Certificate

I hereby certify that the work which is being presented in the thesis entitled, **"Modelling and Analysis of TCSC Application to Transmission System"**, in partial fulfillment of the requirements for the award of degree of Master of Engineering in *Power Systems & Electric Drives* submitted in Electrical & Instrumentation Engineering Department of Thapar University, Patiala, is an authentic record of my own work carried out under the supervision of **Ms. Manbir kaur** (AP, EIED) and **Mr.Virender Kumar** (AE,HPSEB). The matter presented in this thesis has not been submitted for the award of any other degree of this or any other university, except as reported in text and references.

Purnima
(Purnima Singh)
Regn.No.80641017

This is to certify that the above statement made by the candidate is correct and true to the best of my knowledge.

Manbir kaur
15/7/08
(Ms. Manbir Kaur)
Assistant Professor
Electrical & Instrumentation Engg. Department
Thapar University
Patiala

V Kumar
(Mr.Virender Kumar)
Assistant Engineer
(SLDC) HPSEB
TUTU, Shimla

Countersigned by

S. Ghosh
(Dr. Smarajit Ghosh)
Professor & Head
Electrical & Instrumentation Engg. Department
Thapar University
Patiala

RK Sharma
(Dr.R.K.Sharma)
Dean (Academic Affairs)
Thapar University,
Patiala.

Acknowledgement

First of all, I would like to thank Almighty for granting me perseverance. I wish to express my special thanks and deepest regards to my supervisor, **Ms. Manbir Kaur**, Assistant Professor, Electrical & Instrumentation Engineering Department for providing me invaluable guidance, suggestions, and support which have helped me to submit my thesis in time.

This work would not have been possible without the encouragement, guidance and constant moral support of my co-supervisor **Mr. Virender Kumar**, Assistant Engineer, HPSEB. He has always been there for me at times of difficulties and constant source of inspiration.

I take this opportunity to express my gratitude and thanks to **Dr. Smarajit Ghosh**, Professor and Head, Electrical & Instrumentation Engineering Department for his valuable suggestion and for providing me the opportunity to complete my work simultaneously.

I am most indebted to **Dr. Sanjay Kumar Jain**, Assistant Professor and PG coordinator (PSED), Electrical & Instrumentation Engineering Department**,** for his help, assistance and suggestions during my work.

I would also like to thank all the faculty and staff members of Electrical & Instrumentation Engineering Department for providing me all the support required for the completion of this work.

My thanks to all my classmates for their encouragement and help.

Purnima Singh

Abstract

The need for more efficient electricity systems management has given rise to innovative technologies in power generation and transmission. Flexible AC Transmission Systems (FACTS) is one of such technologies that respond to these needs. It significantly alters the way transmission systems are developed and controlled together with improvement in asset utilization, system flexibility and system performance. Different types of FACTS devices are being used now-a-days. Thyristor Controlled Series Compensator is one of the series compensating FACTS devices.

Thyristor Controlled Series Compensator (TCSC) consists of a series compensating capacitor shunted by a Thyristor Controlled Reactor (TCR). The basic idea behind the TCSC scheme is to provide continuously variable impedance by means of partially canceling the effective compensating capacitance by the TCR. Transmission lines compensation by means of TCSC can be used to increase the power transfer capability, improve transient stability, reduce transmission losses and dampen power system oscillations.

In this thesis work device modelling of TCSC has been carried out along with development of transmission system using MATLAB7.5/Simulink. Then this device has been applied to the transmission network using Power System blockset. The response of transmission systems has been studied for various types of faults with and without TCSC, thus analyzing the impact of TCSC on the performance of transmission line in terms of various parameters, under consideration. Impact of variation of degree of compensation on power flow has also been studied which shows that for a fixed angular difference, with the increase in degree of compensation power flow increases.

Table of Contents

List of Figures

Chapter 1
Introduction

1.1 Overview

World's most of the electric power supply systems are widely interconnected. These interconnections are needed because, apart from delivery, the purpose of transmission network is pool power plants and load centers in order to minimize the total power generation capacity and fuel cost. As the power transfers grow, the power system becomes increasingly more and more complex to operate and the system can become less secure for riding through the major outages. It may lead to large power flows with inadequate control, excessive reactive power in various parts of the system, large dynamic swings between different parts of the system, and thus the full potential of transmission interconnections cannot be utilized.

With the increased loading of long transmission lines, the problem of transient stability after a major fault can become a transmission power-limiting factor. Similarly other stability problems may be there due to momentary system conditions. The power system should adapt to momentary system conditions i.e. power system should be flexible. Therefore the idea of the so-called Flexible AC Transmission System (FACTS) was introduced in the 1980s by Electric Power Research Institute (EPRI).

The FACTS is a concept based on power-electronic controllers, which enhance the value of transmission networks by increasing the use of their capacity. As these controllers operate very fast, they enlarge the safe operating limits of a transmission system without risking stability.

Thyristor Controlled Series Capacitor (TCSC) is one of the important members of FACTS family that is increasingly being applied to long transmission lines by the utility in modern power systems. It can have various applications concerned with operation and control of power system, such as scheduling power flow; decreasing unsymmetrical components; limiting short circuit currents; mitigating sub-synchronous resonance (SSR); damping the power oscillations and enhancing transient stability.

Power transmission of grids can always be improved by upgrading or adding of new transmission circuits. This may not be practicable in reality for various reasons. Thyristor- Controlled Series Capacitors offer a strong alternative for optimization of transmission over power links, existing as well as new, by means of increased dynamic stability, power oscillation damping as well as optimized load flow between parallel circuits. [6]

1.2 Literature Review

Several references in technical literature can be found on development of TCSC steady state, dynamic and linearized models.

Vithayathil (1986) proposed a method of “rapid adjustments of network impedance” consisting of the series compensating capacitor shunted by a Thyristor Controlled Reactor. In a practical TCSC implementation, several such basic compensators may be connected in series to obtain the desired voltage rating and operating characteristics.[9]

D J Mc Donald, *et al.* (1994) analyzed a newly developed thyristor for Thyristor Controlled Series Compensation (TCSC). Mathematical modelling based on semiconductor physics and a thorough high current test series were carried out for unusually severe requirements. Results collaborate the accuracy of the model and demonstrate that the thyrisor exceeds the thermal di/dt requirements of the intended insulation. [10]

S Nayati, *et al.* (1994) carried out the simulator tests of TCSC.[13] The structure of control system and the components of the real-time simulator used for the tests were presented. Test results showed performance for switching transient ac faults, power swing damping events and subsynchronous resonance condition. In the same year, Scott G. Helbing and G.G.Karady developed mathematical equations describing the voltages and currents through the capacitor, inductor, and thyristors, analysed, and later verified using the EMTP analysis program. [6]

an EMTP simulation study of the SSR mitigation effect of TCSC operated in vernier mode, based on a simplified model of the North-Western American Power

System(NWAPS).[28] It was shown that TCSC vernier operation provides significant mitigation of SSR in some cases. John J. Paserba, *et.al* [1995] developed a model for TCSC applicable for typical transient and oscillatory stability studies was presented.[17] It included a discussion on relevant information to extend the modelling detail of TCSC for the use with long-term stability analysis.

Thyristor Controlled Series Compensator has dynamic characteristics that differ drastically from conventional series capacitors especially at frequencies outside the operating frequency range. Hisham A. Othman and Lennavt Angquist [1996] presented an accurate analytical model of TCSC which incorporates the thyristor triggering logic, the synchronization system and higher level control loops such as power oscillation damping loops. [14]

Conventional subsynchronous resonance (SSR) study methods such as eigen analysis require a linear dynamic model of each device. FACTs devices like Thyristor Controlled Series Capacitors (TCSC) are difficult to model due to their nonlinear switching behaviour. Brain K.perkins and M.R.Iravani (1997) proposed an approach which exploits the fact that the thyristor controlled reactor associated with the TCSC is switched in a regular pattern. A linear model is obtained by linearizing the half-period map associated with sampling of the TCSC capacitor voltage twice every cycle. Such an approach models the passive damping which varies with the steady-state conduction angle of the TCSC. It is shown that passive damping has a significant effect on the model damping of the torsional modes associated with subsynchronous resonance phenomena. [22]

Zhao Xuequiang(1998) developed mathematical equations of TCSC circuit for any period of time (including the whole transient process from firing the thyristors to a steady state) and for the steady state relating to the voltages and currents of the capacitor, inductor, and thyristor components by using Laplace transformation. Further the accurate mathematical relationship between the fundamental impedance of TCSC and the firing angle of the thyristors were derived by using Fourier analysis. The validity of the mathematical analysis was demonstrated by using the Electro- Magnetic Transient Program (EMTP) digital simulations. [26]

T.Venegas and CR Fuerte-Esquivel (2000) , carried out a steady state mathematical modelling in phase domain considering the TCSC physical structure. A polyphase power flow program based on Newton algorithm was developed in order to implement the proposed model. Analysis of TCSC performance was carried out in both balanced and unbalanced power network operation condition. This allows, quantifying many economical and technical benefits of this technology as well as, examining the applicability and functional specifications of the controller. [25]

A Thyristor Controlled Series Capacitor (TCSC) developed by Bharat Heavy Electricals Limited (BHEL) using Real Time Digital Simulator (RTDS) has been discussed in reference [2]. The TCSC controller was developed for the Kanpur-Ballabhgarh 400kV single circuit ac transmission line located in North India. It was designed to perform important functions like impedance control, current control in the line and damping of power swing oscillation caused by system disturbances.

Dragan Joveie and G.N.Pillai presented an analytical, linear, state space model of Thyristor controlled Series Compensator. [7] A simplified fundamental frequency model of TCSC was proposed and the model results were verified. Using frequency response of the nonlinear TCSC segment, a simplified nonlinear state space model was derived, the nonlinear element was linearized and linked with the ac network model and the TCSC controller model that also included a phase-locked-loop (PLL) model.

Arindam Ghosh, *et al.* modelled a TCSC by a variable capacitor, the value of which changes with the firing angle. The trajectory sensitivity analysis is applied to two different systems - an SMIB system and a 3-machine, 9-bus system. The predicted behaviour using the TSA is validated using PSCAD/EMTDC simulation and further, it is shown that it can be used in the determination of the optimal location for the placement of the TCSC in the 9-bus system. [3]

Mojtaba Khederzadeh and Tarlochan S.Sidhu (2006) presented a comprehensive analysis of the impact of TCSC on protection of transmission lines. [8] The analysis is done first analytically by using simple models then the power system and protective relays are simulated in detail by Real Time Digital Simulator (RTDS).

Sidhartha Panda and N.P. Padhy (2007) presented a systematic approach for modelling and simulation of a power system installed with a Power System Stabilizer (PSS) and a Flexible AC Transmission System (FACTS) based controller. [21] To avoid adverse interactions, PSS and FACTS based controller are simultaneously designed employing Genetic Algorithm(GA).This work has been further carried out in [20] by using different controller structures namely a lead-lag (LL) and a proportional-integral-derivative (PID). Two objective functions namely Integral Square Error (ISE) and Integral of Time multiplied Absolute value of the Error (ITAE) are considered for the optimization of proposed controller parameters. By minimizing the objective function, involving the deviations in oscillatory rotor angle, rotor speed and accelerating power of generator, stability performance of the system is improved.[26,27]

FACTS controller can play an important role in the power system security enhancement but due to high capital cost investment it is necessary to locate these controllers optimally in power system. J.G.Singh, *et al.* proposed a sensitivity based approach to decide optimal location of TCSC and UPFC .The factors have been derived in terms of change in a real power flow performance index with respect to their control parameters. Trajectory sensitivity analysis can also be used in determining the stable operating range of a TCSC. [23]

1.3 Objective

The objective of this thesis work is to model a TCSC along with development of transmission network and apply it to this electric transmission system to analyse its response. The device is connected the transmission system using MATLAB/Simulink Power System Bockset.

To demonstrate the performance of the controller under dynamic conditions in a power system, a three phase transmission system is used extensively with different types of faults occur on the system. [24] Simulation results show the significant improvement in damping of system oscillations with TCSC.

1.4 Organization of Thesis

Chapter 1 gives the overview of the current scenario of the power systems, literature review covering various researches conducted on TCSC modelling, control and analysis and hence the objective of the thesis.

Chapter 2 covers the brief introduction to various types of Flexible AC Transmission Systems based controllers.

Chapter 3 includes the basic operation of Thyristor Controlled Series Capacitor (TCSC), its different control modes of operation, applications and characteristics.

Chapter 4 presents the modelling of TCSC and its case study with application to a transmission network using MATLAB/Simulink Power Systems Blockset.

Chapter 5 shows the simulation results and analysis of the results.

Chapter 6 hence concludes and gives the future scope of the work.

Chapter 2

Flexible AC Transmission Systems

2.1 Definition of FACTS

FACTS devices are used for the dynamic control of voltage, impedance and phase angle of high voltage AC lines. FACTS devices provide strategic benefits for improved transmission system management through better utilization of existing transmission assets, increased transmission system reliability and availability, increased dynamic and transient grid stability, increased quality of supply for sensitive industries (e.g. computer chip manufacture), and enabling environmental benefits. Typically the construction period for a FACTS device is 12 to 18 months from contract signing through commissioning.

The FACTS technology is essential to alleviate some but not all of these difficulties by enabling utilities to get the maximum performance from their transmission facilities and enhance grid reliability. FACTS technology opens up new opportunities for controlling power and enhancing the usable capacity of present, as well as new and upgraded lines. The possibility that the current through a line can be controlled at a reasonable cost enables a large potential of increasing the capacity of existing lines with larger conductors, and use of one of the FACTS controller to enable corresponding power to flow through such lines under normal and contingency conditions. [5]

In the family of FACTS controllers, there are a few controllers, viz STATCOM, TCSC and UPFC that have potent application in India. Here STATCOM will have application right from distribution voltage to EHV level, while TCSC will be specifically applied in those locations where plain series compensation has not been dynamic enough to control the power flow or maintain the voltage profile and provide positive damping in the dynamic condition. In India, there are several locations where TCSC could be effectively applied, but its overall advantage has to be worked out after the system has been provided with first series compensation.

According to IEEE Definitions and Terms[5]

Flexibility of Electric Power Transmission is "*The ability to accommodate the changes in the electric transmission system or operating conditions while maintaining sufficient steady-state and transient margins.*"

Flexible AC Transmission System (FACTS) is *"Alternating current transmission systems incorporating power electronic-based and other static-controllers to enhance controllability and increase power transfer capability."*

FACTS Controller is "*A power electronic-based system and other static equipment that provide control of one or more AC transmission system parameters.*"

2.5 Benefits of FACTS devices

(i) Control of power flow as ordered. The use of control of the power flow may be to follow a contract, meet the utilities own needs, ensure optimum power flow, ride through emergency conditions, or a combination thereof.

(ii) Increasing the loading capability of lines to their thermal capabilities, including short term and seasonal.

(iii) Increasing the system security through raising the transient stability limit, limiting short circuit currents and overloads, managing cascading black outs and damping electromechanical oscillations of power systems and machines.

(iv) Providing secure tie line connections to neighboring utilities and regions thereby decreasing overall generation reserve requirements on both sides.

(v) Providing greater flexibility in siting new generation.

(vi) Upgradation of lines.

(vii) Reduction in reactive power flows, thus allowing the lines to carry more active power.

(viii) Reduction in loop flows.

(ix) Increasing utilization of lowest cost generation.

Because the voltage, current, impedance, real power, and reactive power are interrelated, each controller has multiple attributes of what they can do in terms of controlling the voltage, power flow, stability and so on.

2.3 FACTS devices

The FACTS devices have been mainly classified as follows:

i. Series Controllers
ii. Shunt Controllers
iii. Combined Series-Series Controllers
iv. Combined Series-Shunt Controllers

2.3.1 Series Controllers

The series controllers may be variable impedance, such as capacitor, reactor etc. or power electronics based variable source of main frequency, sub synchronous and the harmonic frequencies or a combination to serve the desired need. In principle, all series controllers inject voltage in series with the line. As long as the voltage is in phase quadrature with the line current, the series controller only supplies or consumes variable reactive power. Any other phase relationship will involve handling of real power as well.

The detailed classification of series controllers is as following:

(a) Thyristor Controlled Series Capacitor (TCSC)
(b) Static Synchronous Series Compensator (SSSC)
(c) Thyristor Switched Series Capacitor (TSSC)
(d) Thyristor Controlled Series Reactor (TCSR)
(e) Thyristor Switched Series Reactor (TSSR)

Various series connected controllers are discussed in brief as following:

Thyristor Controlled Series Capacitor (TCSC)

TCSC is a capacitive reactance compensator which consists of a series capacitor bank shunted by a thyristor-controlled reactor in order to provide a smoothly variable series capacitive reactance. The TCSC is based on thyristors without the gate turn-off capability. A variable reactor such as Thyristor Controlled Reactor (TCR) is connected across a series capacitor.

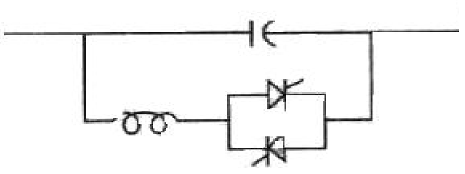


Fig 2.1 Schematic diagram of TCSC

Depending on the TCR firing angle, the capacitive impedance is varied. The TCSC may be single large unit or may consist of several equal or different-sized smaller capacitors in order to achieve a superior performance.

Static Synchronous Series Compensator (SSSC)

SSSC consists of a static synchronous generator, operated without an external electric energy source as a series compensator whose output voltage is in quadrature with, and controllable independently of, the line current for the purpose of increasing or decreasing the overall reactive voltage drop across the line and thereby controlling the transmitted electric power. The SSSC may include transiently rated energy storage or energy absorbing devices to enhance the dynamic behavior of the power system by additional temporary real power compensation, to increase or decrease momentarily, the overall real (resistive) voltage drop across the line.

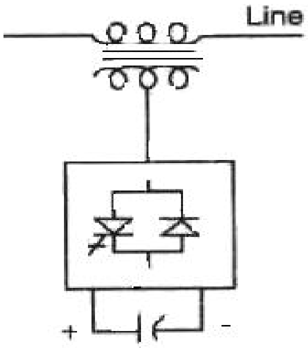


Fig 2.2 Schematic dia. of SSSC

Thyristor Switched Series Capacitor (TSSC)

TSSC is a capacitive reactance compensator which consists of a series capacitor bank shunted by a thyristor-switched reactor to provide a stepwise control of series capacitive reactance. Instead of continuous control of capacitive impedance, this approach of switching inductors at firing angle of 90 degrees or 180 degrees but without firing angle control could reduce cost and losses of the controller. It is reasonable to arrange one of the modules to have thyristor control, while others could be thyristor switched.

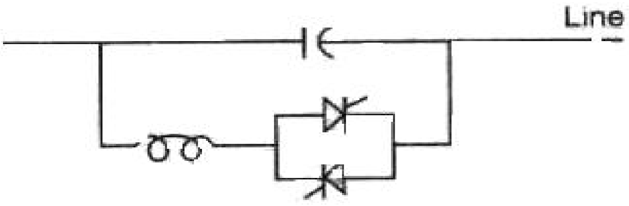


Fig 2.3 Schematic diagram of TSSC

Thyristor-Controlled Series Reactor (TCSR)

TCSR is an inductive reactance compensator which consists of a series reactor shunted by a thyristor TCSR is an inductive reactance compensator which consists of a series reactor shunted by a thyristor controlled reactor in order to provide a smoothly variable series inductive reactance. When the firing angle of the thyristor controlled reactor is 180 degrees, it stops conducting, and the uncontrolled reactor acts as a fault current limiter. As the angle decreases below 180 degrees, the net inductance decreases until firing angle of 90 degrees, when the net inductance is the parallel combination of the two reactors. As in TCSC, the TCSR may be a single large unit or several smaller series units.

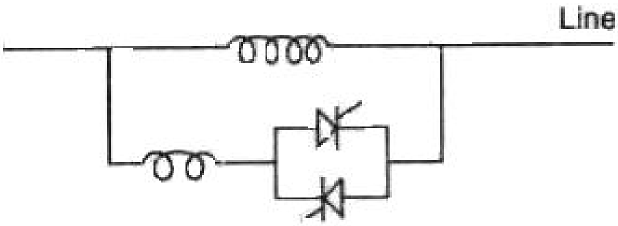


Fig 2.4 Schematic diagram of TCSR

Thyristor-Switched Series Reactor (TSSR)

TSSR is an inductive reactance compensator which consists of a series reactor shunted by a thyristor-controlled switched reactor in order to provide a stepwise control of series inductive reactance. This is complement of TCSR, but with thyristor switches fully on or fully off to achieve a combination of stepped series inductance.

2.3.2 Shunt Controllers

These may be variable impedance, variable source, or a combination of these. In principle, all shunt controllers inject current into the system at the point of connection. Even variable shunt impedance connected to the line voltage source causes a variable current flow and hence represents injection of current into the line. As long as the injected current is in phase quadrature with the line voltage; the shunt controller only supplies or consumes variable reactive power. Any other phase relationship will involve handling of real power as well. The classification of shunt controllers is as following:

(a) Static Var Compensator (SVC)

(b) Static Synchronous Compensator (STATCOM)

(c) Static Synchronous Generator (SSG)

(d) Thyristor Controlled Reactor (TCR)

(e) Thyristor Switched Reactor (TSR)

Various shunt connected controllers are discussed in brief as following:

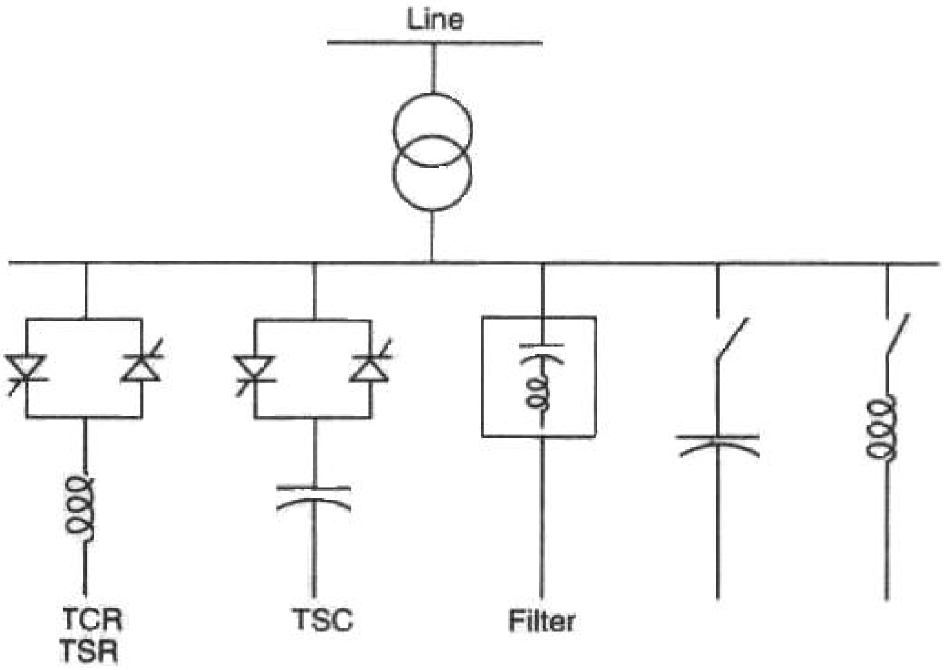


Fig 2.5 Schematic diagram of a line with Static VAR Compensator(SVC),Static VAR Generator(SVG),Static VAR System(SVS),Thyristor Controlled Reactor (TCR),Thyristor Switched Capacitor (TSC),and Thyristor Switched Reactor(TSR).[5]

Static Var Compensator (SVC)

SVC is “A shunt-connected static var generator or absorber whose output is adjusted to exchange capacitive or inductive current so as to maintain or control specific parameters of the electrical power system.”

Static Synchronous Compensator (STATCOM)

STATCOM is a static synchronous generator operated as a shunt connected static var compensator whose capacitive or inductive output current can be controlled independent of the a.c. system voltage. STATCOM is one of the key

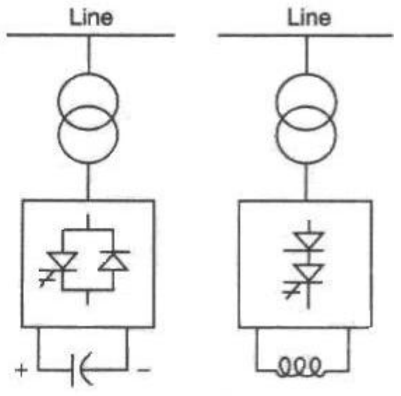


Fig 2.6 Schematic dia. of STATCOM

FACTS controllers. It may be based on a voltage- sourced or current-sourced converter. According to IEEE Static Synchronous Generator (SSG) is "A static self-commutated switching power converter supplied from an appropriate electric energy source and operated to produce a set of adjustable multiphase output voltages, which may be coupled to an a.c. power system for the purpose of exchanging independently controllable real and reactive power ."

Static Synchronous Generator (SSG)

SSG is a static self-commutated switching power converter supplied from an appropriate electric energy source and operated to produce a set of adjustable multiphase output voltages, which may be coupled to an ac power system for the purpose of exchanging independently controllable real and reactive power. SSG is a combination of STATCOM and any energy source to supply or absorb power.

