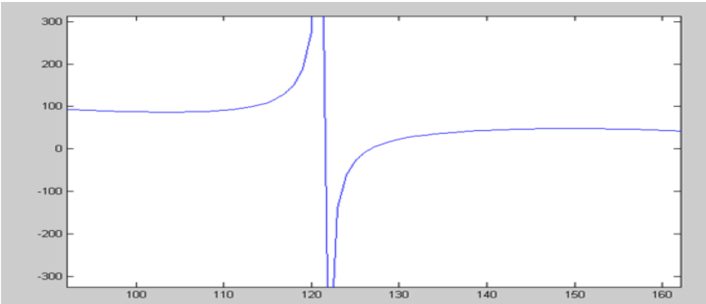

Fig. 8 Firing angle verses reactance curve L=6.9_{mH}, C=500_{uF}

5.2 Various parameters of TCSC circuit:

If the equation used is as given above , where instead of firing angle ,conduction angle is used in the calculation and parameters are also according to one of the places where TCSC is really installed and frequency of the power system is also 60 Hz. Simulation response of this equation written above is as given below:

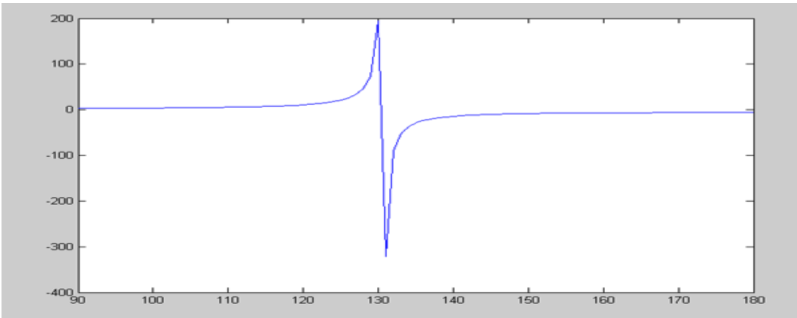

Fig. 9 Firing angle verses reactance curve at L=6.85mH,C=174uF

If parameters of the equation are varied by a small value then the response curve gets disturbed and we could get more then one resonance points in the given firing angle range as shown below the point just after 90 degree there is a small kink showing some effect on the reactance if its parameters are disturbed.