Thyristor Controlled Reactor (TCR)

TCR is a subset of SVC, in which conduction time and hence, current in a shunt reactor is controlled by a thyristor based a.c. switch with firing angle control. TCR is "A shunt connected, thyristor controlled inductor whose effective reactance is varied in a continuous manner by partial conduction control of the thyristor valve." The schematic diagram of TCR is as shown in Fig.2.2 showing symbolic representations of its parts.

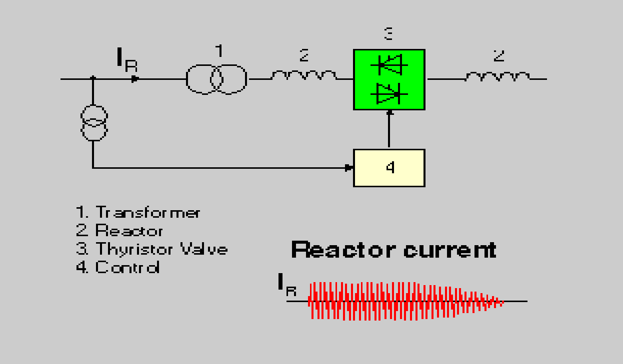


Fig. 2.7 Schematic diagram of TCR

Thyristor Switched Reactor (TSR)

TSR is also subset of SVC and is "A shunt-connected, thyristor-switched inductor whose effective reactance is varied in a stepwise manner by full or zero conduction operation of thyristor valve."

Thyristor Switched Capacitor (TSC)

TSR is also subset of SVC and is “A shunt-connected, thyristor-switched capacitor whose effective reactance is varied in a stepwise manner by full or zero conduction operation of thyristor valve.” The schematic diagram of TSC is as shown in Fig.2.3 showing symbolic representations of its parts.

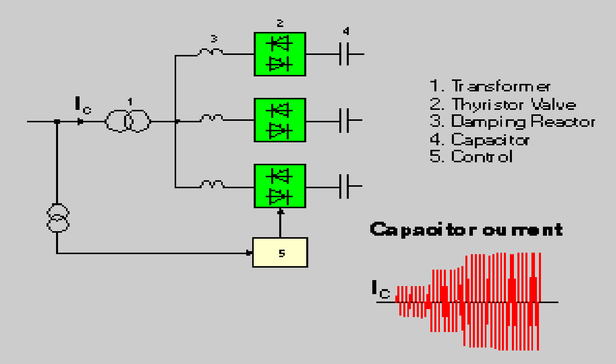


Fig.2.8 Schematic diagram of TSC

2.3.3 Combined Series -Series Controllers

This may be a combination of separate series controllers, which are controlled in a coordinated manner, in a multi-line transmission system. It may be otherwise a unified controller; in which series controllers provide independent series reactive compensation for each line but also transfer real power among the lines via the power link. The real power-transfer capability of the unified series-series controller, referred to as Interline Power Flow Controller, makes it possible to balance both the real and reactive power flow in the lines and thereby maximize the utilization of transmission system. Here the term “unified” means that the d.c. terminals of all controller converters are all connected together for real power transfer. Interline Power Flow Controller is the main combined series -series controller.

Interline Power Flow Controller (IPFC)

IPFC is recently introduced controller and is “The combination of two or more Static Synchronous Series Compensators which are coupled via a common d.c. link to facilitate bi-directional flow of real power between the a.c. terminals of the SSSC, and are controlled to provide independent reactive compensation for the adjustment of real power flow in each line and maintain the desired distribution of reactive power flow among the lines.”

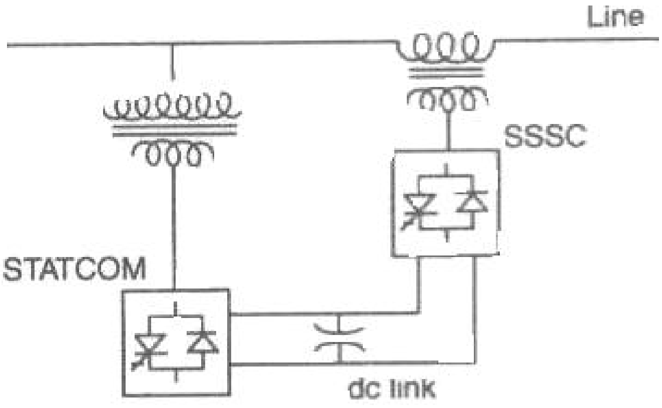


Fig 2.9 Schematic diagram of UPFC

2.3.4 Combined Series-Shunt Controllers

This may be a combination of separate shunt and series controllers, which are controlled in a coordinated manner or a Unified Power Flow Controller with series and shunt elements. In principle, combined shunt and series controllers inject current into the system with shunt part of controller and voltage with the series part of controller. Also, when the shunt and series controllers are unified; there can be a real power exchange between the series and shunt controllers via the power link.

The classification of series-shunt controllers is as following:

(a) Unified Power Flow Controller (UPFC)

(b) Thyristor Controlled Phase Shifting Transformer (TCPST)

(c) Interphase Power Controller (IPC)

Unified Power Flow Controller

Unified Power Flow Controller (UPFC) is “A combination of Static Synchronous Compensator (STATCOM) and a Static Synchronous Series Compensator (SSSC) which are coupled via a common d.c. link to allow bi-directional flow of real power between the series output terminals of the SSSC and the shunt output terminals of the STATCOM; and are controlled to provide concurrent real and reactive series line compensation without an external electric energy source.”

The UPFC, by means of angularly unconstrained voltage injection, is able to control, concurrently or selectively, the transmission line voltage, impedance and the angle or, alternatively, the real and reactive power flow in the line. The UPFC may also provide independently controllable shunt reactive compensation. The

UPFC is a device, which is capable of instantaneous control of three-system parameters transmission line impedance, phase angle and reactive power. From the conceptual viewpoint; the UPFC is a generalized synchronous voltage source; represented at the fundamental power system frequency by a voltage phasor, with controllable magnitude and angle in series with the transmission line.

The UPFC consists of two voltage-sourced converters, which operate from a common d.c. Circuit consisting of a storage capacitor. The UPFC could be described as consisting of a parallel and series branch. Each converter can independently generate or absorb reactive power. This arrangement enables free flow of active in either direction between the a.c. terminals of the two converters.

Chapter 3

Thyristor Controlled Series Capacitor

A capacitive reactance compensator, which consists of a series capacitor bank shunted by a thyristor-controlled reactor in order to provide a smoothly variable series capacitive reactance.

A variable reactor such as a Thyristor-controlled Reactor (TCR) is connected across a series capacitor. Considering an ideal case, when the TCR firing angle is 180 degrees, the rector becomes nonconducting and the series capacitor has its normal impedance. As the firing angle is advanced from 180 degrees to less than 180 degrees, the capacitive impedance increases. At the other end, when the TCR firing angle is 90 degrees, the reactor becomes fully conducting, and the total impedance becomes inductive, because the reactor impedance is designed to be much lower than the series capacitor impedance. With 90-degree firing angle, the TCSC helps in limiting fault current.

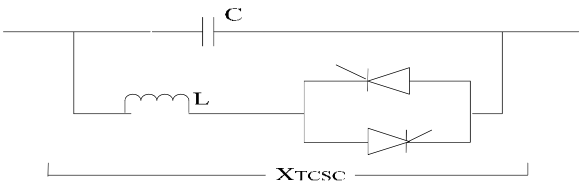


Fig 3.1 Schematic diagram of TCSC

The TCSC may be single, large unit, or may consist of several equal or different sized smaller capacitors in order to achieve a superior performance.

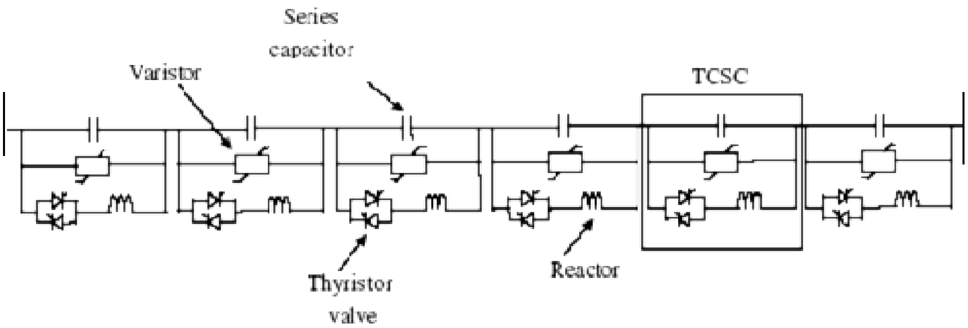


Fig.3.2 Number of TCSC units connected [1]

A basic TCSC module consists of a TCR in parallel with a fix capacitor. An actual TCSC comprises one or more modules. Fig.3.2 shows number of TCSC units connected.

3.1 Principle of Operation

A TCSC is a series-controlled capacitive reactance that can provide continues control of power on the ac line over a wide range. From the system viewpoint, the principle of variable-series compensation is simply to increase the fundamental frequency voltage across an fixed capacitor (FC) in a series-compensated line through appropriate variation of the firing angle, α. This enhanced voltage changes the effective value of the series-capacitive reactance.

A simple understanding of TCSC functioning can be obtained by analyzing the behavior of a variable inductor connected in parallel with FC.The equivalent impedance; Z_{eq} of this LC combination is expressed as

$$Z_{eq} = \left[\frac{-j}{\omega C}\right] \,||\, [j\omega L] = -j\left(\frac{1}{\left(\omega C - \left(\frac{1}{\omega L}\right)\right)}\right) \tag{3.1}$$

A variable inductor connected in shunt with a FC has been shown in Fig.3.3.

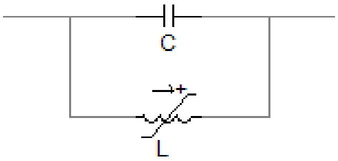


Fig.3.3 Equivalent diagram of TCSC

The impedance of FC alone, however, is given by $-j\left(\frac{1}{\omega C}\right)$

If $\omega C - \left(\frac{1}{\omega L}\right) > 0$ or, in other words, $\omega C - \left(\frac{1}{\omega L}\right)$, the reactance of the FC is less than that of the parallel-connected variable rector and that this combination provides a variable capacitive reactance are both implied. Moreover, this inductor increases the equivalent-capacitive reactance of the LC combination above that of the FC.

If $\omega C - \left(\frac{1}{\omega L}\right) = 0$, a resonance develops that results in an infinite- capacitive impedance – an obviously unacceptable condition. If however, $\omega C - \left(\frac{1}{\omega L}\right) < 0$, the LC combination provides inductance above the value of the fixed inductor. This situation corresponds to the inductive – vernier mode of the TCSC operation.

In the variable capacitive mode of the TCSC, as the inductive reactance of the variable inductor is increased, the equivalent capacitive reactance is gradually decreased. The minimum equivalent capacitive reactance is obtained for extremely large inductive reactance or when the variable inductor is open circuited, in which the value is equal to the reactance of the FC itself.

The behavior of TCSC is similar to that of the parallel LC combination. The difference is that the LC combination analysis is based on the presence of pure sinusoidal voltage and current in the circuit, whereas in TCSC, because of voltage and current in the FC and thyristor-controlled reactor (TCR) are not sinusoidal because of thyristor switchings.

3.2 Modes of TCSC operation

There are essentially three modes of TCSC operation;

1. **Bypassed-Thyristor Mode:** In this bypassed mode, the thyristors are made to fully conduct with a conduction angle of 180°.Gate pulses are applied as soon as the voltage across the thyristors reaches zero and becomes positive, resulting in a continuous flow of current through the thyristor valves. The TCSC module behaves like a parallel capacitor-inductor combination. However, the net current through the module is inductive, for the susceptance of the reactor is chosen to be greater than that of the capacitor.
2. **Blocked- Thyristor mode:** In this mode, also known as the waiting mode, the firing pulses to the thyristor valves are blocked. If the thyristors are conducting and a blocking command is given, the thyristors turn off as soon as the current through them reaches a zero crossing. The TCSC module is thus reduced to a fixed- series

capacitor, and the net TCSC reactance is capacitive .In this mode, the dc-offset voltages of the capacitors are monitored and quickly discharged using a dc-offset control without causing any harm to the transmission-system transformer.

3. **Partially conducting Thyristor, or Vernier, mode:** This mode allows the TCSC to behave either as a continuously controllable capacitive reactance or as a continuously controllable inductive reactance. It is achieved by varying the thyristor-pair firing angle in an appropriate range. However, a smooth transition from the capacitive to inductive mode is not permitted because of the resonant region between the two modes.

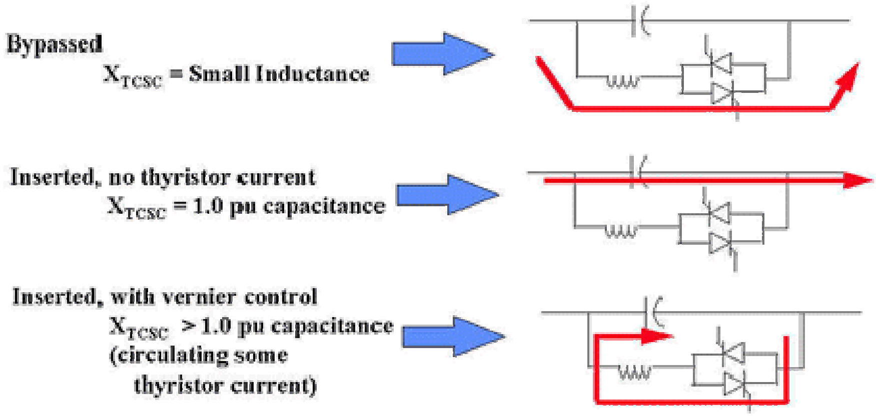


Fig 3.4 Modes of operation TCSC

A variant of this mode is the capacitive-vernier-control mode, in which the thyristors are fired when the capacitor current have opposite polarity. This condition causes a TCR current that has a direction opposite to that of the capacitor current, thereby resulting in a loop-current flow in the TCSC controller. The loop current increases the voltage across the fixed capacitor, effectively enhancing the equivalent-capacitive reactance and the series-compensation level for the same value of line current. To preclude resonance, the firing angle α of the forward-facing thyristor, as measured from the positive reaching a zero crossing of the capacitor voltage, is constrained in the range $\alpha_{min} \leq \alpha \leq 180°$. This constraint provides a continuous vernier control of the TCSC module reactance. The loop current increases as α is decreased from 180° to $\alpha_{min.}$ The maximum TCSC reactance permissible with $\alpha = \alpha_{min}$ is typically two-and-a-half to three times the capacitor reactance at fundamental frequency.

Another variant is the inductive-vernier mode, in which the TCSC can be operated by having a high level of thyristor conduction. In this mode, the direction of the circulating current is reversed and the controller presents net inductive impedance. [6]

The current in the reactor can be controlled from maximum to zero by the method of firing delay angle control. That is, the closure of the thyristor valve is delayed with respect to the peak of the applied voltage in each half cycle, and thus the duration of the current conduction intervals is controlled.

The steady state impedance of TCSC is that of parallel LC circuit, consisting of fixed capacitive impedance (X_C) and variable inductive impedance (X_L) that is

$$jX_{TCSC} = \frac{jX_L\,(-jX_C)}{jX_L + (-jX_C)}$$

$$X_{TCSC} = \frac{X_L X_C}{X_L - X_C} \tag{3.2}$$

where X_L is the reactance of the TCR (Thyristor Controlled Reactor) and X_C is the reactance of the fixed capacitor connected in parallel with it. The effective impedance of the TCSC terminals can be varied by controlling the firing angle α of the thyristor ($0 \leq \alpha \leq 90^o$), which results variation in X_L. During computation of $X_{L;}$ the inductive current is pulsating and not continuous.

3.3 Analysis of the TCSC Operation

The analysis of TCSC operation in the vernier mode is performed based on simplified TCSC circuit shown in Fig 3.5. Transmission line is assumed to be the independent-input variable and is modelled as an external current source, $i_s(t)$. It is further assumed that the line current is sinusoidal, as derived from actual measurements demonstrating that very few harmonics exist in the line current.

The current through the fixed-series capacitor, C, is expressed as

$$C\frac{dv_c}{dt} = i_s\,(t) - i_T(t).u \tag{3.3}$$

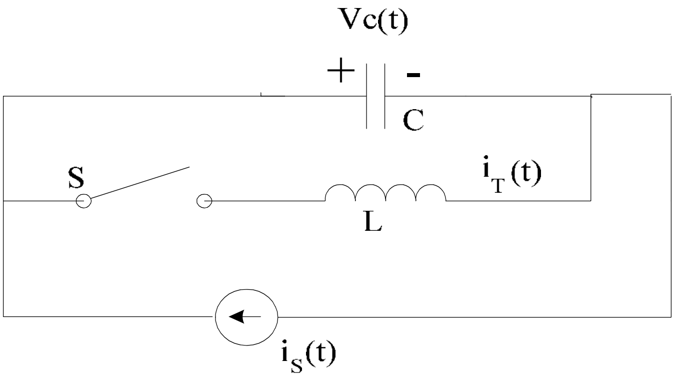


Fig 3.5 Simplified TCSC Circuit

The switching variable u = 1 when the thyristor valves are conducting, that is, when the switch S is closed. On the other hand, u = 0 when the thyristors are blocked, that is, when switch S is open. The thyristor-valve current, $i_T(t)$, is then described by

$$\frac{L\,di_T}{dt} = v_c.u \tag{3.4}$$

Let the line current, $i_s\,(t)$ be represented by

$$i_s(t) = I_m \cos \omega t \tag{3.5}$$

Equations (3.1) & (3.2) can be solved with the knowledge of the instants of switching. In equidistant firing-pulse control, for balanced TCSC operation, the thyristor are switched on twice in each cycle of line current at instants t_1 and t_3 , given by

$$t_1 = -\frac{\beta}{\omega} \tag{3.6}$$

$$t_3 = \frac{\pi - \beta}{\omega} \tag{3.7}$$

where β is the angle of advance . Or,

$$\beta = \pi - \alpha; \qquad 0<\beta < \beta_{max}$$

The firing angle α is generated using a reference signal that can be in phase with the capacitor voltage. The thyristor switch S turns off at the instants

$$t_2 = t_1 + \frac{\sigma}{\omega} \tag{3.8}$$

$$t_4 = t_3 + \frac{\sigma}{\omega} \tag{3.9}$$

where σ is the conduction angle, which is assumed to be the same in both the positive and the negative cycle of conduction. Also,

$$\sigma = 2\beta \tag{3.10}$$

Solving the TCSC equations (3.1) - (3.3) results in the steady state thyristor current, i_T as

$$i_T\ (t) = \frac{k^2}{k^2 - 2} I_m \left[\cos\omega t - \frac{\cos\beta}{\cos k\beta}\cos\omega_r t\right], \qquad -\beta \leq \omega t \leq \beta \tag{3.11}$$

where

$$\omega_r = \frac{1}{\sqrt{LC}}, \text{resonance frequency} \tag{3.12}$$

$$k = \frac{\omega_r}{\omega} = \sqrt{\frac{1}{\omega L} \cdot \frac{1}{\omega C}} = \sqrt{\frac{X_C}{X_L}} \tag{3.13}$$

and X_C is the nominal reactance of the fixed capacitor only. The fundamental component of capacitor voltage, v_c , about the axis $\omega t = 0$, is expressed as

$$V_{CF} = \frac{4}{\pi}\int_0^{\pi/2} v_c\,(t)\sin\omega t\ d(\omega t) \tag{3.14}$$

The equivalent TCSC reactance is computed as the ratio of V_{CF} to I_m :

$$X_{TCSC} = \frac{V_{CF}}{I_m} \tag{3.15}$$

therefore, the expression for the TCSC reactance can be written as

$$X_{TCSC} = X_C - \frac{X_C^2}{(X_C - X_L)}\left[\frac{2\beta + \sin 2\beta}{\pi}\right] + \frac{4X_C^2}{(X_C - X_L)}\frac{(\cos\beta)^2}{(k^2 - 1)}\left[\frac{k\tan k\beta - \tan\beta}{\pi}\right] \tag{3.16}$$

The variation of TCSC reactance with the change in firing angle is shown in Fig 3.6.

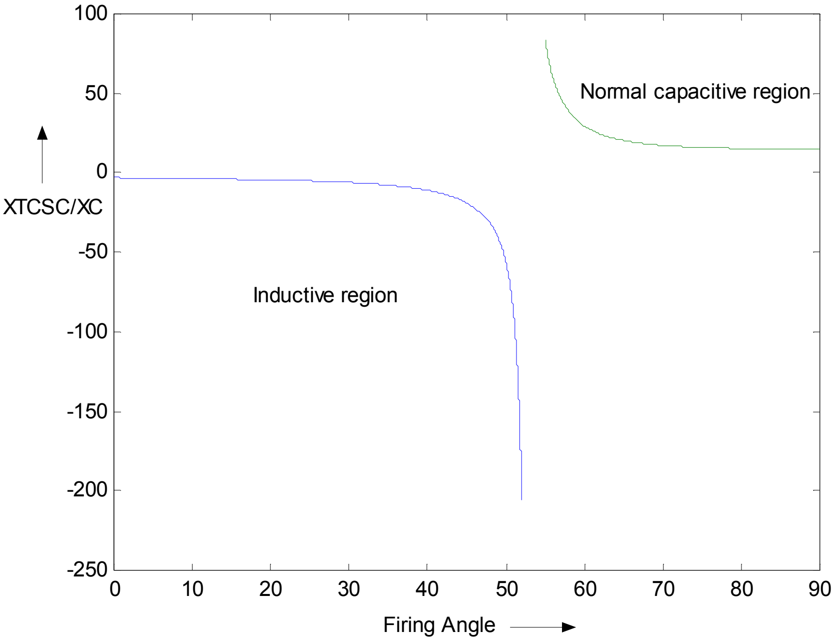


Fig.3.6 Variation of TCSC Reactance with Firing Angle

The fundamental impedance of the TCSC is similar to that of a parallel LC circuit with a variable inductance. Therefore, at some value of $\alpha = \alpha_{res}$, the value of effective inductive reactance equals the value of the fixed capacitive reactance connected in parallel with it; therefore results resonance.

When α is close to α_{res} (near resonance); The TCSC has high impedance and correspondingly voltage drop and internal current. Therefore operation into the area of resonance should be avoided; even if it is temporary.

The value of α for which resonance occurs is given by:

$$\alpha_{res} = \frac{\pi}{2} - \frac{(2n-1)\pi\omega}{2\omega_r}; n = 1,2,3 \tag{3.17}$$

Here ω_r would be chosen in such a manner that only one resonance point exists between ($0 < \alpha < 90^o$). [11]

3.4 TCSC Application

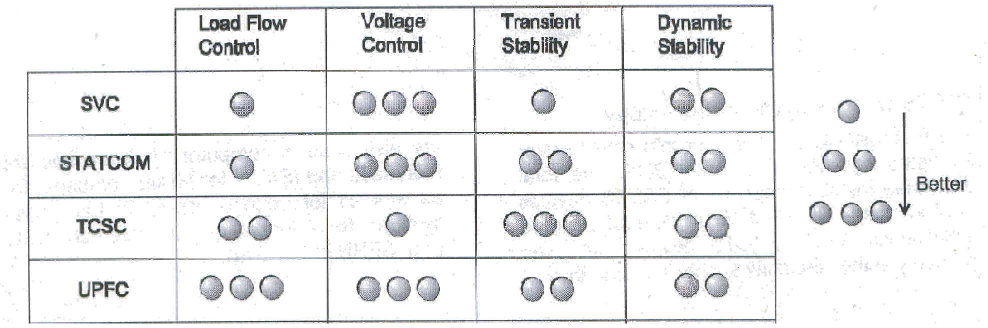
Series capacitors have been successfully utilized for many years in electric power networks. With series compensation, it is possible to increase the power transfer capability of power transmission systems at a favorable investment cost and with a short installation time compared to the building of additional lines. This is due to the inherent ability of series capacitors to achieve:

(i) Increased dynamic stability of power transmission systems

(ii) Improved voltage regulation and reactive power balance

(iii) Improved load between parallel lines

With the advent of Thyristor Control, the concept of series compensation has been broadened and its usefulness has been increased further. [29] The performance comparison of FACTS devices is as shown in Fig. 3.7



	Load Flow Control	Voltage Control	Transient Stability	Dynamic Stability
SVC	●	●●●	●	●●
STATCOM	●	●●●	●●	●●
TCSC	●●	●	●●●	●●
UPFC	●●●	●●●	●●	●●

Fig. 3.7 Performance Comparison of FACTS Devices

Thyristor–controlled series compensation introduces a number of important new benefits in the application of series capacitors:

(a) Mitigation of SSR

(b) Damping of Power Oscillations

(c) Post-Contingency Stability Improvement and Load ability Control

(d) Power Flow Control

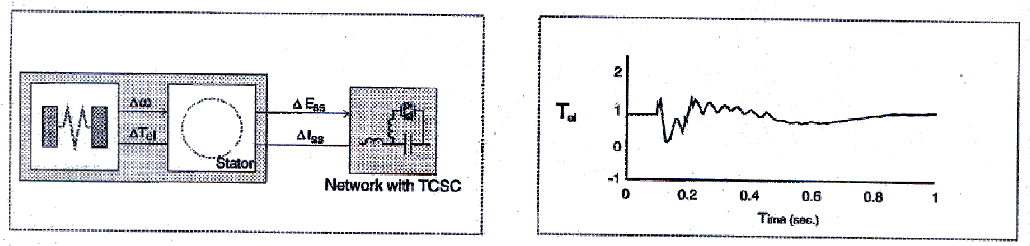
3.4.1 Applicable in New as well as Existing Systems

The benefits of Thyristor-controlled series compensation are by no means attainable only for installations starting from scratch. It is fully possible and practicable also to up rate existing series capacitors by making all or part of them thyristor controlled, thereby extending their impact and usefulness in the grid most considerably.

3.4.2 Mitigation of SSR

The phenomenon of sub synchronous resonance (SSR) has caused concern in the past in situations where the risk for occurrence of SSR has acted as an impediment to the use of series compensation in cases where the technology would otherwise have offered the best and the most economical solution.

With the advent of TCSC, no such concerns need be entertained any longer and series compensation can be used to its fullest merit. The SSR risk used to be linked to the utilization of series compensation of transmission lines fed by thermal generation, particularly in cases of high degrees of compensation, where analysis showed that the complementary series resonance frequency of the compensated line(s) coincided with some poorly damped torsional vibration frequency of the turbo-generator shaft, and could hence induce increased mechanical stresses in the shafts.



SSR mitigation: with TCSC, torsional vibrations die out due to elimination of the resonant behaviour for SSR frequencies in the electric system.

Fig. 3.8 Mitigation of SSR

TCSC acts to eliminate this risk for coinciding resonance frequencies by making the series capacitor(s) act inductive in the sub synchronous frequency band, thereby rendering the occurrence of series resonance in the transmission system for sub synchronous frequencies altogether impossible.

This inductive character of the TCSC is made possible by the use of a thyristor-controlled inductor in parallel with the series capacitor. This system is governed by an advanced, patented control scheme called Synchronous Voltage Reversal (SVR).

3.4.3 Damping of Power Oscillations

Oscillations of active power in power transmission systems may arise in corridors between generating area as a result of poor damping of the interconnection, particularly during heavy power transfer. Such oscillations can be excited by a number of reasons such as line faults or a sudden change of generator output.

The presence of active power oscillations acts to limit the power transmission capacity of interconnections between areas or regions or even countries. It is often possible to find remedy by building additional lines or upgrading existing lines, but this costs a lot of money and time. In some cases, it may also be possible to introduce Power System Stabilizers (PSS) on generators, but this does not always work, particularly not for inter-area power oscillations which tend to be a low frequency (typically 0.2 Hz to 0.7 Hz).[2]

In either case, TCSC is an attractive alternative to consider. It offers a cost-effective, robust power oscillation damper, insensitive to its location in the system and non-interacting with local oscillation modes. In a number of cases, it turns out to be the best practicable solution. Application of TCSC for the damping of power oscillations has been shown in Fig. 3.9 and Fig. 3.10

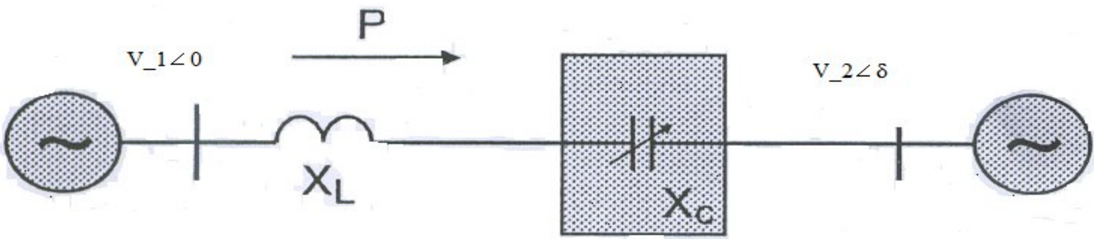
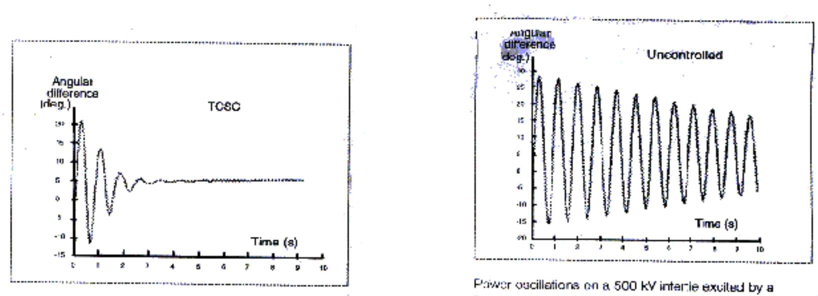


Fig. 3.8 Damping of Power Oscillations

Power transmission P over a series compensated line is governed by the expression

$$P = \frac{V_1 V_2}{X_L - X_C} \sin\partial \tag{3.17}$$

By proper control of the TCSC, the overall transfer reactance is modulated in time in such a way that the power oscillations are damped out.



Power oscillations damped out by means of TCSC.

Power oscillations on a 500 kV intertie excited by a temporary short circuit. Power flow through the intertie: 2000 MW.

Fig. 3.9 Damping of Power Oscillations

3.4.4 Post-Contingency Stability Improvement and Loadability Control

An important benefit of TCSC is its ability for quick boosting of its degree of compensation, making it very useful for improving the post-contingency behavior of networks. By means of this quality of the TCSC, the degree of compensation of a series capacitor can be increased temporarily following upon a network contingency, thereby adding to the dynamic stability of the network (voltage and angle) precisely when it is needed. By this means, the series capacitor can be lower rated for steady-state conditions, thereby keeping transmission losses smaller.

3.4.5 Power Flow Control

In interconnected power systems, the actual transfer of power from one region to another might take unintended routes depending on impedances of transmission lines connecting the areas. Controlled series compensation is a useful means for optimizing power flow between regions for varying loading and network configurations.

It becomes possible to control power flows in order to achieve a number of goals:

(i) Minimizing of system losses

(ii) Reduction of loop flows

(iii) Elimination of the line overloads

(iv) Optimizing of load sharing between parallel circuits

(v) Directing of power flows along contractual paths

3.5 Placement of the TCSC

The placement of FACTS controllers at appropriate locations is a critical issue. An optimally placed FACTS device require a lower rating to achieve the same control objective than if it were located elsewhere. At times, however, the FACTS controllers may need to be placed at nonoptimal locations to minimize costs, especially when land prices and environmental concerns become important. The following conditions generally apply when considering the placement of TCSCs:

(a) The TCSC must be located in lines that experience limiting power oscillations.

(b) The swings of voltages on each sides of TCSC must be within acceptable limits otherwise, multiple sites may be necessary.

(c) The control action of TCSC in one transmission path should not cause undue power swings in parallel path. If it does, then variable series compensation may become necessary in the parallel path.

(d) Sometimes, it may be advisable to distribute the control action among multiple TCSCs rather than confining the control action to one large-rating TCSC. Doing so ensures some system reliability if one of the TCSC fails. [11]

Chapter 4

Modelling of Thyristor Controlled Series Capacitor

4.1 Modelling of Power Circuit of TCSC

In the modeling of TCSC, thyristors are modelled as switches. The derivation of the mathematical model is based on the following assumptions:

(i) The switches are assumed to be ideal i.e. the turn-on and turn-off time is neglected.

(ii) The thyristors are assumed to be lossless.

(iii) The TCR resistance R_{tcr} is neglected.

The functional schematic diagram of TCSC is as shown in Fig. 4.1:

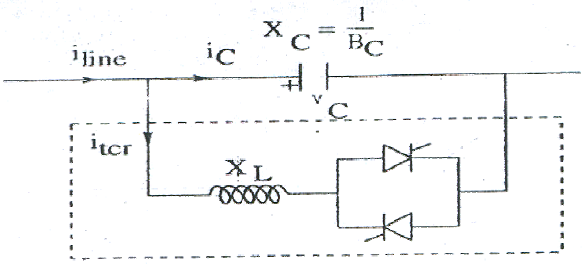


Fig.4.1 Schematic Diagram of TCSC

From the Fig 4.1 we can obtain the equation:

$$i_C = i_{line} - i_{tcr} \tag{4.1}$$

$$\text{and, } i_C = C\frac{dV_C}{dt} \tag{4.2}$$

$$\text{therefore,} \quad i_{line} - i_{tcr} = C\frac{dV_C}{dt} = \frac{1}{\omega X_C}.\frac{dV_C}{dt} \tag{4.3}$$

$$\text{also,} \quad L\frac{di_{tcr}}{dt} = U.V_C \tag{4.4}$$

$$\text{or,} \quad \frac{X_L}{\omega}\frac{di_{tcr}}{dt} = U.V_C \tag{4.5}$$

where U is called as the switching function and is defined as

U = 1 when thyristor is ON ($\omega t \geq \alpha$) in each half cycle.

= 0 when thyristor current goes to zero i.e. thyristor is OFF.

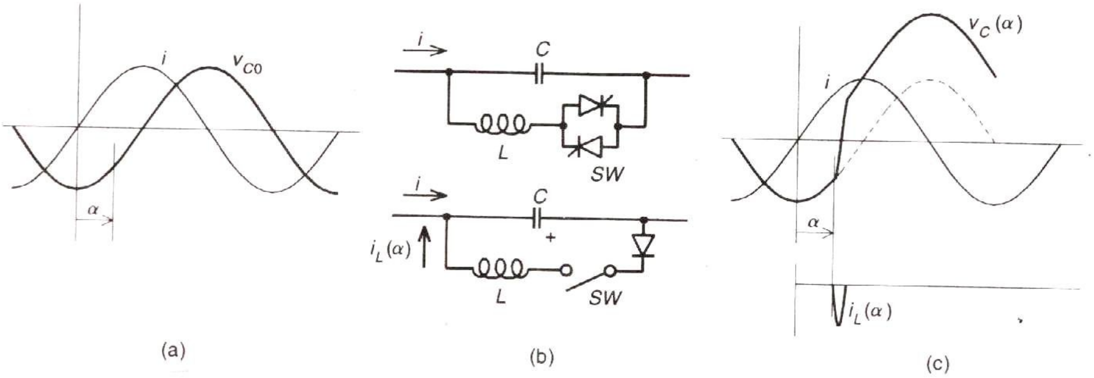
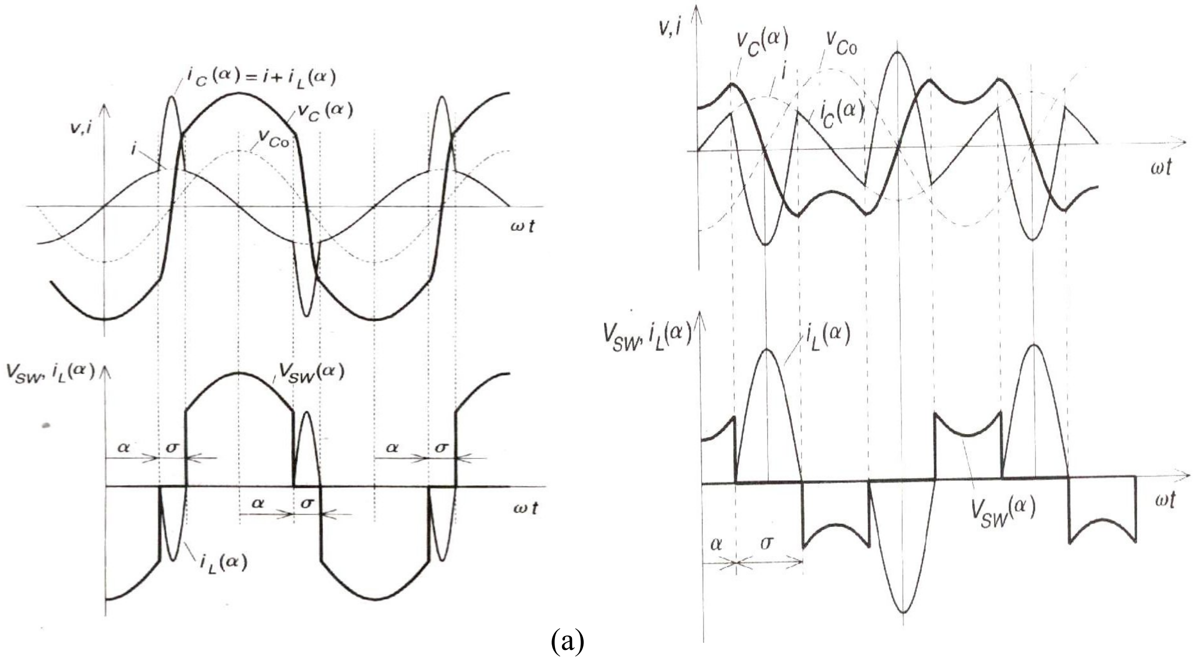


Fig.4.2 Capacitor Voltage reversal by TCR(a) line current and capacitor voltage, (b) equivalent circuit of TCSC at firing instant α, and (c) resulting capacitor voltage and related TCR current.[5]

The basic scheme of TCSC is shown in Fig.4.2(b). It is assumed that the thyristor valve *sw* is initially open and the line current *i* produces voltage v_{co} across the fixed series capacitor. As the TCR is turned on at α, measured from the negative peak of the capacitor voltage. At this instant,the capacitor voltage is negative, line current is positive and thus charging the capacitor in positive direction. Two substantially independent events will take place,one is that the line current, being a constant current current source, continues to (dis)charge the capacitor. The other is that the charge of the capacitor will be reversed during the resonant half-cycle of the LC circuit. The resonant charge reversal produces a dc offset for the next half cycle(positive) of the capacitor voltage, as shown in Fig.4.2(c). For the next half-cycle (negative), this dc offset can be reversed by maintaining the same α, and thus a voltage waveform symmetrical to the zero axis can be produced, as shown in Fig.4.2(c).

The control of TCSC depends upon the reversal of the capacitor voltage. The time duration of the voltage reversal is dependent on X_L/X_C ratio and on the line current. If $X_L << X_C$, then the reversal is almost instantaneous, and periodic voltage reversal produces a square wave across the capacitor that is added to the sine wave produced by the line current.



(a) (b)

Fig 4.3 Capacitor Voltage and current waveforms, together with TCR voltage and current waveforms characterisizing the TCSC in (a) capacitive and (b) inductive region under steady-state operation.[5]

The TCR reactor does not significantly alter the physical operation of the TCSC, provided that it is sufficiently small in relation to the impedance of the capacitor to facilitate the desired control of the series compensation. However, the design of the reactor for an actual compensator requires careful considerations to reconcile contradictory requirements. Small X_L is advantageous in providing well-defined charge reversal and control of the time period of the compensating voltage. A small reactor is also advantageous in facilitating an effective protective bypass for large surge current encountered during system faults. But, small X_L increases the magnitude of the current harmonics generated by the TCR and circulated through the series capacitor, and thus alo increases the magnitude of the capacitor voltage harmonics injected into the line. It also decreases the range of actual delay angle control and thus possibly makes the closed-loop parameters regulations more difficult. Also small X_L produces large short duration current pulses in the thyristor valve, necessitating the increase of its current rating and voltage rating. Generally the X_L/X_C ratio for practical TCSCs are 0.1 to 0.3 range, depending on the application requirements and constraints.

Consider an ideal case of instantaneous voltage reversal. Initially the TCR is gated on at $\alpha = \pi/2$, at which the TCR current is zero and the capacitor voltage is entirely due to the line current. To produce a dc offset, the periodically repeated gating in the second cycle is advanced by a small angle θ to $\pi - \theta$. This action produces a phase advance for the capacitor voltage with respect to the line current and, as a result, the capacitor absorbs energy from the line, charging it to a higher voltage. If this phase advance is maintained, the offset charge of the capacitor keeps increasing its charge at every half cycle without a theoretical limit. However, if the θ phase advance is negated, when the sufficient offset level of the capacitor voltage is reached, then the capacitor voltage at the desired magnitude is maintained by continuing periodic gating at line current zeroes.

4.2 Block Diagrams

The simple block diagrams used for the modeling of Thyristor Controlled Series Capacitor have been presented:

4.2.1 TCSC (main)

The block diagram in Fig. 4.4 shows that line current is first transformed to d-q frame of reference using d-q transformation. Then angle θ is calculated using expression (4.6) and the difference (alpha - θ) is used for the generation of firing pulses for phases a, b and c. The current i_{tcr} is found for phases a, b and c using expression (4.3) and also V_c is found using expression (4.5) derived from the schematic diagram of the TCSC.

Expressions used to calculate θ is:

$$\theta = \tan^{-1}\left[\frac{i_{lineD}}{i_{lineQ}}\right] \tag{4.6}$$

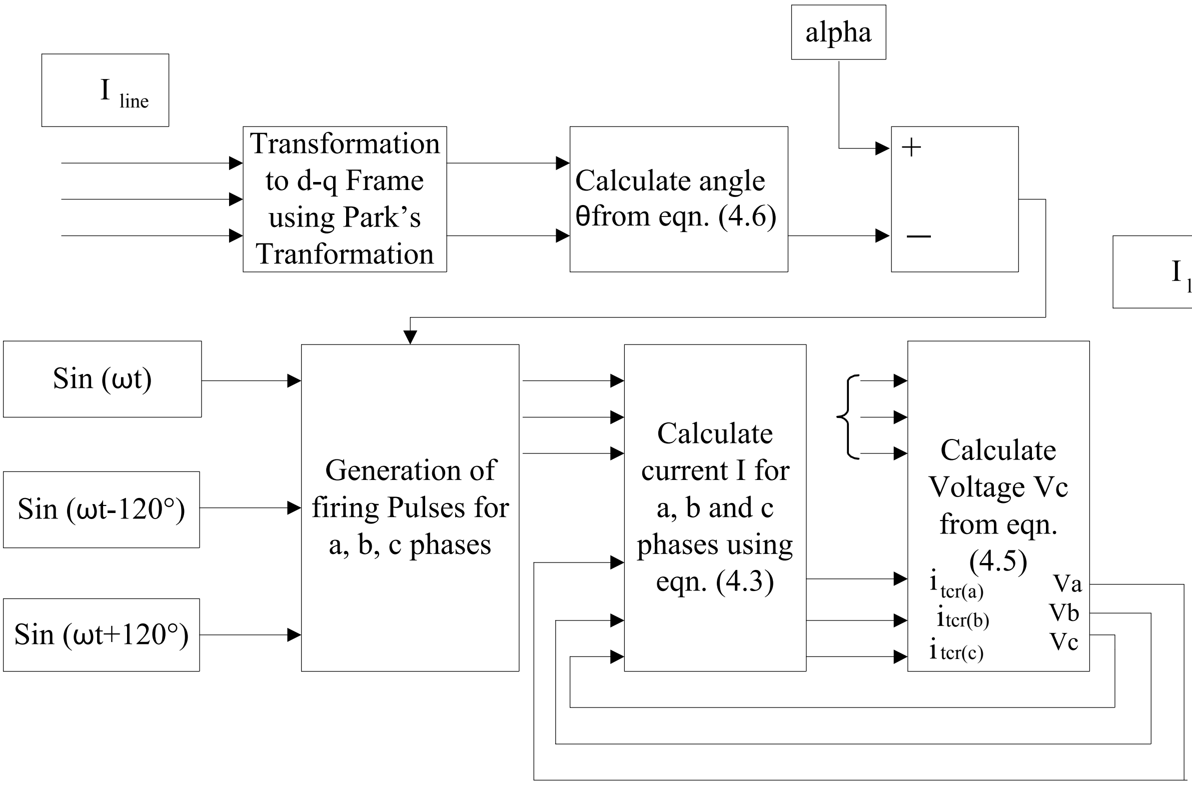


Fig. 4.4 Block Diagram of TCSC (Main)

4.2.2 Park's Transformation

In this block diagram of Park's transformation on performing certain transformations of variables, a great simplification in the mathematical description is obtained. This transformation defines a new set of variables such as currents, voltages, or flux linkages in terms of actual winding variables. The new quantities are obtained from the projection of the actual variables on three axes:

One along the direct axis of the rotor field winding, called the direct axis, a second, along the quadrature axis and third, on a stationary axis. The expressions of Park's Transformation used in the modelling are as following:

$$i_D = \sqrt{\frac{2}{3}}\left[i_a \cos\theta + i_b \cos(\theta - 2\pi/3) + i_c \cos(\theta + 2\pi/3)\right]$$

$$i_Q = \sqrt{\frac{2}{3}}\left[i_a \sin\theta + i_b \sin(\theta - 2\pi/3) + i_c \sin(\theta + 2\pi/3)\right]$$

$$s1 = \left[i_a \cos\theta + i_b \cos(\theta - 2\pi/3) + i_c \cos(\theta + 2\pi/3)\right]$$

$$s2 = \left[i_a \sin\theta + i_b \sin(\theta - 2\pi/3) + i_c \sin(\theta + 2\pi/3)\right] \qquad (4.7)$$

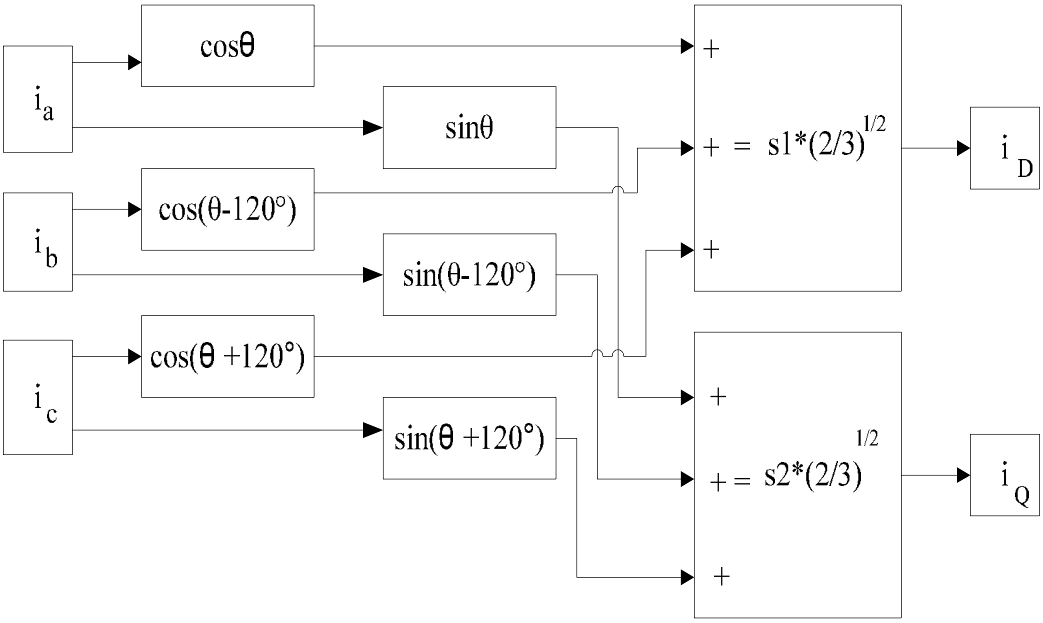


Fig. 4.5 Block Diagram of Park's Transformation

4.2.3 TCR Voltages and Currents

Using this block diagram the phase currents have been transformed to d-q frame of reference as shown in Fig4.5 and then outputs of Park's Transformation are used to construct a complex output from real and/or imaginary input. Difference between theta (θ) and alpha (α) is then fed to other subsystem as shown in Fig.4.6 used to find the currents and voltages V_a ,V_b, V_c, $I_{a(tcr)}$, $I_{b(tcr)}$, $I_{c(tcr)}$.

The block diagram shown in Fig. 4.6 is useful in finding the TCR currents and voltage on its implementation in SIMULINK toolbox in MATLAB. The TCR currents and capacitor voltages are obtained for the different values of the firing angles.