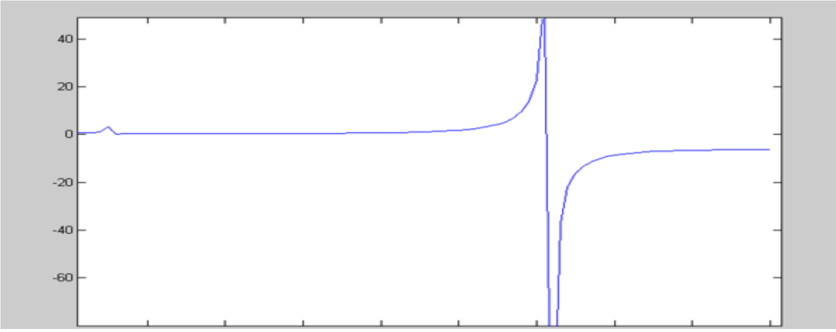

Fig. 10 Firing angle verses reactance curve at L=6.8 C=174uF

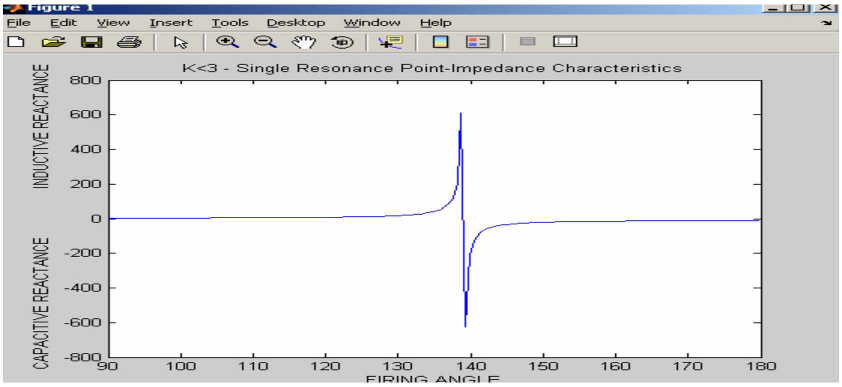

Fig 11. Frequency Response at C=247.5 UFAND L=7.6mH

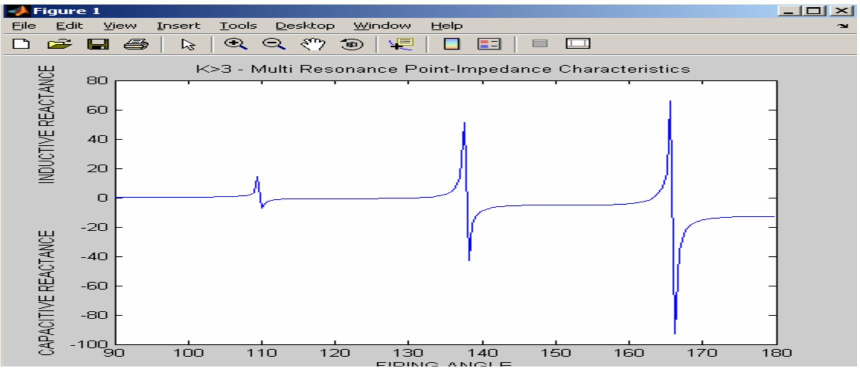

Fig 12. Frequency Response at C=247.5UFAND L=1mH

Here in mat lab various blocks like voltage generator, series RLC circuit block, series RLC load branch block, current meter, voltage meter, scopes to view various signals, power meter block, thyristor block, Demultiplexer bus block are all interconnected to make an open loop TCSC Simulink model which is connected in series with the single source transmission line. For analyzing the thyristor, capacitor current and capacitor voltage, firing pulses are given to the circuit through pulse generator. Fig. 12 shows Thyristor current, Thyristor voltage, Thyristor output power and output voltage and to analyze the circuit in capacitive mode and inductive mode of TCSC, the pulse to be applied are in region of vernier capacitive which lies in $160^{o}$to 180^{o} and 90^{o} to 135^{o} i.e. the delay of 8.8ms to 10ms and 5ms to 7.5ms respectively This gives the analysis of waveform of capacitor voltage, line current, thyristor current and capacitor current of TCSC as shown in fig..The objective of investigating the dynamic stability of a power system with TCSC is to assure that TCSC can operate in a steady-state vernier operation mode. Due to the nonlinear characteristics of TCSC in vernier operation mode, the waveforms of TCSC system such as line current and capacitor voltage etc. distort significantly When either of the anti-polarity parallel thyristors conducts, the TCSC is said to be in the ON state. When both thyristors are turned off, the TCR current remains zero and the system is said to be in the OFF state. It has been concluded that at if alpha=117^{o} for positive waveform then there should be a difference or phase delay of 180^{o} for the negative waveform then only thyristor will fire at the same interval and hence the conduction time will be equal and output will be symmetrical. In practical applications, a lookup table method is used to describe this relationship. When the desired value of reactance Xtcsc is determined from the power system state, the required value of the firing angle is obtained from the table which shows the reactance step response of the TCSC to demanded change in from 1 p.u. to 2.1p.u., corresponding to a change in firing angle from to 175^o to151^o. It can be seen from scope output that more than 200 ms is needed for the fundamental frequency reactance to reach its new steady-state value. Simulation results of the TCSC model with pulsar having phase delay of 5.2ms=91.2^o will give the results as shown below. As shown below it takes almost 200ms or we can say about five complete cycles for fundamental frequency to reach its new steady state value.

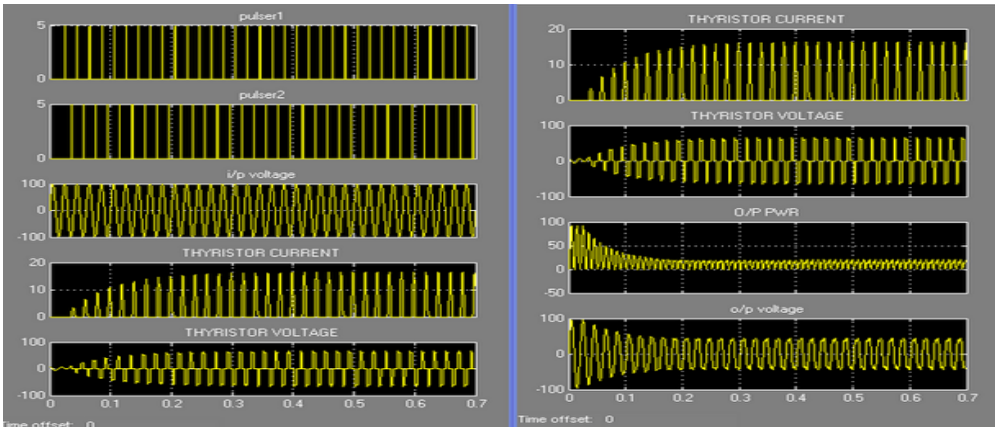

Fig. 13 shows Thyristor current, Thyristor voltage, Thyristor output power and output voltage.