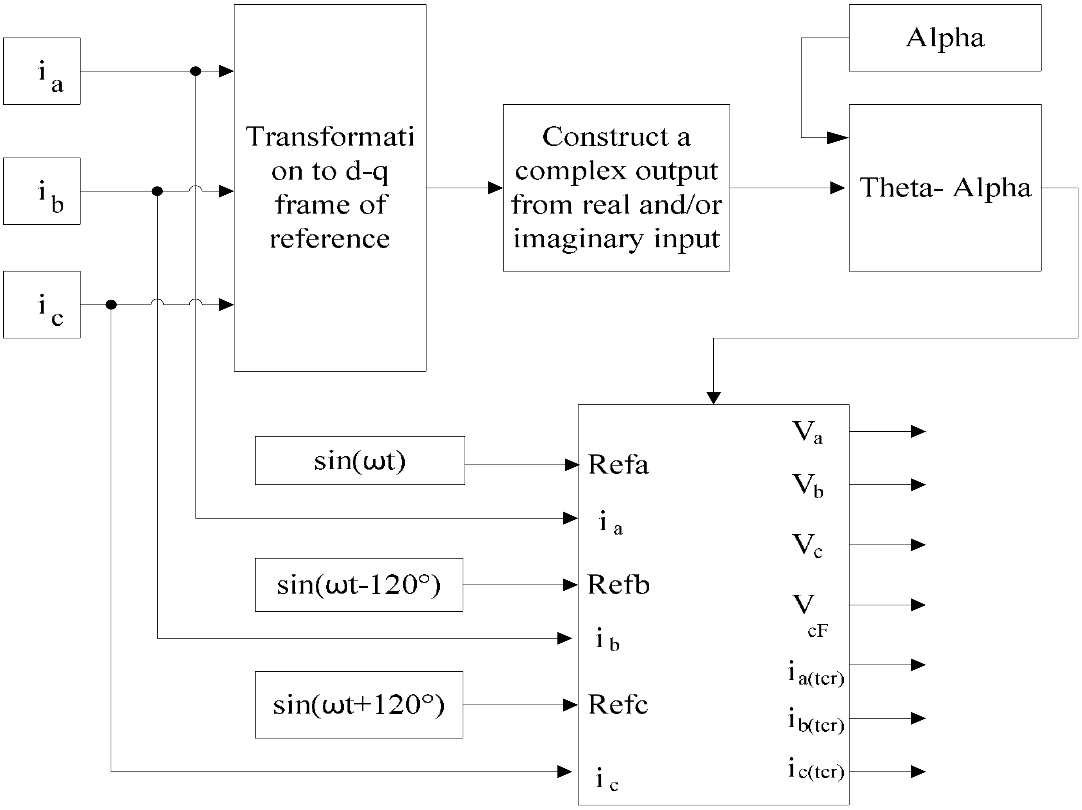


Fig. 4.6 Block Diagram for Voltages and TCR Currents

4.2.4 Generation of Firing Pulses

The line current is used as a reference for generating the firing pulses because the line current can be considered sinusoidal but not the capacitor voltage. The phasor I_{line} leads the reference phasor in d-q domain as an angle θ (eq.4.6).

Hence a firing angle of α_{ref} for phase 'a' is translated in d-q domain as $(\alpha_{ref} - \theta)$. Thus in d-q domain, firing pulses are generated with a reference wave (sinωt) (q-axis). To generate the firing pulses; the value from the instant of $(\alpha_{ref} - \theta)$ is compared with unity slope ramp generated from the zero-crossing of the reference wave. The firing pulses for phase 'a' are generated in d-q reference frame; as shown in the Fig. 4.7.

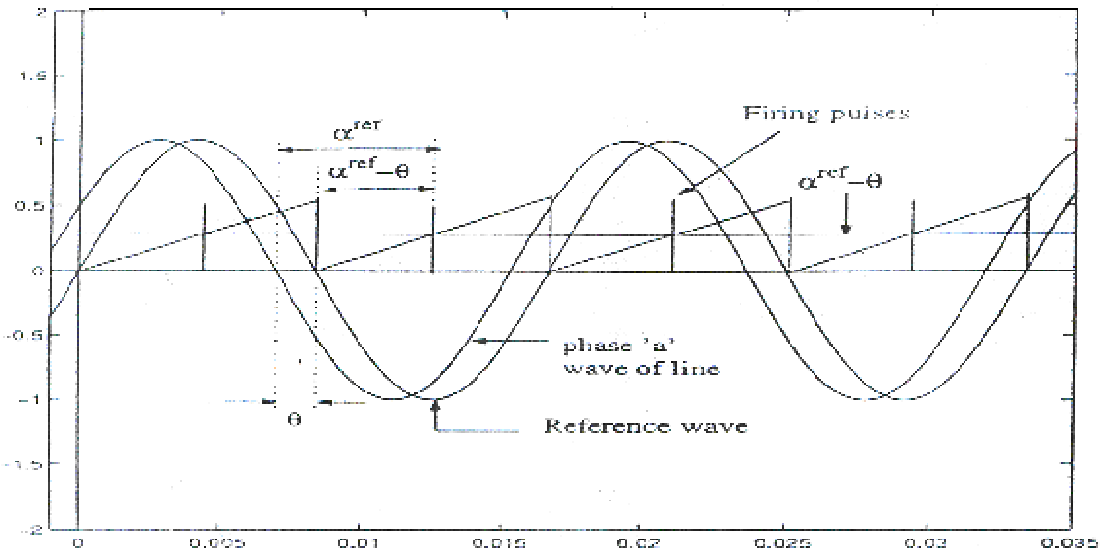


Fig. 4.7 Generation of Firing Pulses

In the same way the reference waves for phase ‘b’ and ‘c’ are phase shifted by 120 degrees and 240 degrees respectively with respect to reference wave of phase ‘a’.

4.2.5 Thyristor Controlled Reactor (TCR)

In Thyristor Controlled Reactor (TCR) a trigger is applied to switch2 and the output of this is applied to the SR-flip flop and other output to this flip-flop is the output of the subsystem (zcd1). SR flip flop has been used to implement the switching function U.

The output of SR-flip flop is then applied to other switch. Second input to this three-way switch is ground and third input is obtained on performing certain operation on i_c. The equations used to find out i_{tcr} and V_c are:

$$\frac{dV_C}{dt} = \omega X_C(i_{line} - i_{tcr}) \tag{4.8}$$

$$\frac{di_{tcr}}{dt} = \frac{\omega U V_C}{X_L} \tag{4.9}$$

The difference ($i_{line} - i_{tcr}$) is found out and is multiplied by gain K= ω * X_C which gives dV_C/dt & on integrating dV_C/dt, expression for V_C is obtained.

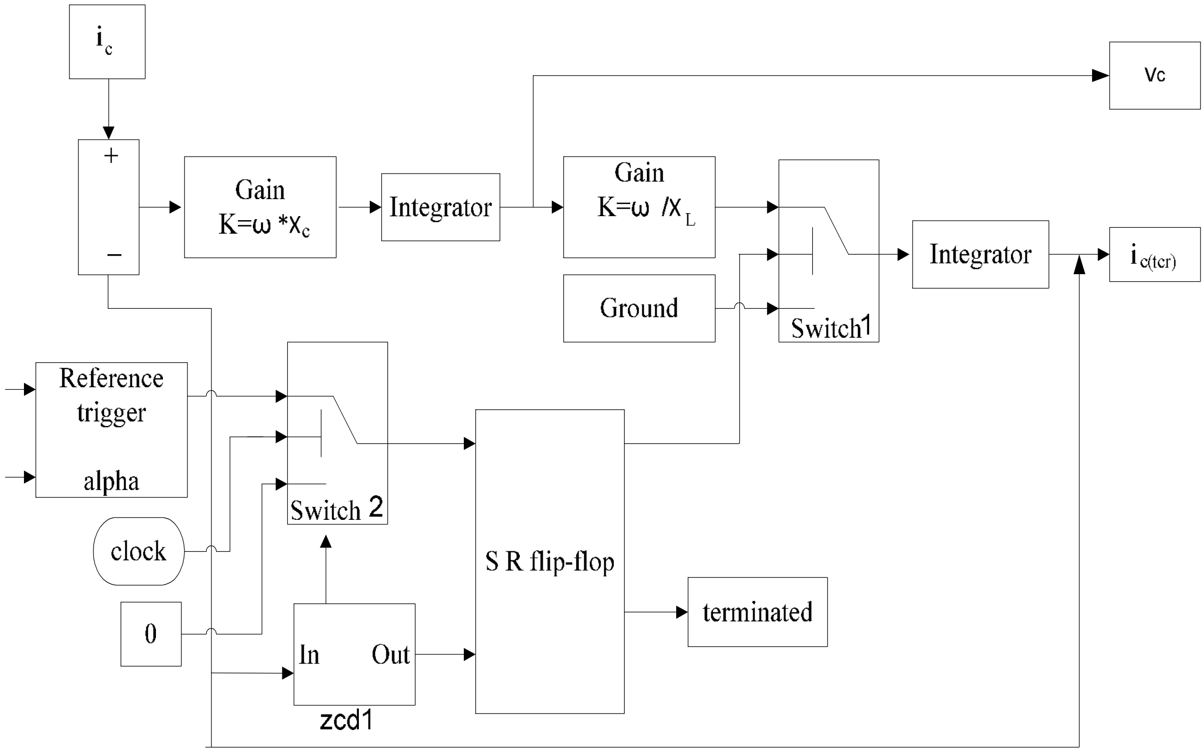


Fig. 4.8 Block Diagram of Thyristor Controlled Reactor

After multiplying V_C with gain (K= ω / X_L), it is given as input to the switch as shown in Fig.4.8. Now a switching function U is used for the proper switching of thyristors. To obtain this, switch2 used. The output of switch, di_{tcr}/dt is obtained & on integrating this, current i_{tcr} is obtained.

For SR – Flip Flop

SR-Flip Flop:

S	R	Output Q_{n+1}
0	0	Q_n
1	0	1
0	1	0
1	1	?

Here Q_n = output for bit time n; S, R = Inputs to SR- Flip Flop

Case1. When S = 1 & R = 0; then we have output Q = 1 and is applied at the switch.

Case2. When S = 0 & R = 1; Then output is Q = 0 and is applied at the switch.

4.3 Case Study of TCSC in a Transmission System

Electric power flow though an alternating current transmission line is a function of the line impedance, the magnitudes of the sending-end and receiving-end voltages, and the phase angle between these voltages. The power flow can be decreased by inserting an additional inductive reactance in series with the transmission line, thereby increasing the effective reactance of the transmission line between its two ends. Also, the power flow can be increased by inserting an additional capacitive reactance in series with the transmission line, thereby decreasing the effective reactance of the transmission line between its two ends. In the proceeding topics a transmission system is selected and the response of the system is studied without, with a TCSC connected and different faults.

4.3.1 Transmission network Description

A three-phase, 60 Hz, 735 kV power system transmitting power from a power plant consisting of six 350 MVA generators to an equivalent network through a 600 km transmission line has been taken into consideration.

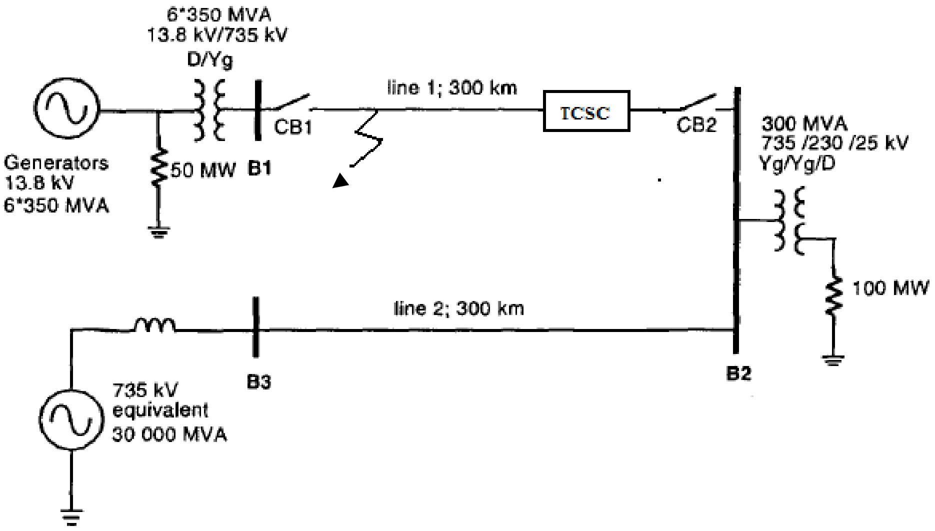


Fig 4.9 Equivalent circuit of the Transmission network

The transmission line is split in two 300 km lines connected between buses B1, B2 and B3. The TCSC is located at the B2 substation where a 300 MVA 735/230 kV transformer with a 25 kV tertiary winding feeds a 230 kV, 250 MW load. CB1 and CB2 are the two line circuit breakers.

The generators are simulated with a Simplified Synchronous Machine block. Universal transformer blocks (two-windings and three-windings) are used to model the two transformers and saturation is implemented on the transformer connected at bus B2. Voltages and currents are at B1 and B2 buses. Three-phase V-I Measurement blocks are connected at B1 and B2 where voltage
impedance of the machine.

The voltage and current response of the system at B2 is studied. First the system response is studied without TCSC connection and then with TCSC connected between B1 and B2. Different elements in the Transmission system are explained in brief as under:

(a) Simplified Synchronous Machine

The Simplified Synchronous Machine block models both the electrical and mechanical characteristics of a simple synchronous machine. The electrical system for each phase consists of a voltage source in series with RL impedance, which implements the internal Simplified Synchronous Machine block consists solely of a voltage source behind a synchronous reactance and resistance. All the other self- and magnetizing inductances of the armature, field, and damping windings are neglected.

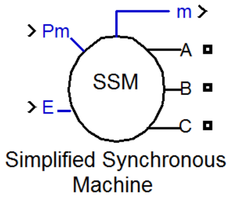


Fig 4.10

Limitations: The Simplified Synchronous Machine blocks in discrete systems, is used with a small parasitic resistive load, connected at the machine terminals, in order to avoid numerical oscillations. Large loads sample times.

(b) Three-Phase Series RLC Load

The Three-Phase Series RLC Load block implements a three-phase balanced load as a series combination of RLC elements. At the specified frequency, the load exhibits constant impedance. The active and reactive powers absorbed by the load are proportional to the square of the applied voltage.

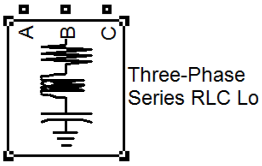


Fig 4.11

(c) Three-Phase Transformer (Two Windings)

The Three-Phase Transformer (Two Windings) block implements a three-phase transformer using three single-phase transformers. The saturable core can be simulated simply by setting the appropriate check box in the parameter menu of the block.

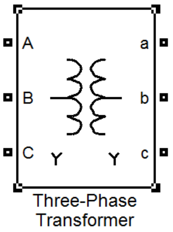


Fig 4.12

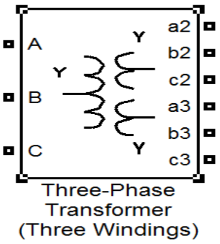


Fig. 4.13

(d) Three-Phase Transformer (Three Windings)

This block implements a three-phase transformer by using three single-phase transformers with three windings. The saturable core can be simulated simply by setting the appropriate check box in the parameter menu of the block.

(e) Three-Phase V-I Measurement

The Three-Phase V-I Measurement block is used to measure three-phase voltages and currents in a circuit. When connected in series with three-phase elements, it returns the three phase-to-ground or phase-to-phase voltages and the three line currents. The block can output the voltages and currents in per unit (p.u) values or in volts and amperes.

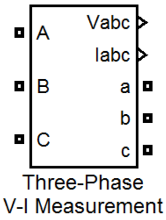


Fig 4.14

(f) Three-Phase Breaker

The Three-Phase Breaker block implements a three-phase circuit breaker where the opening and closing times can be controlled either from an external Simulink signal (external control mode),

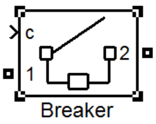


Fig 4.15

or from an internal control timer (internal control mode).The Three-Phase Breaker block uses three Breaker blocks connected between the inputs and the outputs of the block. This block can be used in series with the three-phase element to be switched.

(g) Distributed Parameter Line

The Distributed Parameter Line block implements an N-phase distributed parameter line model with lumped losses. The model is based on the Bergeron's travelling wave method used by the Electromagnetic Transient Program (EMTP). In this model, the lossless distributed LC line is characterized by two values (for a single-phase line): the surge impedance and the phase velocity.

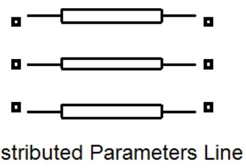


Fig 4.16

Limitations: This model does not represent accurately the frequency dependence of RLC parameters of real power lines. Indeed, because of the skin effects in the conductors and ground, the R and L matrices exhibit strong frequency dependence, causing an attenuation of the high frequencies.

(h) Three-Phase Fault

The Three-Phase Fault block implements a three-phase circuit breaker where the opening and closing times can be controlled either from an external Simulink signal (external control mode), or from an internal control timer (internal control mode).The Three-Phase Fault block uses three Breaker blocks that can be individually switched on and off to program phase-to-phase faults, phase-to-ground faults, or a combination of phase-to-phase and ground faults.

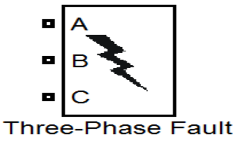


Fig 4.17

(i) Three-Phase Source

The Three-Phase Source block implements a balanced three-phase voltage source with internal R-L impedance. The three voltage sources are connected in Y with a neutral connection that can be internally grounded or made accessible. We can specify the source internal resistance and inductance either directly by

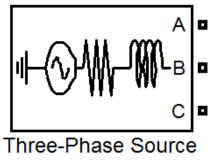


Fig 4.18

entering R and L values or indirectly by specifying the source inductive short-circuit level and X/R ratio.

(j) Thyristor Controlled Series Capacitor (TCSC)

The TCSC modelled previously has been connected between the bus B1 and B2.The whole model has been converted in a small simulink block having different subsystems inside it with three inputs and three outputs. The parameters set are X_C= 15 ohm, X_L= 2.56 ohm, alpha = 60˚ at 60 Hz.

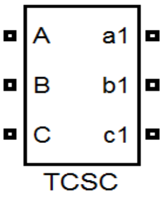


Fig 4.19

The transient performance of this circuit when line-to-ground and three-phase-to-ground faults are applied on line 1 is studied. The fault and the two line circuit breakers CB1 and CB2 are simulated with blocks from the three-phase library.

Chapter 5
Simulation and Analysis

5.1 Simulation of TCSC

In the simulation the Thyristor Controlled Series Capacitor (TCSC), the following system parameters are considered.

Capacitive reactance (X_C) = 15 Ω
Inductive reactance (X_L) = 2.56 Ω
System frequency (ω) = 2*pi*60
Angle of advance (β) = (pi/2)-(Alpha*pi/180)
Alpha (α) = Firing angle

In the beginning only the fixed series compensating capacitor is in the circuit since thyristors in TCR branch have not been fired thus the line current i_L passes through the capacitor and charging of the capacitor takes place. Therefore the TCR branch is open and prevailing line current i_L produces voltage across the fixed series compensating capacitor. The thyristors of TCR branch are fired at firing angle $\alpha = 60^o$.

(a) Response of Capacitor Voltages at Firing Angle ($\alpha = 60^o$)

The simulation response of capacitor voltages for phases a, b and c at firing angle $\alpha = 60^o$ have been presented from time t=0 sec. to t=1 sec. in Fig.5.1 to Fig.53. Thyristor Controlled Series Capacitor (TCSC) consists of a fixed series compensating capacitor in parallel with the TCR. The capacitor voltage waveform at $\alpha=60^o$, for phase a, is shown in Fig. 5.1 from time t=0 to t=1.0 sec. It has been observed that voltage amplitude remains almost same from t=0.2 sec. to t=0.5 sec. After t=0.5 sec. transients have been observed as shown in Fig. 5.1. The capacitor voltage amplitude before t=0.5 is 0.25 as shown in Fig. 5.2, but after t=0.5 sec. transients are observed and the voltage amplitude is increased to a value of 0.35. this sudden rise in the capacitor voltage is observed due to the reason that, at the instant of turn on of thyristors in TCR branch; two substantially independent events occur; one is that (for first half cycle) line current i_L, being a constant source of current continues to (dis)charge the capacitor; other is that, the charge of the capacitor will be reversed during the resonant half cycle of the LC circuit formed by the conduction of TCR branch. The resonant charge reversal produces a d.c. offset for the next half cycle of the capacitor voltage as shown in Fig. 5.3. This is the reason for the sudden rise in the capacitor voltage after the firing of thyristors of TCR branch. Similarly the simulation response of capacitor voltages for phases b and c can be explained as shown in Fig. 5.4 to Fig. 5.9.

(b)Response of TCR currents at Firing Angle (α =60^o)

The simulation response of TCR currents for phases a, b and c at firing angle α =60^o have been presented from time t=0 sec. to t=1 sec. in Fig.5.4 to Fig.5.6. The TCR current at α =60^o for phase 'a' is as shown in Fig. 5.4 and it is observed that from t=0 to t=0.5 sec. value of current is zero since thyristors are not conducting. At t=0.5 sec. thyristors in TCR branch are fired at α =60^o and hence after t=0.5 sec. In TCR current, spikes are observed,this is due to the sudden rise in the capacitor voltage; observed earlier in capacitor voltage waveform for phase 'a'. Similarly the simulation response of TCR currents for phases b and c can be explained as shown in Fig. 5.5 and Fig. 5.6.

(c) Response of Capacitor currents at Firing Angle (α =60^o)

The simulation response of capacitor currents at firing angle α =60^o have been presented in Fig.5.7. The current i_c in the series fixed capacitor is equal to the sum of line current (i_L) and TCR current.

The simulation response of TCR currents and capacitor voltages for phases a, b and c with respect to time, have been shown for a firing angle of 60°. The line currents and capacitor currents have also been shown.

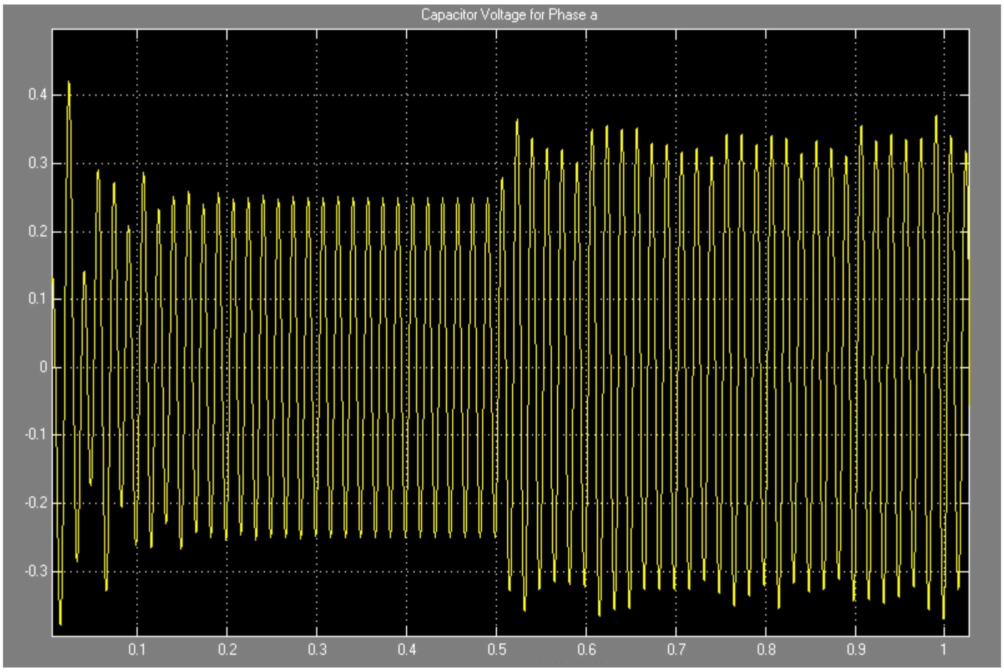


Fig.5.1 Capacitor Voltage for Phase a (α=60°)

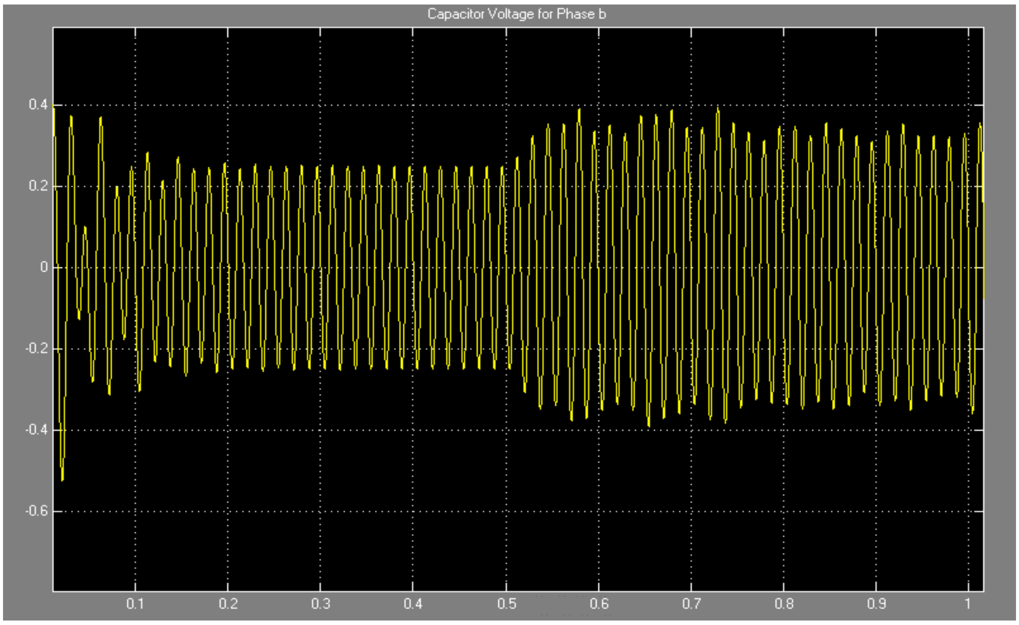


Fig.5.2 Capacitor Voltage for Phase b (α=60°)

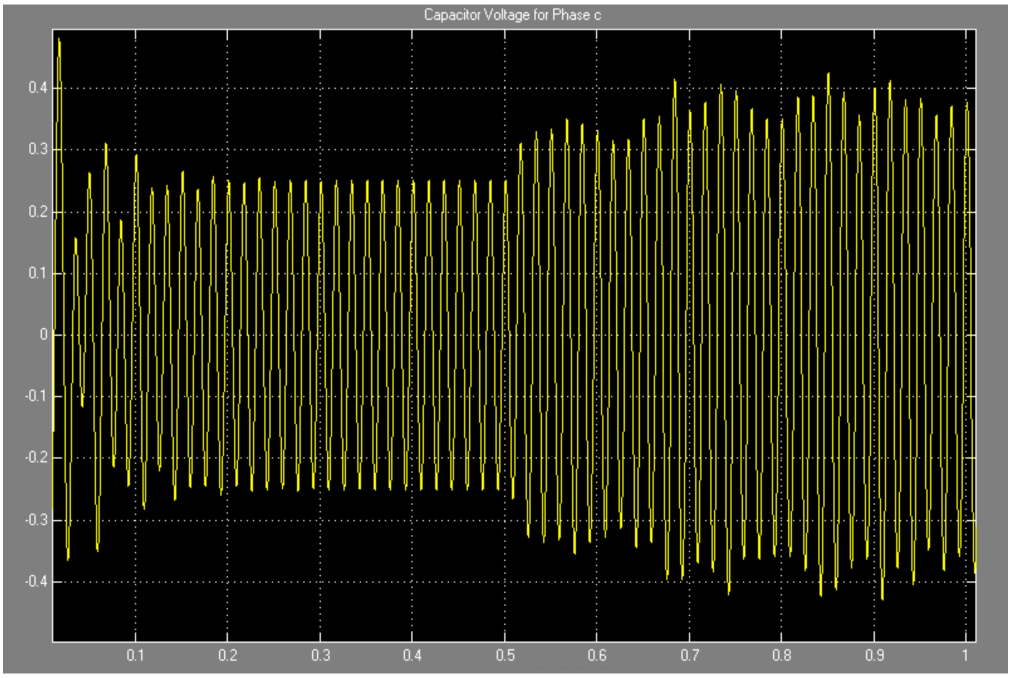


Fig.5.3 Capacitor Voltage for Phase c (α=60°)

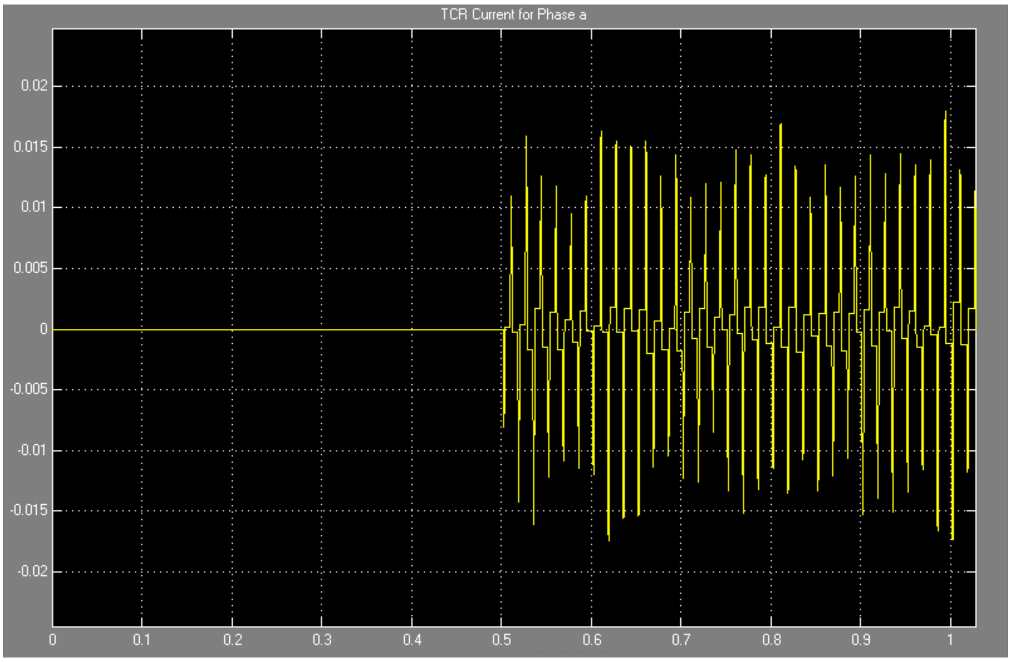


Fig.5.4 TCR Current for Phase a (α=60°)

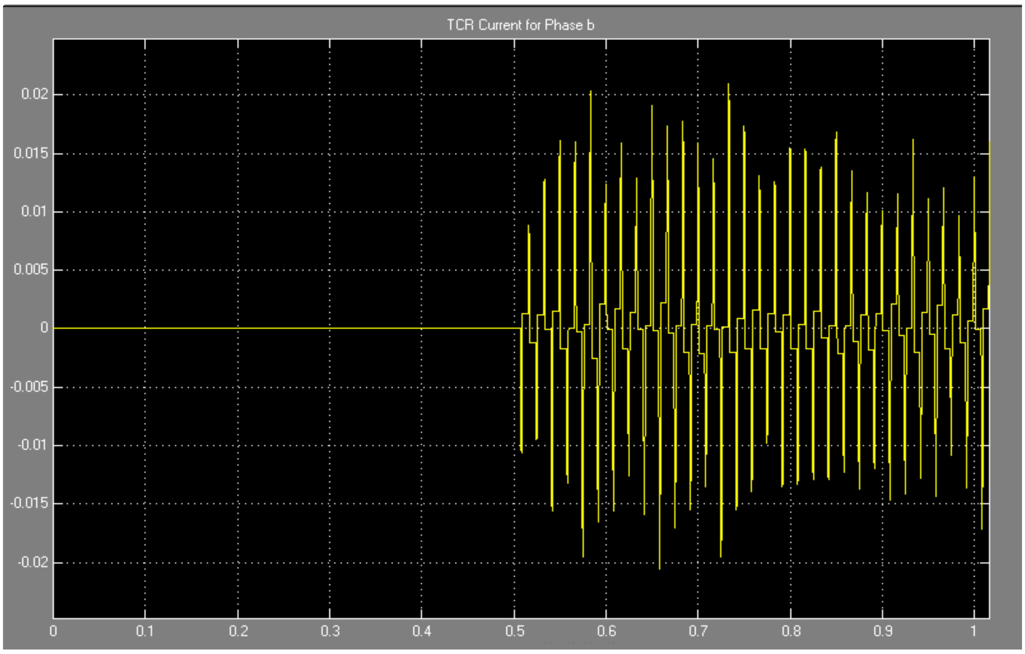


Fig.5.5 TCR Current for Phase b (α=60°)

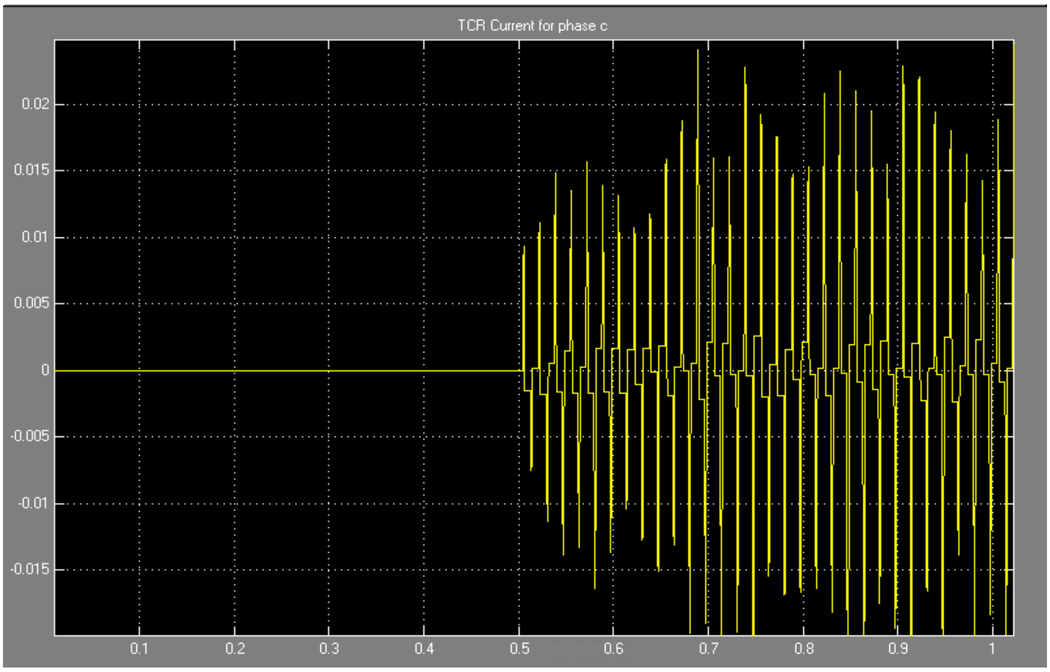


Fig.5.6 TCR Current for Phase c (α=60°)

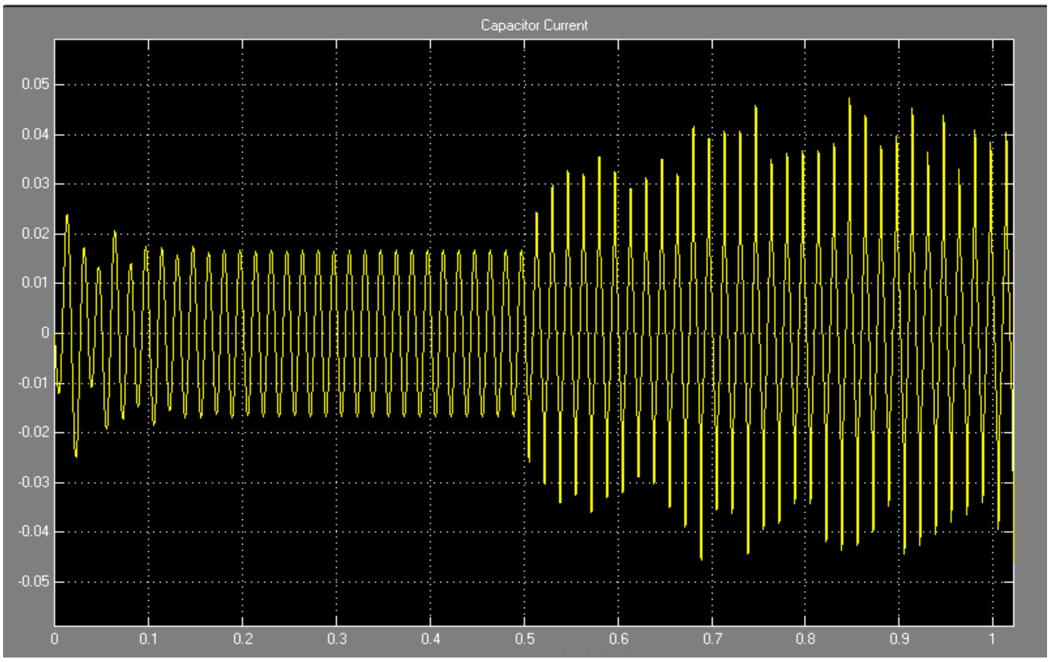


Fig.5.7 Capacitor Current for Phase c (α=60°)

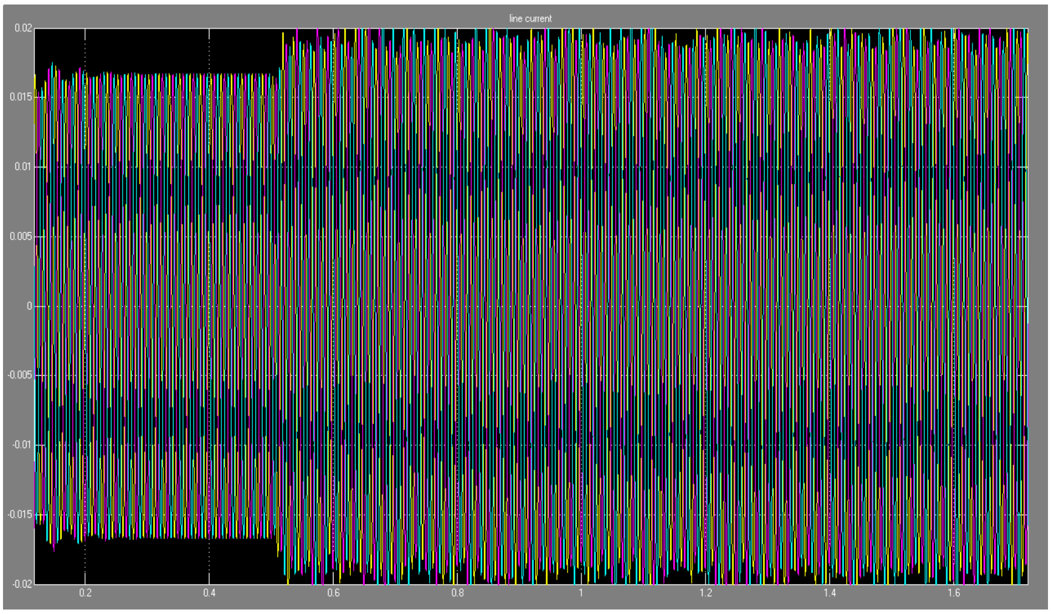


Fig.5.8 Line current

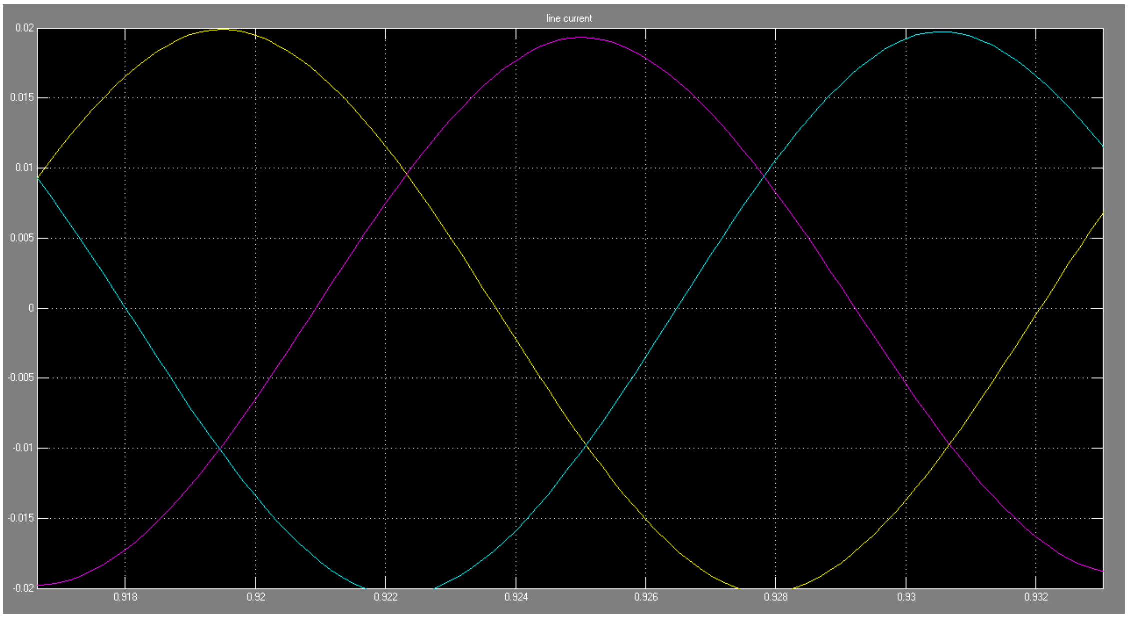


Fig.5.9 Expanded view of line current

5.2 Case Study of Application of TCSC to Transmission Network and its simulation

5.2.1 Without TCSC and a three phase fault

The TCSC modelled before is applied to a transmission network, faults have been applied and the response has been taken. First the system is studied without TCSC being connected and a three phase fault applied between bus B1 and B2. When the voltage and current waveforms are studied at B1, it seen that the waveforms are initially distorted and after that it settles down. These disturbances can be due to the harmonics in the system which after some time damp out themselves. The response of the system at B2 has been studied. Analyses for different phases are discussed under:

(a) Response at phase 'a'

In phase a it is seen that voltage waveform has a very sharp peak of 2.05 p.u and after that in each cycle there are number of spikes. It gets regular after 0.15 seconds but still it is not an ideal and not an acceptable response. This may be due to the current flowing in the phase which is non sinusoidal. Ia has a peak of 35p.u but then it goes to zero after 0.085 seconds.

(b) Response at phase 'b'

In phase b the current response can be seen to have peak of 65 at around 0.055 seconds but with a many small spikes at each interval. Due to this type of current response the voltage in phase b is also not smooth. The voltage waveform peaks to 1.5 at around 0.02 seconds and then settles after 0.145 seconds.

(c) Response at phase 'c'

In phase c the voltage waveform can be seen to have a peak of 1.2 p.u around 0.1 second and settles after 0.14 seconds. The current also peaks upto 70 at around 0.06 seconds and then goes to zero after 0.09 seconds.

Studying the waveforms in much detail we can see that the system response is not healthy and due to many disturbances in the early cycles the waveforms are distorted. The main reason for this kind of behavior in voltage waveform can be due to the nonsinusodal currents in the phases. The harmonics in the system are also not damped out completely resulting in undesirable effects.

5.2.2 With TCSC and a three phase fault

Now a TCSC is connected between bus B1 and B2. Since system oscillations are greatly influenced by line impedance, TCSC can be effective in providing additional power oscillation damping .When we connect a TCSC in the line between bus B1 and B2 the system response is much more improved and acceptable. The harmonics in the system are damped out in early cycles and there are no disturbances as such after that. The response of the three phase are discussed as under:

(a)Response at phase 'a'

The voltage waveform in phase a after 0.1 seconds gets stable with a peak of 15.Now the only difference in the response from the ideal is that there is a capacitor in the circuit and so each alternate cycle of the wave oscillates between two different maximum values. Current waveform is seen to get stable after 0.12 seconds.

(b) Response at phase 'b'

In phase b the voltage wave is seen to get stable after 0.12 seconds with a peak of 12.5 and the current wave gets stable after 0.13 seconds.

(c) Response at phase ‘c’

In phase c the voltage wave gets stable after 0.115 seconds and peaks to a value of 15.5 p.u with the current wave getting stable after 0.12 seconds.

So it is seen that after connecting TCSC in the system, the system gets improved with lesser number of disturbances and smooth response.

In the similar manner we can see the case with single line to ground fault being applied. It is seen that TCSC is effective in damping the oscillations. The waveforms can be seen from Fig 5.27 to Fig 5.42.