5.3 Simulink Model of TCSC:

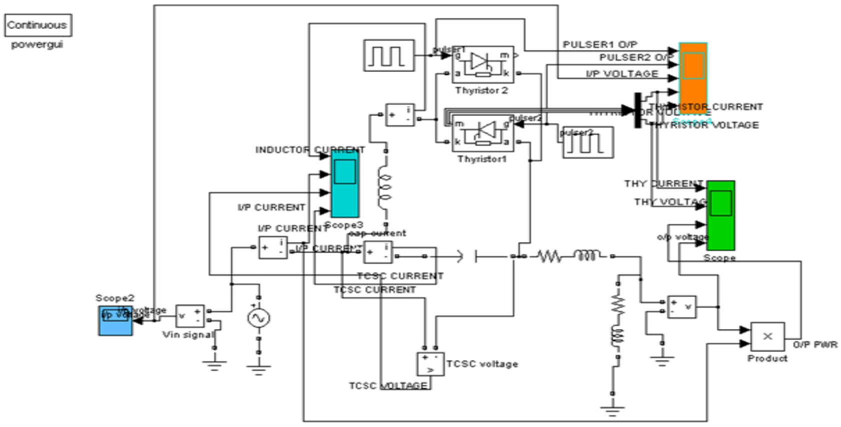

Fig. 14 shows the Simulink Model of TCSC

5.4 Simulation Results of TCSC:

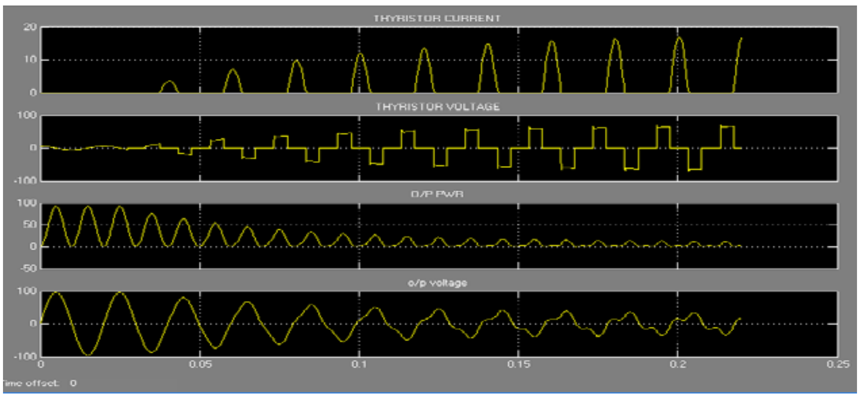

Fig. 15 Simulation results of Thyristor current, Thyristor voltage, o/p power, o/p voltage when Delay of pulser1=0.0275s and delay of pulser2=0.0375s i.e. α=135^o and 315^o