5.1 Simulation results

5.3.1 Transmission network without TCSC and three phase fault

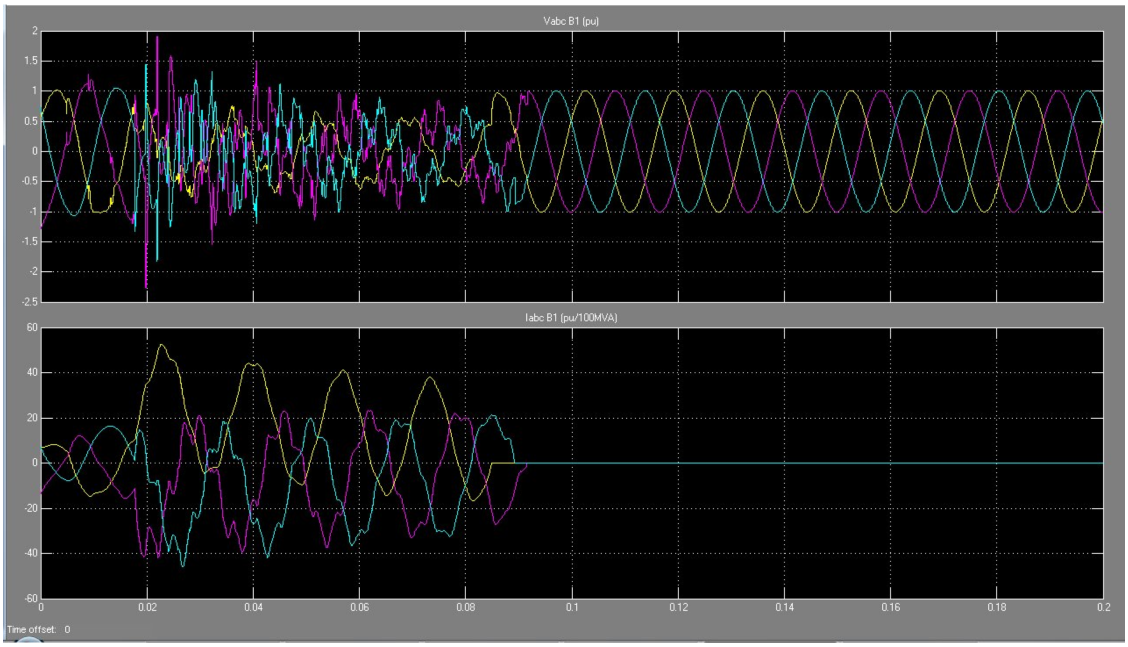


Fig 5.10 Three phase voltages and currents at B1 bus bar

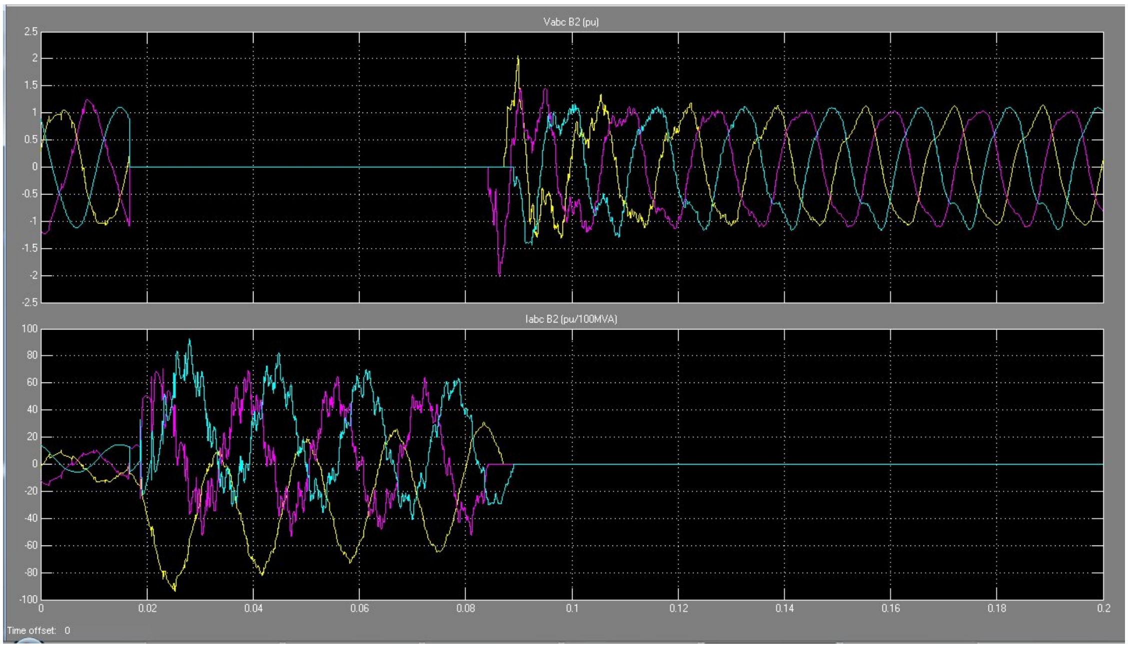


Fig 5.11 Three phase voltages and currents at B2 bus bar

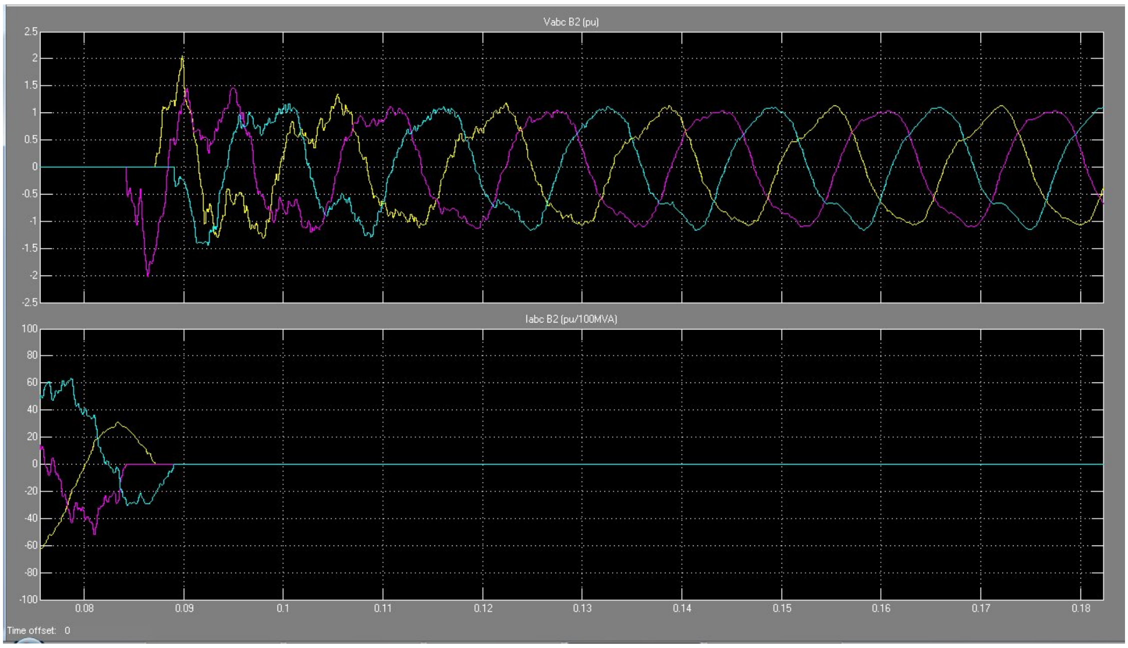


Fig 5.12 Extended view of 5.11

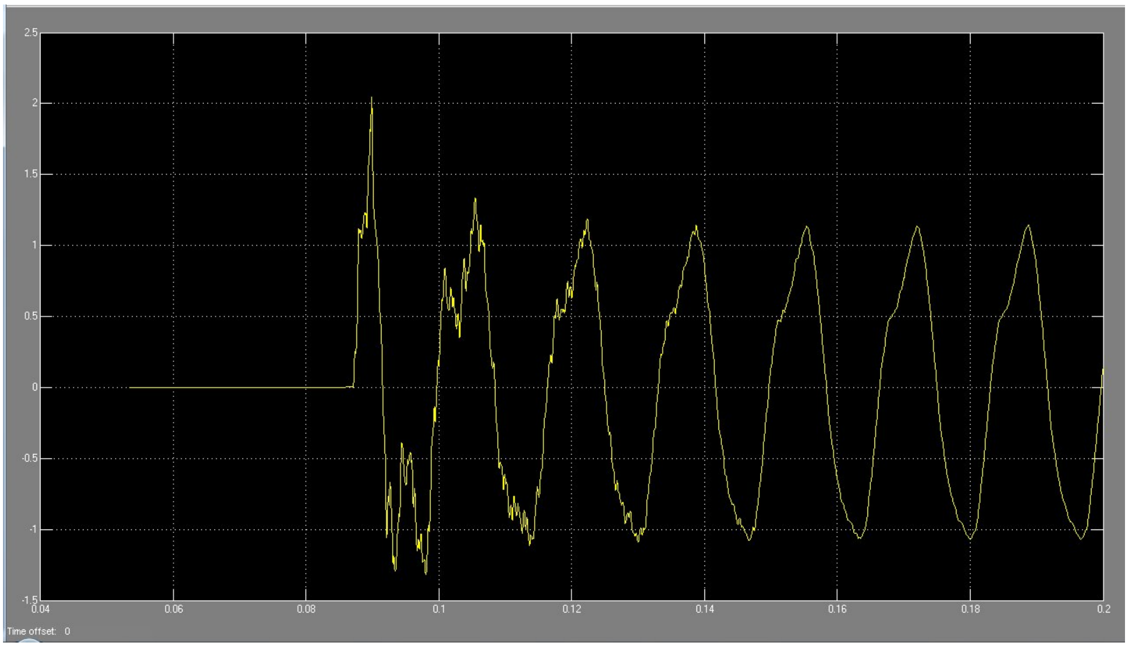


Fig 5.13 Voltage for phase ‘a’ at B2

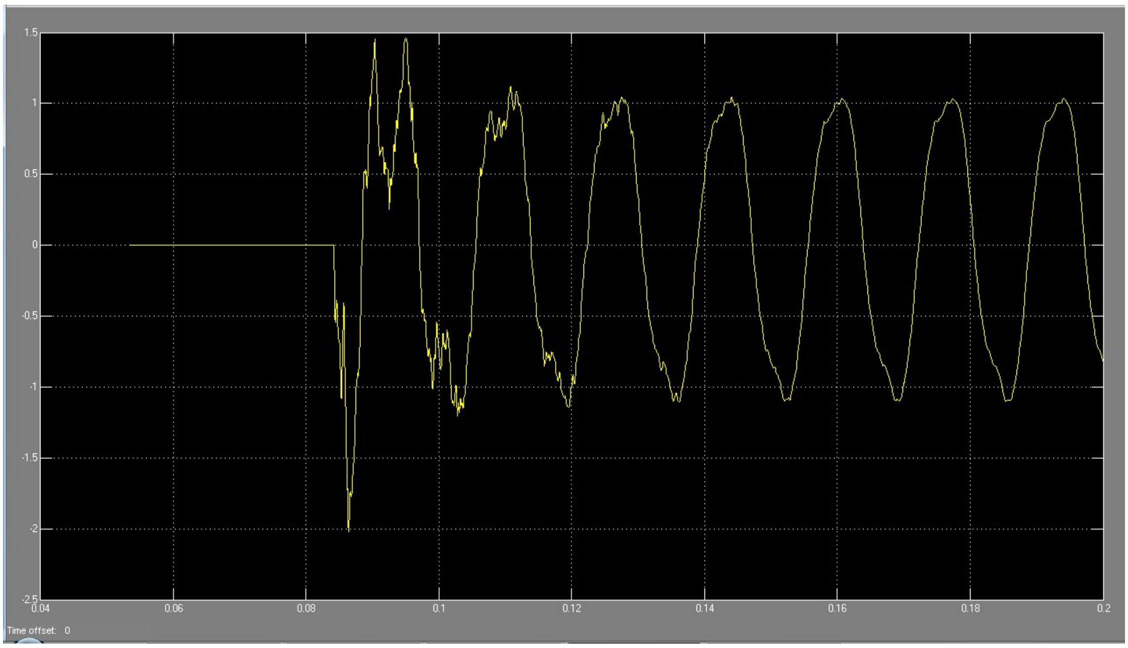


Fig 5.14 Voltage for phase ‘b’ at B2

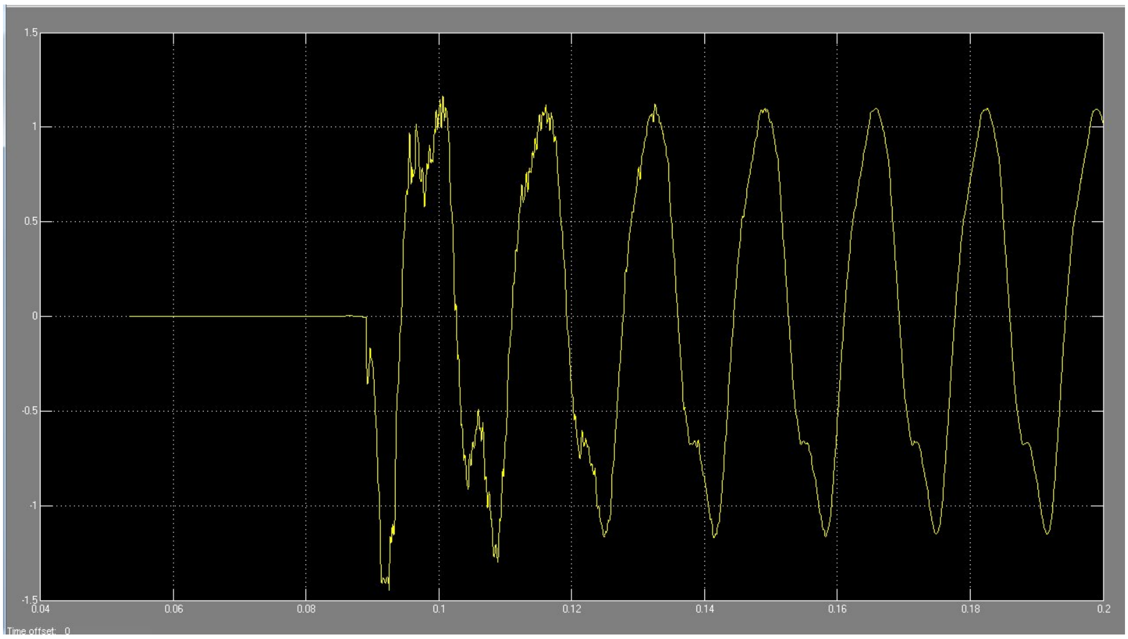


Fig 5.15 Voltage for phase 'c' at B2

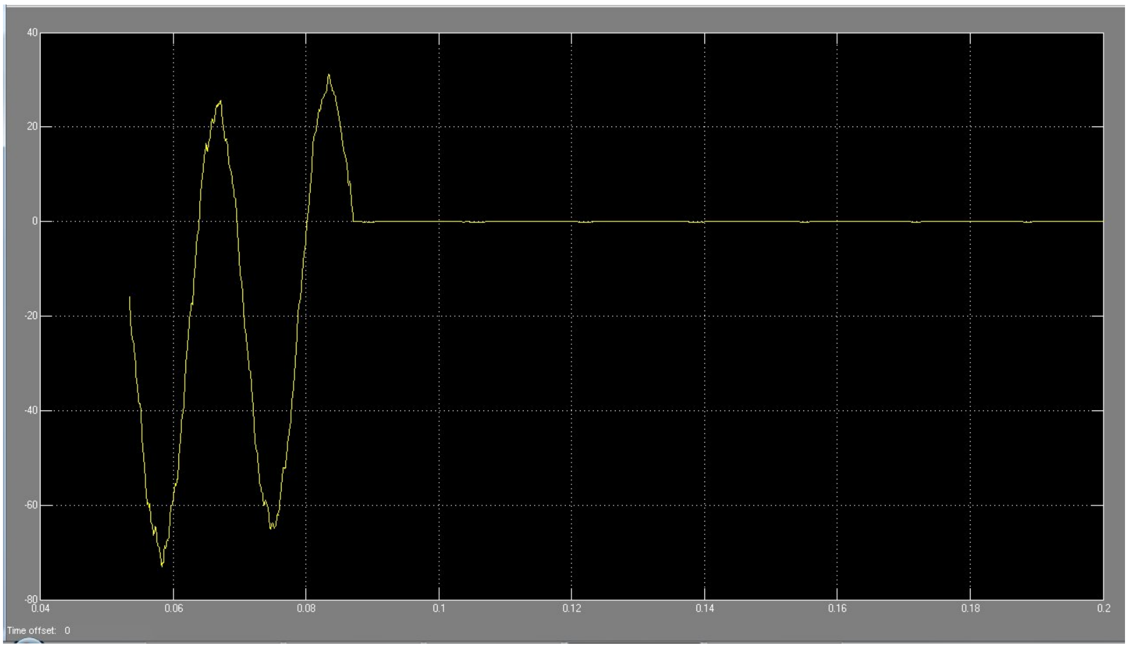


Fig 5.16 Current for Phase 'a' at B2

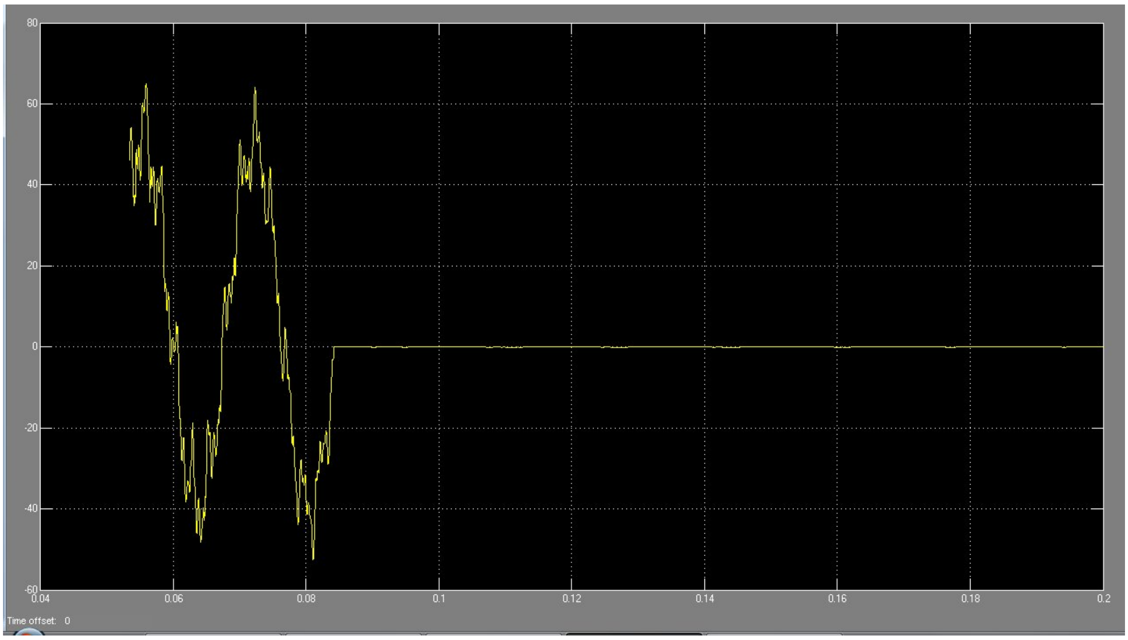


Fig 5.17 Current for phase ‘b’ at B2

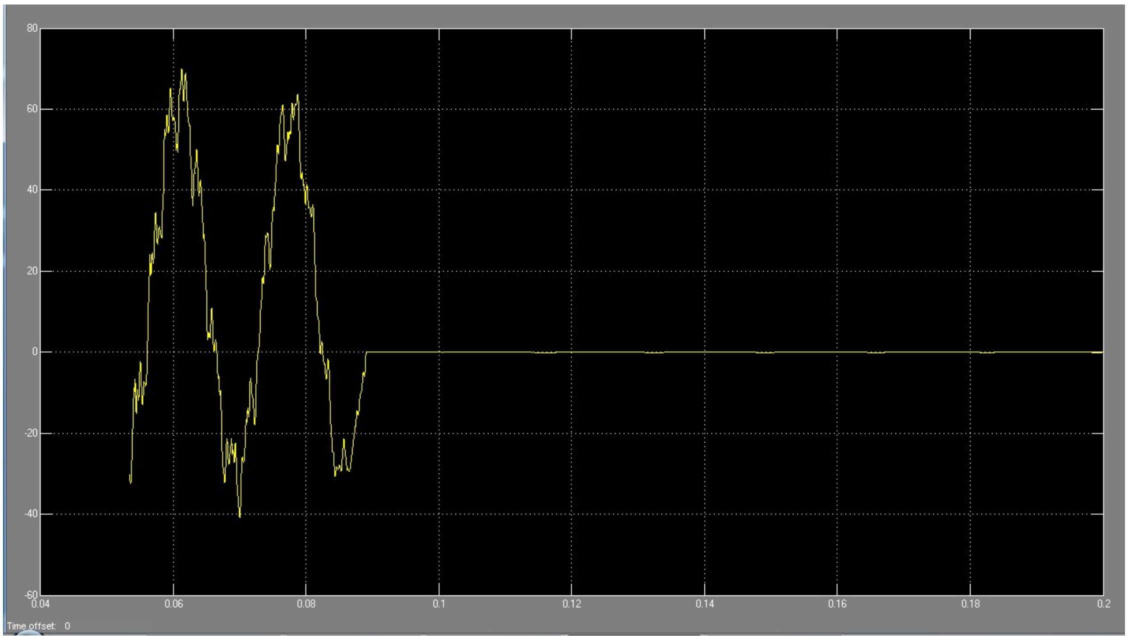


Fig 5.18 Current for Phase ‘c’ at B2

5.3.2 Transmission network with TCSC and three phase fault

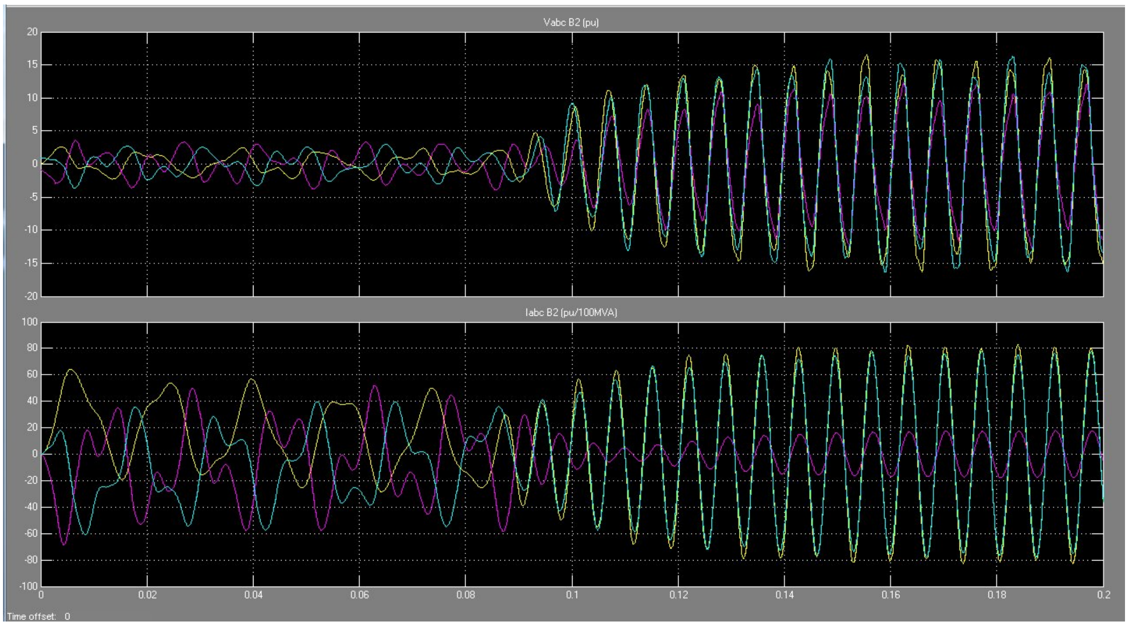


Fig 5.19 Three phase voltages and currents at B2

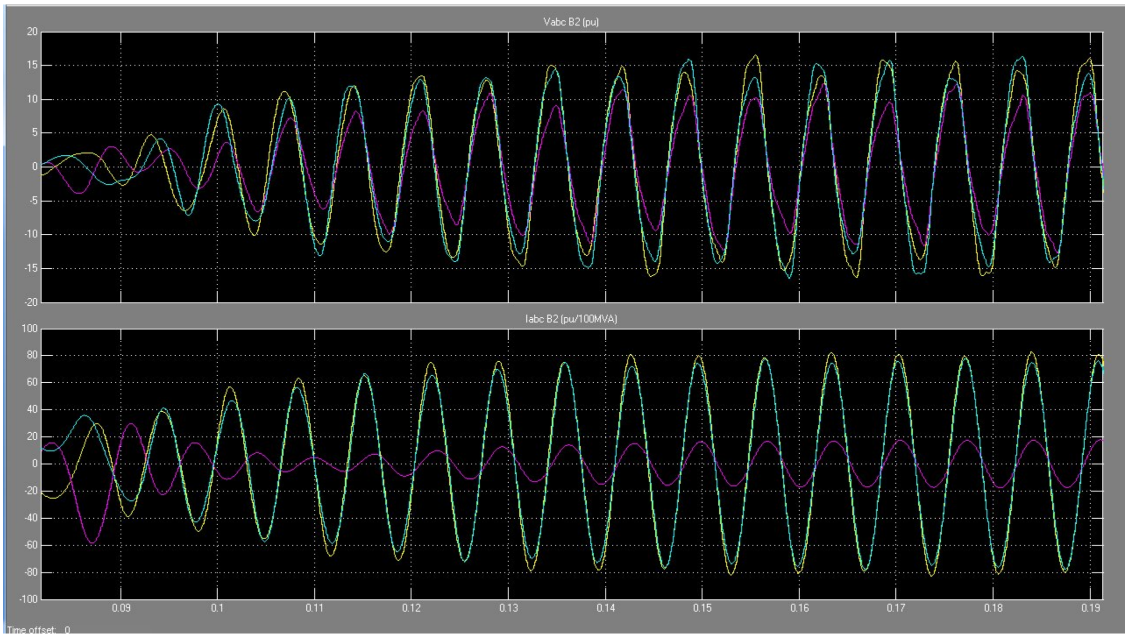


Fig 5.20 Extended view of fig 5.19

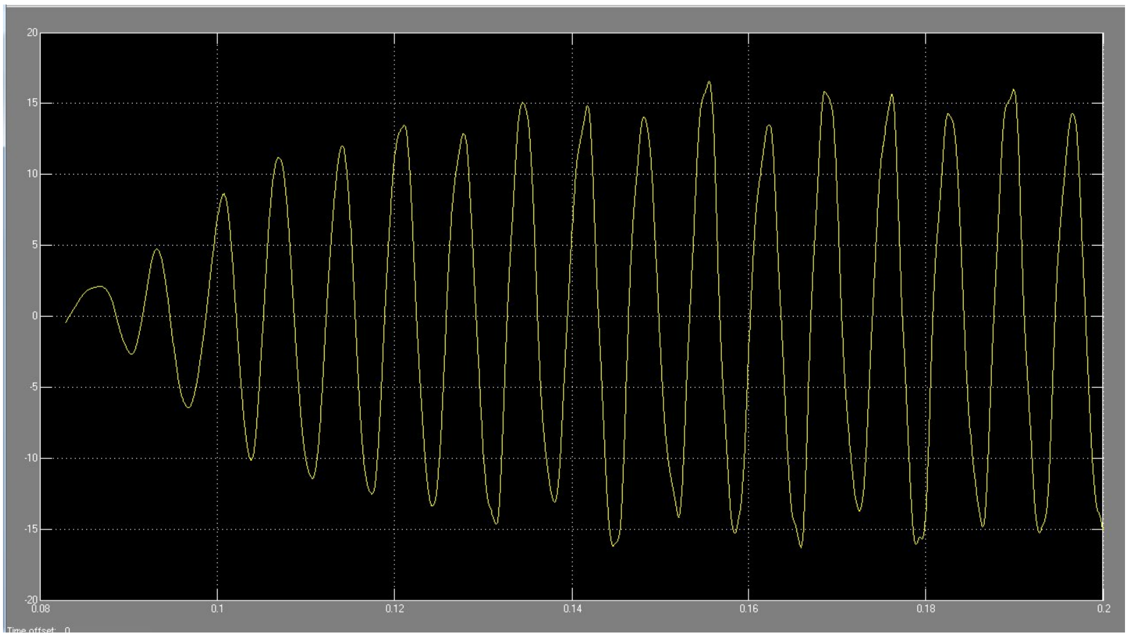


Fig 5.21 Voltage for phase ‘a

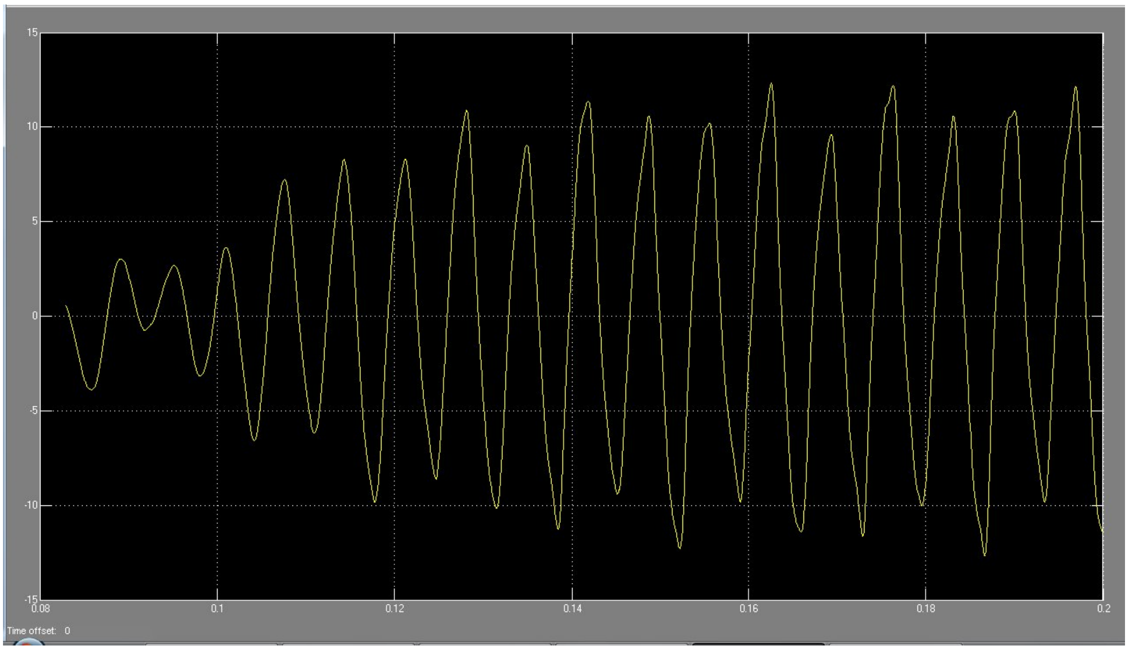


Fig 5.22 Voltage for phase ‘b’

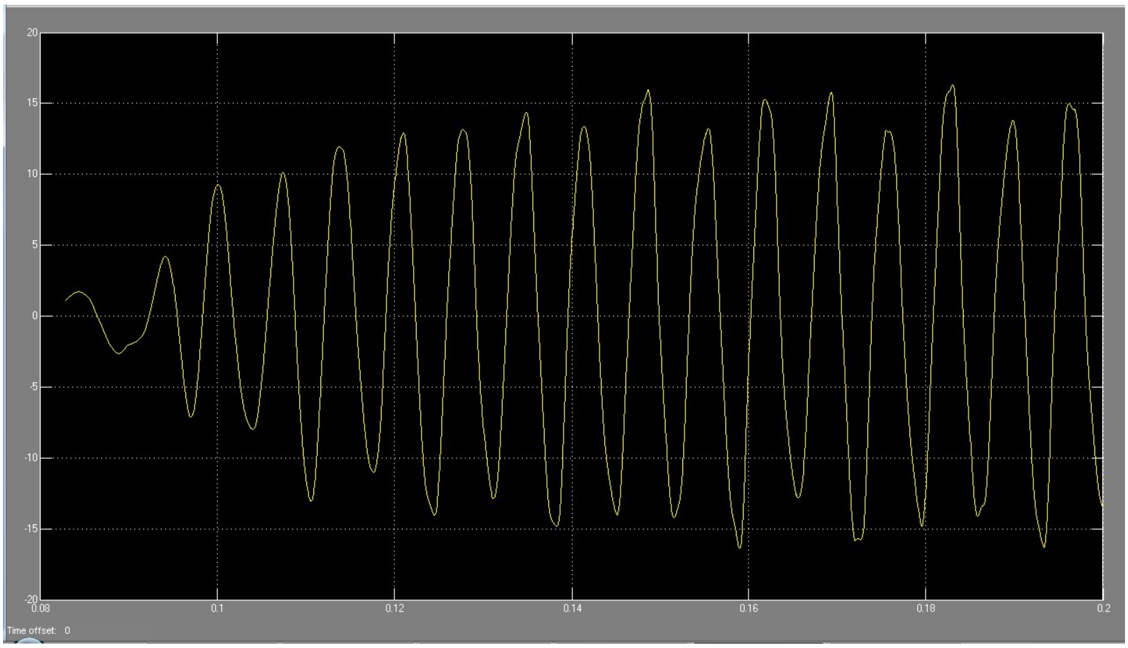


Fig 5.23 Voltage for phase ‘c’

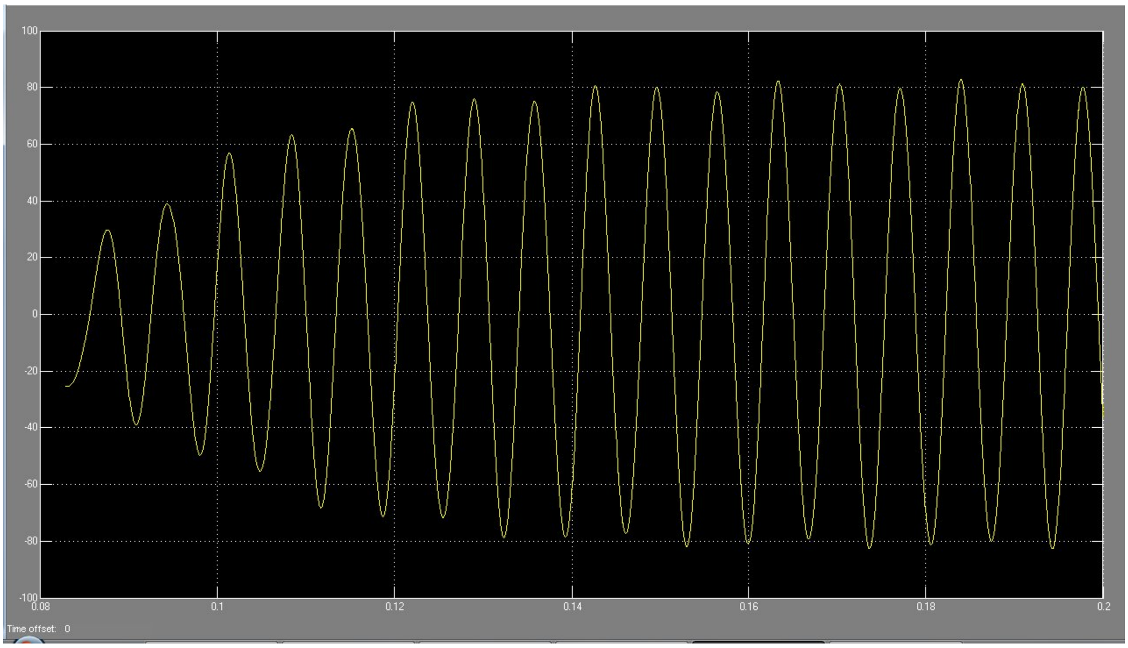


Fig 5.24 Current for phase ‘a’

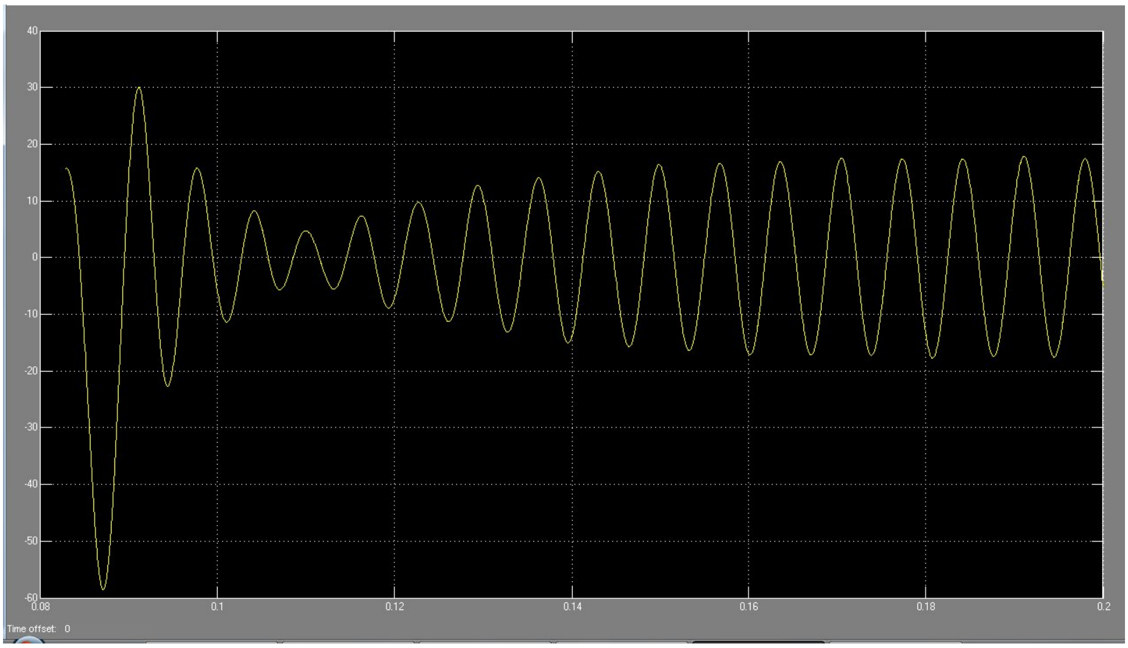


Fig 5.25 Current for phase ‘b’

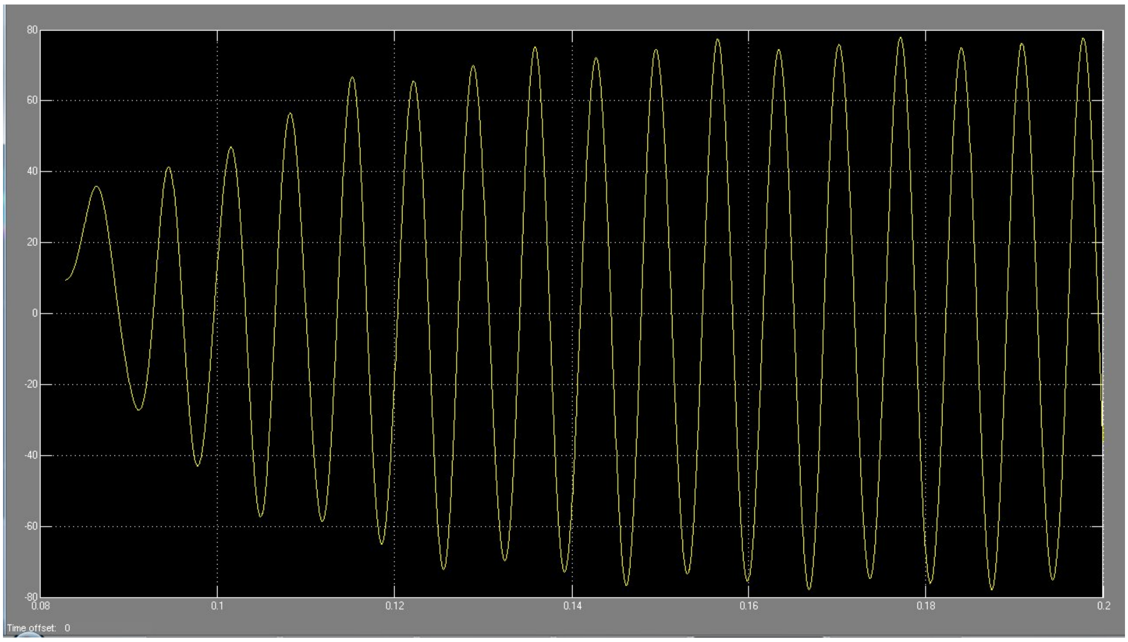


Fig 5.26 Current for phase ‘c’

5.3.3 Transmission network without TCSC and single line to ground fault at phase 'a'

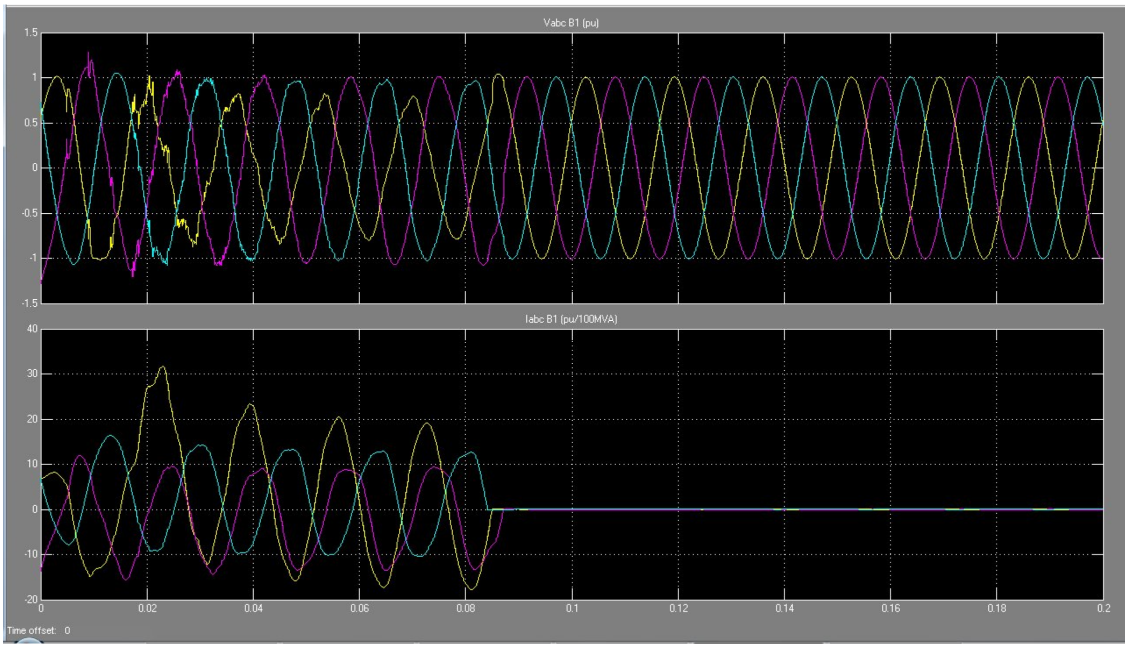


Fig 5.27 Three phase voltages and currents at B1

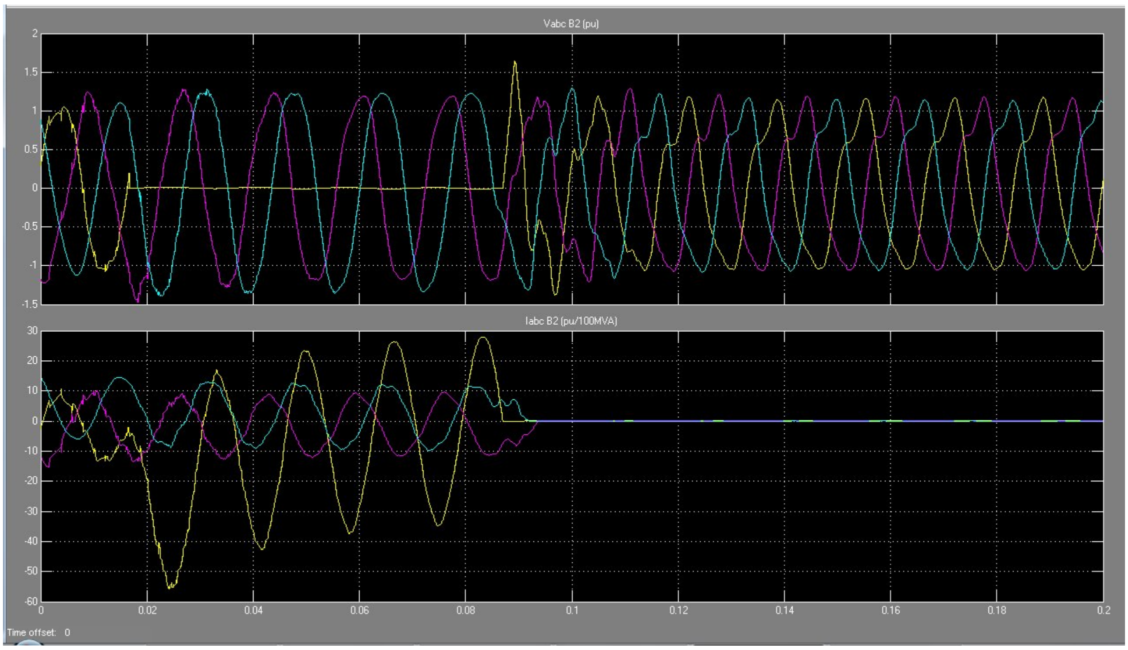


Fig 5.28 Three phase voltages and currents at B2

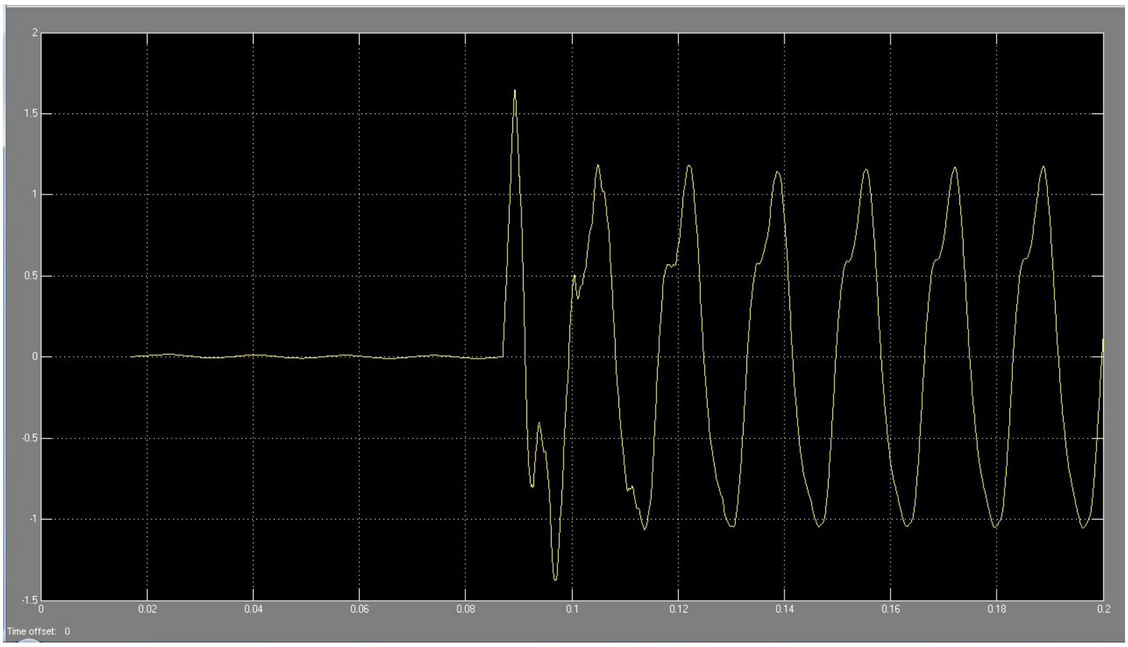


Fig 5.29 Voltage for phase ‘a’

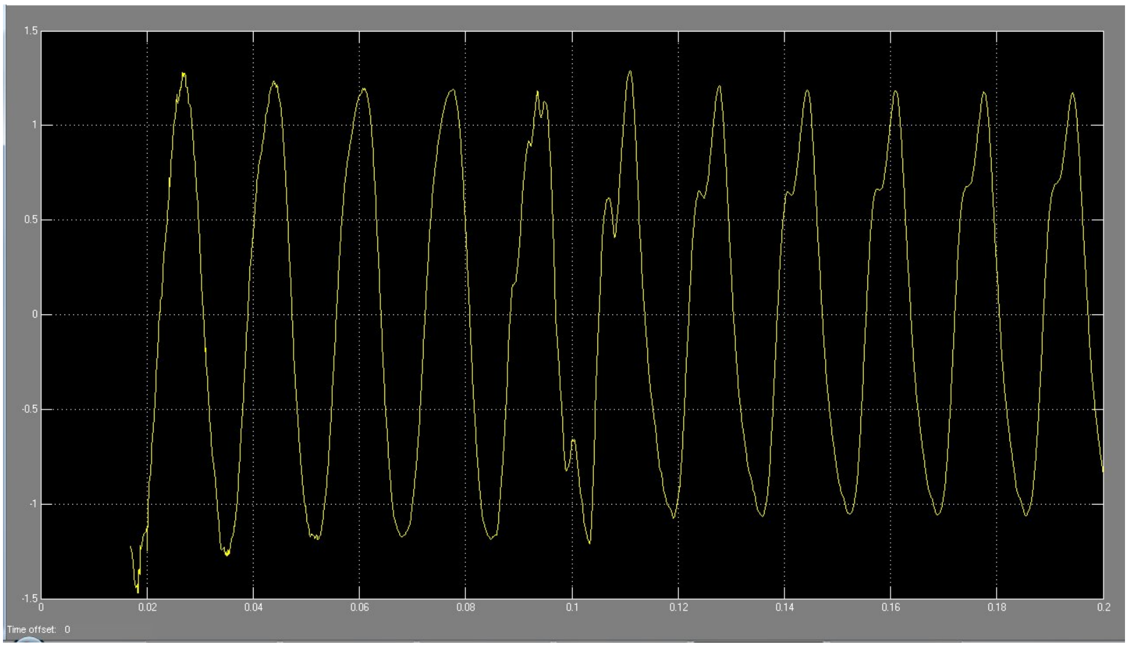


Fig 5.30 Voltage for phase ‘b’

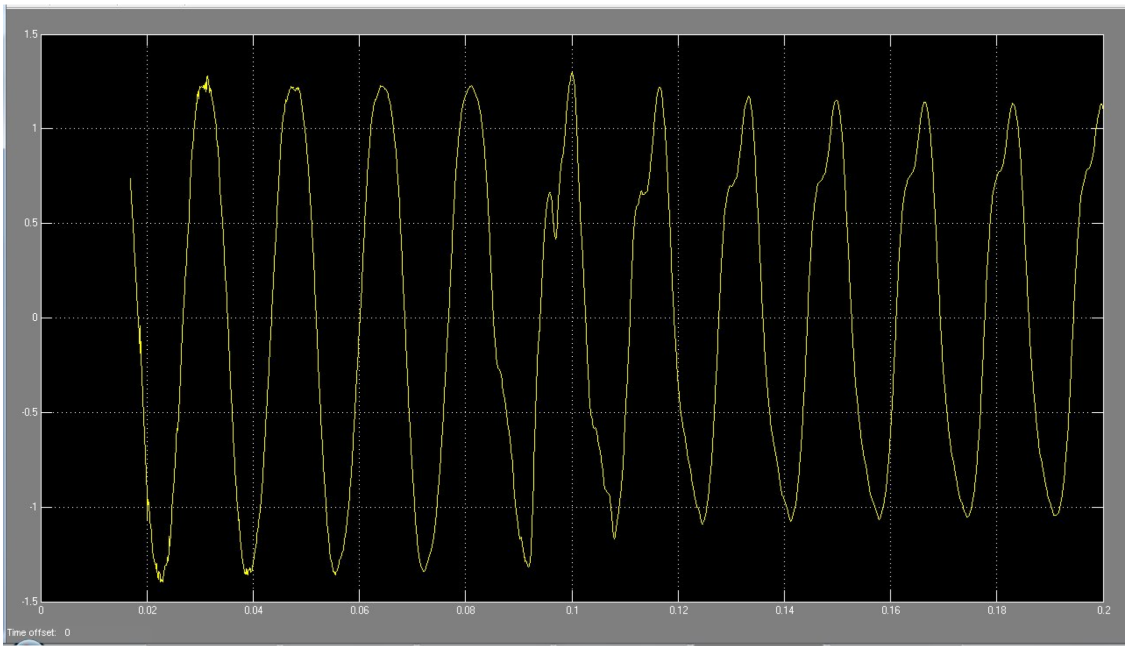


Fig 5.31 Voltage for phase ‘c’

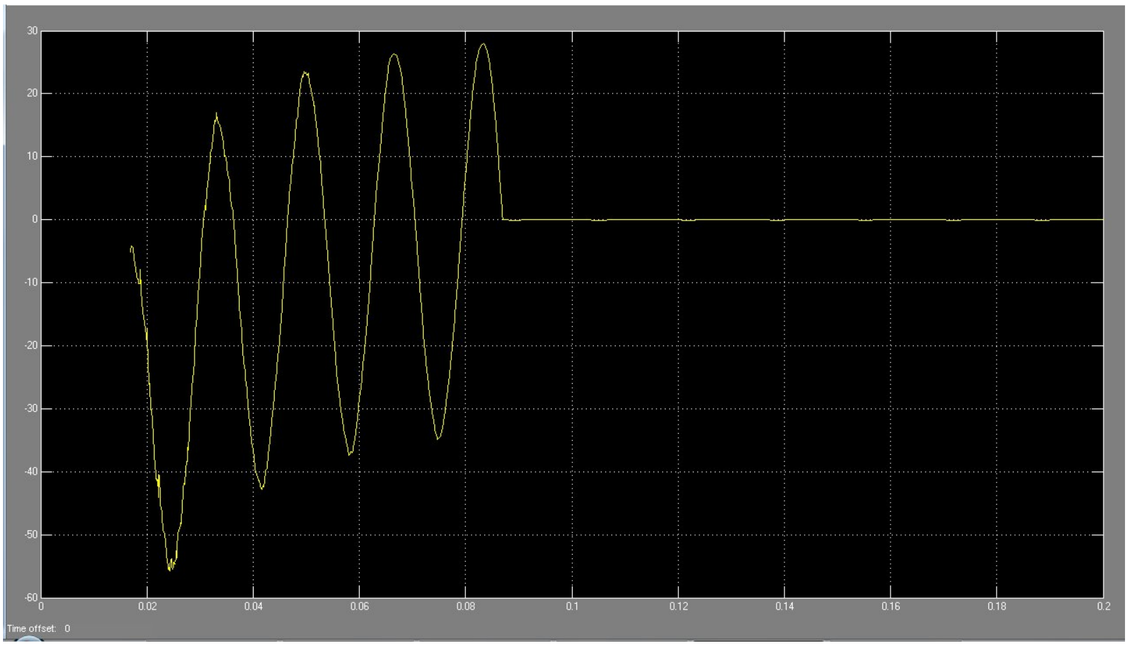


Fig 5.32 Current for phase ‘a’

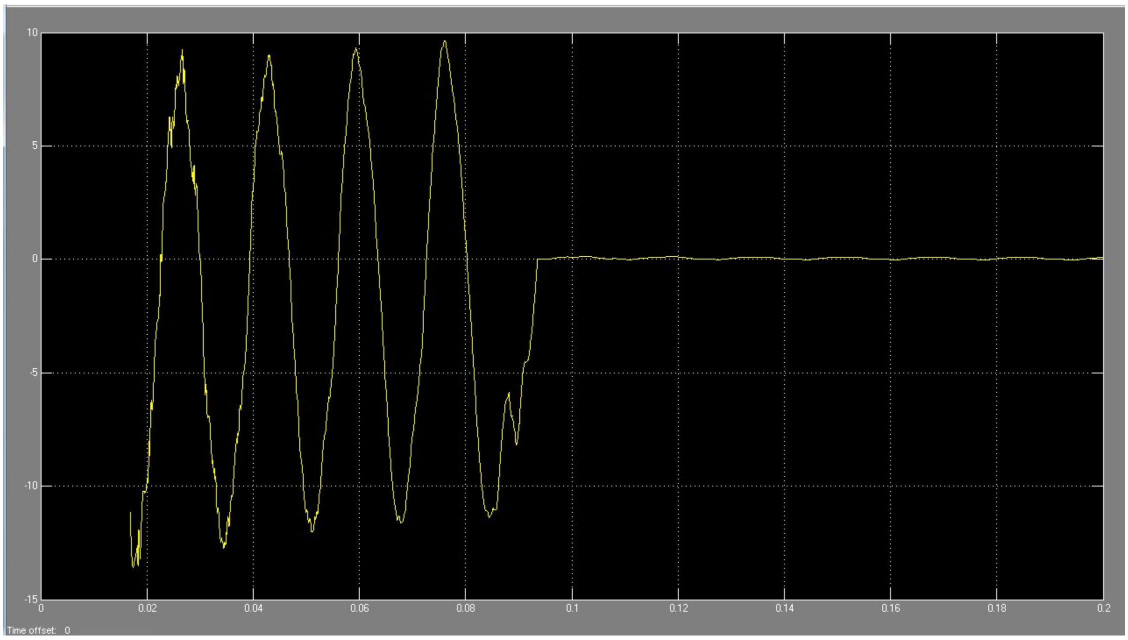


Fig 5.33 Current for phase ‘b’