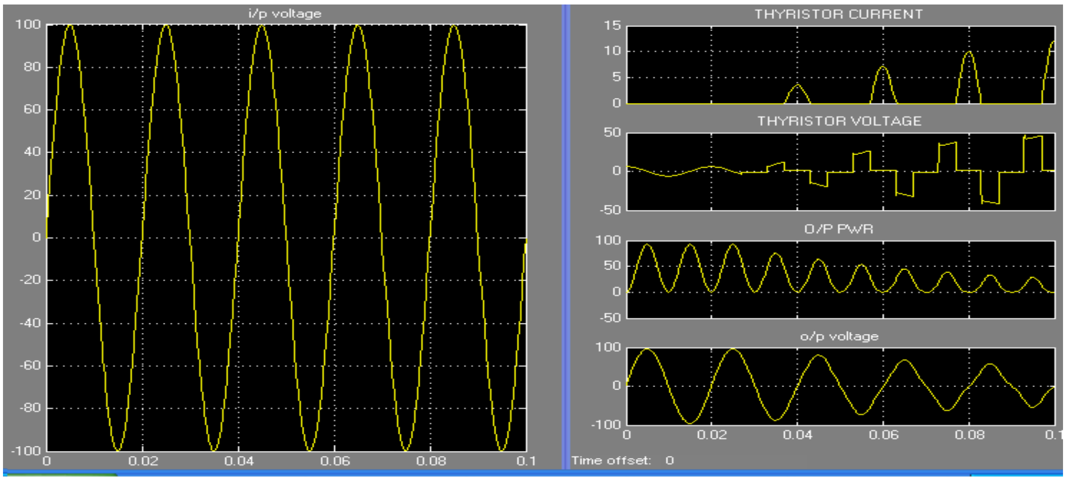

Fig. 16 Simulation results shows of output Thyristor current, Thyristor voltage, o/p power, o/p voltage when Delay of pulser1=0.0175s and delay of pulser2=0.0275s i.e. $\alpha=125^o$ and 300^o

Transient response of TCSC is analyzed by increasing the simulation time. The response got stable after few seconds of the firing as shown above.

VI. CONCLUSION AND FUTURE SCOPE OF WORK

This paper is to analyze the actual behavior of the TCSC FACTS device. The steps followed to develop a lab scale single-phase TCSC is exposed, as well as performance tests that corroborate the proper functioning of the device. Thyristors are operated in the bypass mode during the fault. It is assumed that only the open loop impedance control mode is embedded in the TCSC control system and as a result, the firing angle from the lookup table could be taken as one of the inputs to the TCSC's controller part to vary its reactance to get the desired results. The equations to determine the line impedance to the fault are derived based on the TCSC bypass mode assumption during the fault. It is worth noting that not only during normal operation the capacitive reactance is not fixed and depends on the operating point and control strategy, but also the TCSC does not always transit to bypass mode for all the faults. For example, when the fault current is large, it will operate between the blocked and bypass modes to protect the capacitor and MOV. On the other hand, when the fault current is small for the high impedance ground fault, the MOV does not conduct and the TCSC branch will remain in the vernier mode operation. Different modes taken by TCSC control system during the fault would change the impedance of the line significantly. Meanwhile, the transition from normal operation to other possible modes does not occur instantly. The transition time is considerable in the time frame of the protection of Transmission lines. During simulation it was observed that it took almost 200ms for a system to get stable in its new mode. Hence, ignoring the dynamics of TCSC and modeling it as constant impedance during the fault normally leads to erroneous results that are not in conformity with real systems. For a comprehensive analysis of the impact of TCSC on protection of the lines, both aspects of the TCSC operation: (i) dynamics of TCSC; and (ii) contribution of the TCSC to power system operation and control along with its hardware designing is done on a small scale laboratory model. The objective of this project is to analyze and investigate the impact of series compensation using TCSC on the performance of impedance-based power system model under normal operation and fault conditions at different firing delays taken from the look up table. In this project, TCSC is modeled with detailed characteristics such as firing angle control and overvoltage protection by Metal Oxide Varistor (MOV); and the power system model is designed with line resistance and inductance with travelling wave transmission line models having line inductance and resistance, inductive load of value 4_{ohms} and 14_{mH} respectively and TCSC (Thyristor controlled inductor in parallel with capacitor). For a complete analysis, the simulation is done by PSpice/MATLAB first and the results are then verified by small scale microcontroller based power model. Finally, required TCSC design requirements are tabulated and clearly depending upon the firing angle of thyristor, reactance range, and voltage across the TCSC is varied as well as output voltage is varied. These sequences form the duty cycles that all of the components of the TCSC bank should be designed to withstand. The duty cycle should be consistent with the manner in which the surrounding power system will be operated. The programmer defines duty cycles for various operational modes. It means that there is no unique behavior of the TCSC's in the compensated lines. Depending on the firing angle TCSC transits from the existing mode to one of the possible modes based on its control system strategy after 200ms. In this section, different cases are discussed. The results are in good consistency with each other and indicate the necessity of modeling and analyzing the TCSC control strategy. It has been concluded that with the advent of thyristor control the concept of series compensation has been widened and its usefulness has been increased further.

Similarly in future implementation could be of a three-phase device as well as the evolution to series compensation may be by voltage sourced converters it can also be implemented with Neuro and fuzzy logic or some different strategies may now be developed to control the reactance of the TCSC through firing angle adjustments.

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