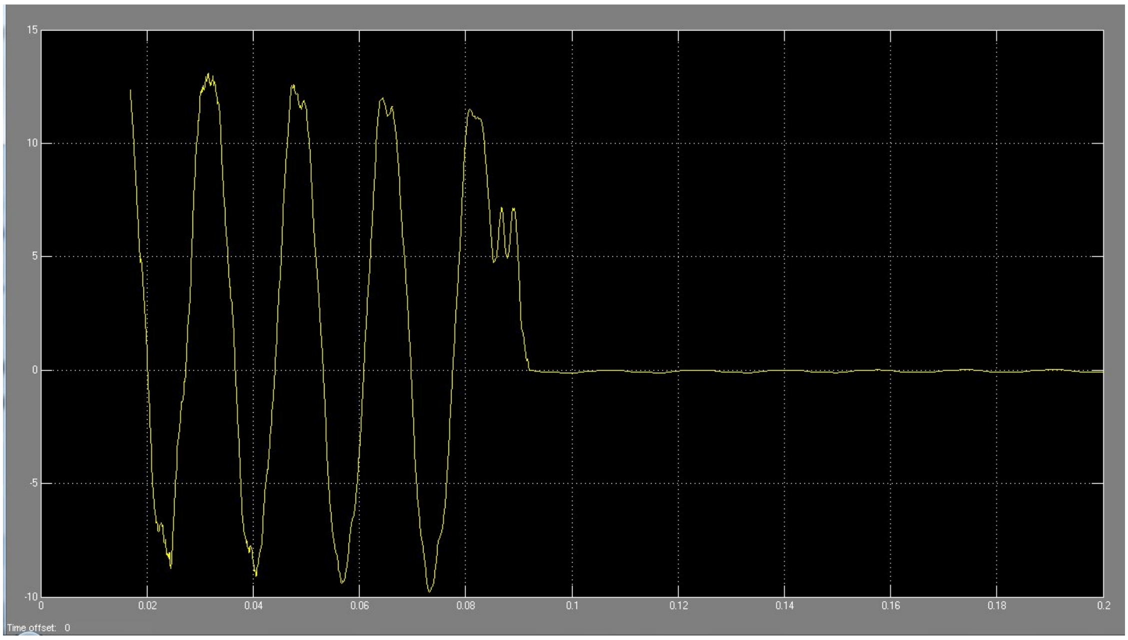


Fig 5.34 Current for phase ‘c’

5.3.4. Transmission network with TCSC fault at phase a’

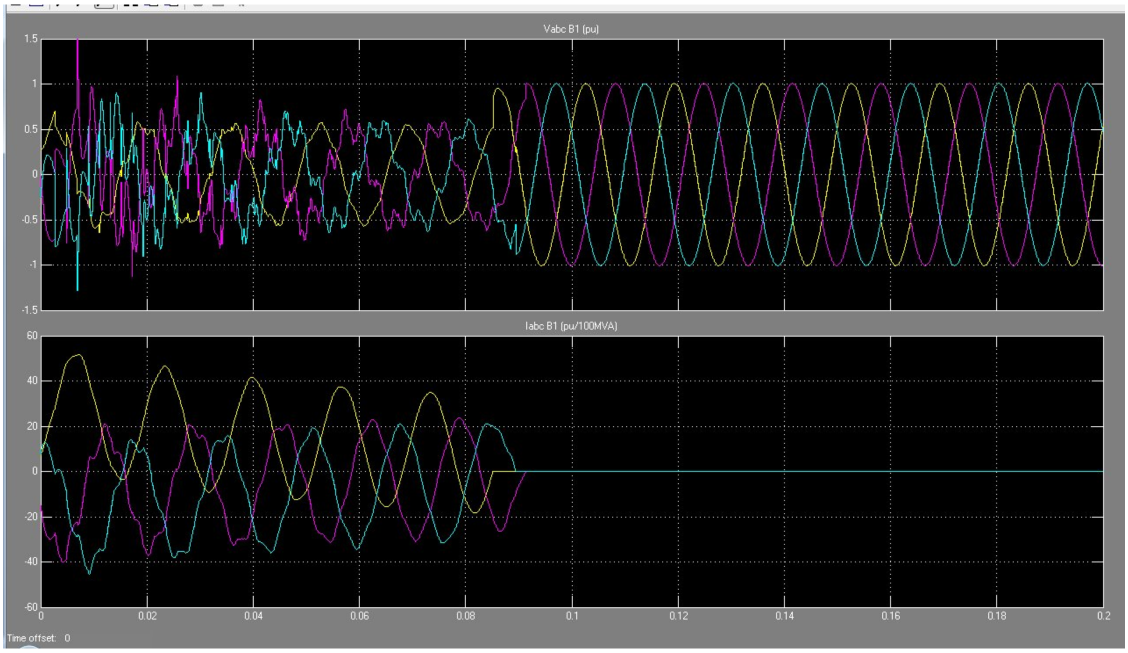


Fig 5.35 Three phase voltages and currents at B1

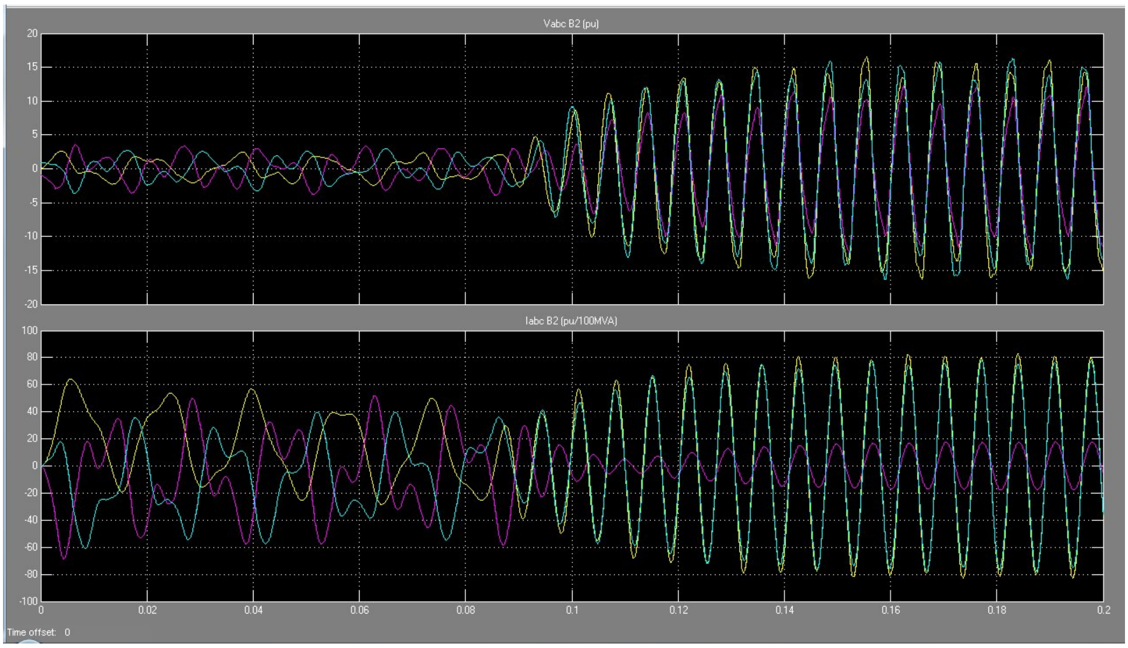


Fig 5.36 Three phase voltages and currents at B2

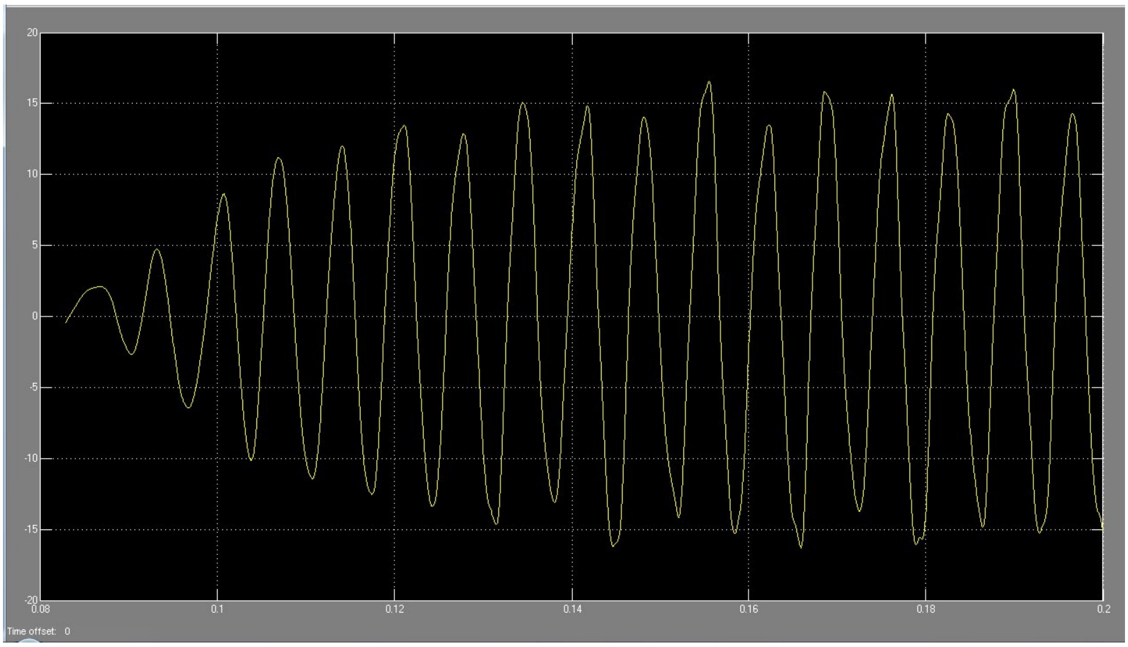


Fig 5.37 Voltage for phase ‘a’

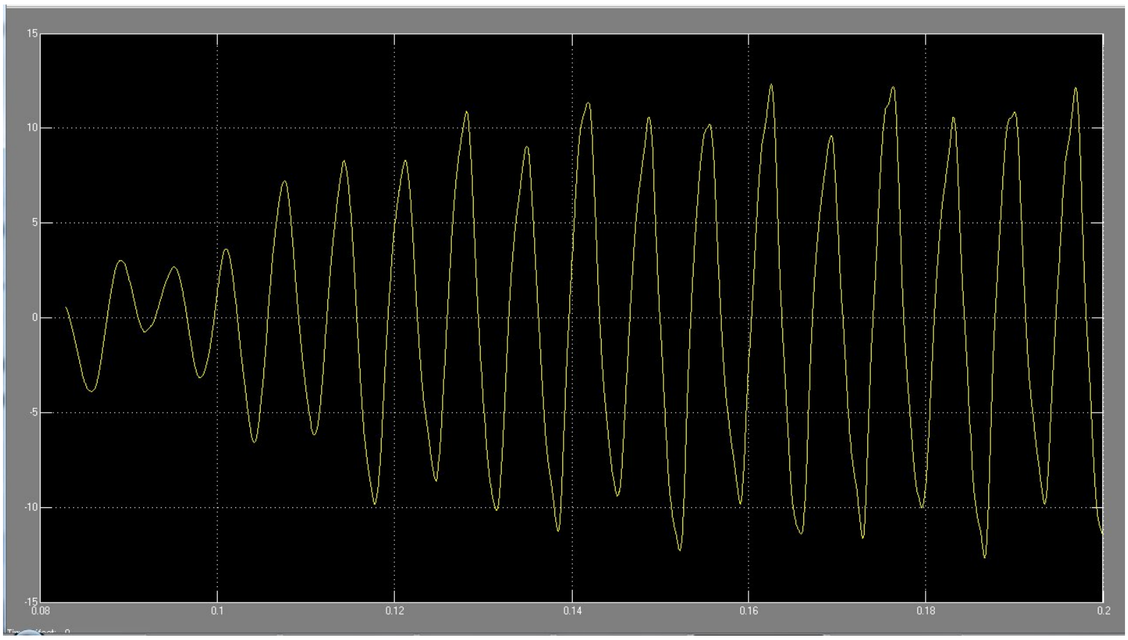


Fig 5.38 Voltage for phase ‘b’

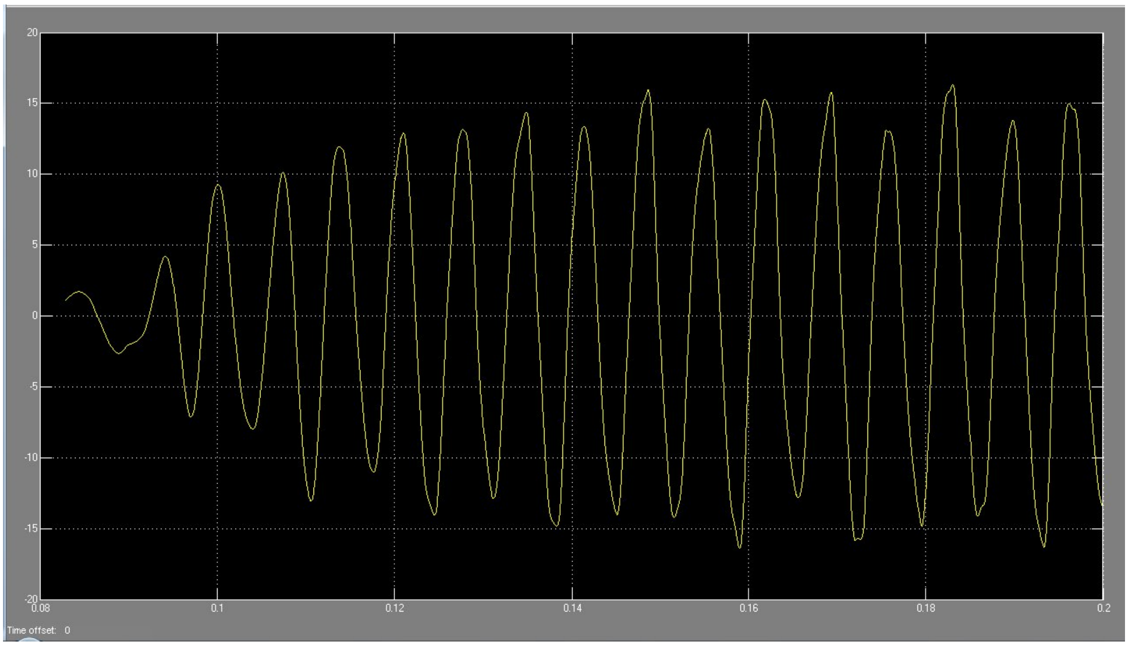


Fig 5.39 Voltage for phase ‘c’

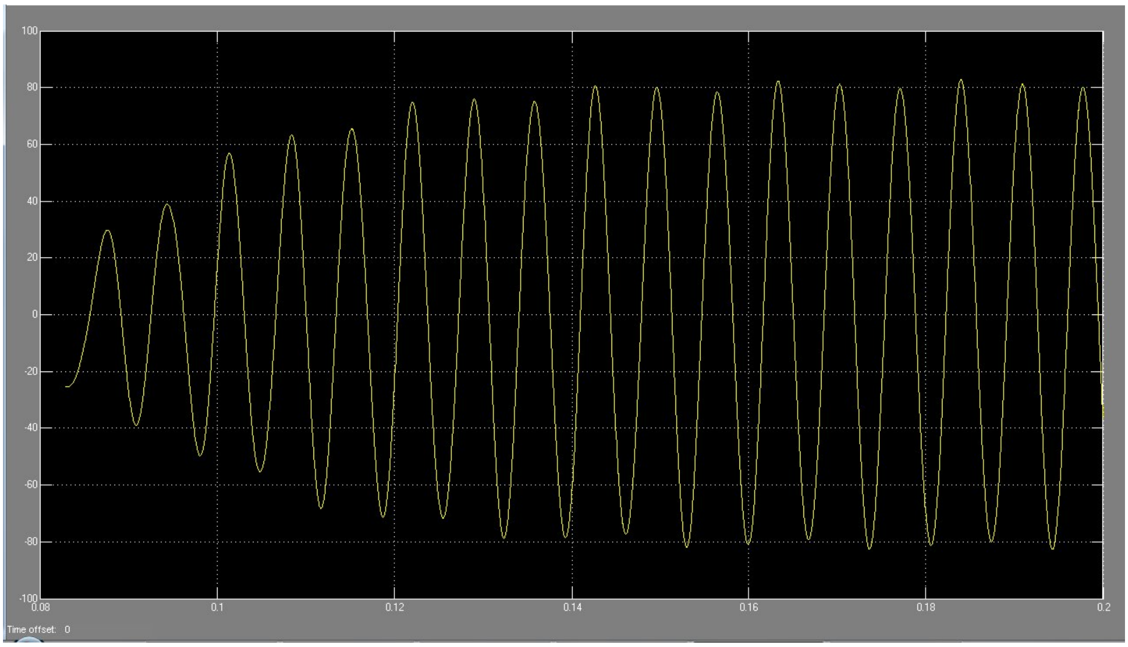


Fig 5.40 Current for phase ‘a’

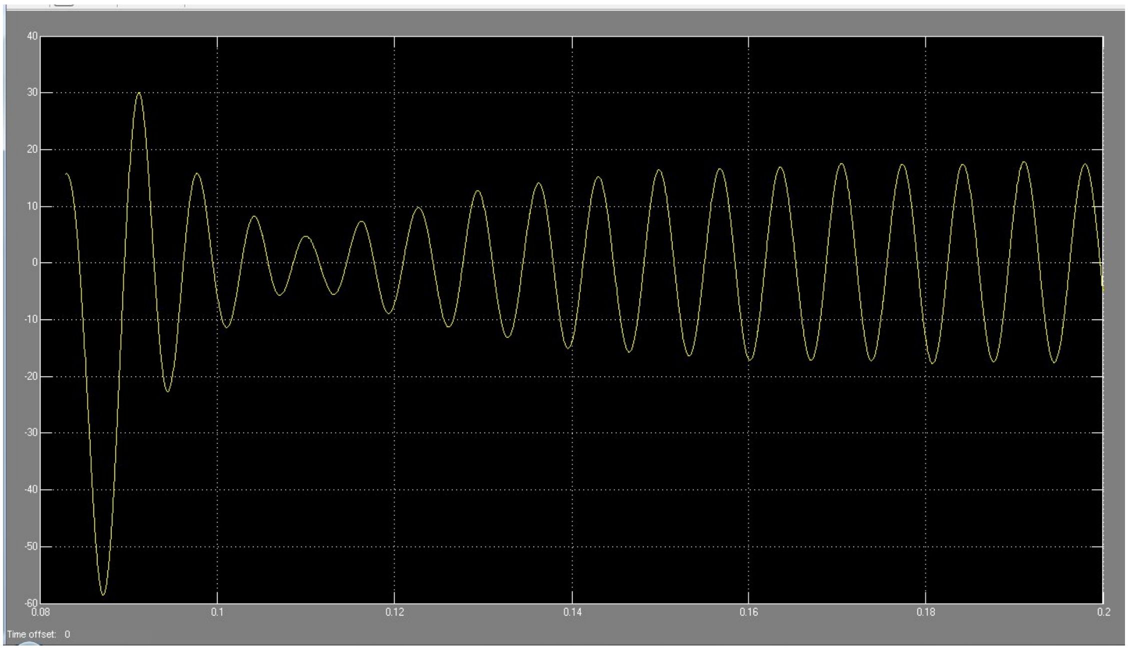


Fig 5.41 Current for phase 'b'

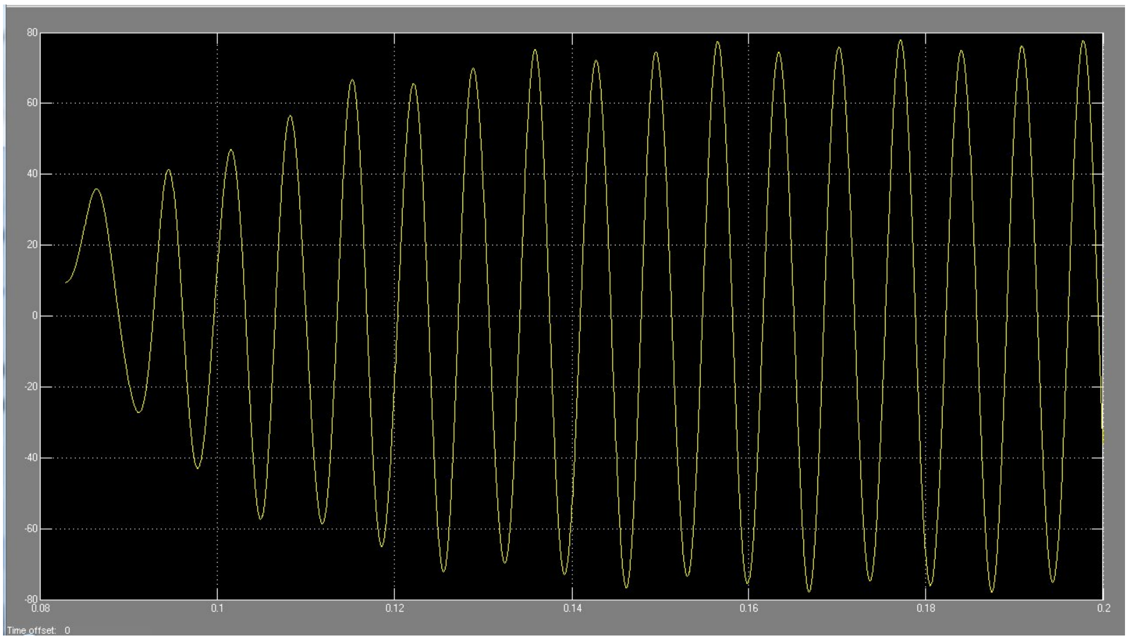


Fig 5.42 Current for phase 'c'

5.4 Impact of Degree of Compensation on Power flow

The function of the TCSC as a power oscillation damper can be explained from the expression for power transmission as a function of angular difference and transfer reactance

$$P = \frac{V_1 V_2 \sin\delta}{X} \tag{5.1}$$

When active power oscillations build up over a transmission corridor, the angular difference between the end voltages varies periodically with time, as well. If a mechanism is devised to introduce a “counter-oscillation” in some other member of the formula, i.e. the line reactance, the two oscillations can be made to cancel each other out The TCSC technology offers precisely this possibility. By introducing a time-varying element to the degree of compensation, the resulting transfer reactance X_L - X_C(t) can be made time-varying in a periodic way. With proper control of the TCSC, very effective power oscillation damping can be achieved

The Impact of variation of degree of compensation (k) on transmission capability is illustrated in table shown below. Here, the quantity k is the degree of compensation of the series capacitor, equal to the relationship between the capacitive reactance of the series capacitor (X_C) and the inductive reactance (X_L). δ is the angular difference between end voltages of the line. For a fixed angular difference, the active power transmission capability of the line increases as the degree of compensation increases. Vice versa, for a fixed amount of power transmission over the line, the angular difference decreases as k increases, which is a measure of increased dynamic stability of the transmission system.

Power transmitted in the 735 kV, 60 Hz transmission network under consideration with TCSC has been found using equation (5.1). The equivalent reactance of TCSC has been calculated using equation (3.14). α =60˚, X_C=15 ohm, δ=90˚ (maximum power transfer assumed), V_1 = V_2=735kV, base kV=735 kV and base MVA=2100 MVA has been used. It is seen that as the degree of compensation increases the power flow also increases. Graphical results can be seen in Fig.5.43&5.44.

The accepted limits of k are $0 \le k \le 5$.

Table 5.1 Effect of variation of k on P

α = 60°			
X_L(Inductive Reactance)Ω	k(Degree of Compensation)	P(Real Power)p.u	Q(Reactive Power)p.u
10	1.2247	2.3267	3.7687
8.5	1.3348	2.3328	3.7787
7	1.4639	2.3389	3.7885
4	1.9365	2.3509	3.8080
2.56	2.4206	2.3566	3.8172
2	2.738	2.3588	3.8207
1	3.8730	2.3627	3.8270
0.5	5.5772	2.3646	3.8302

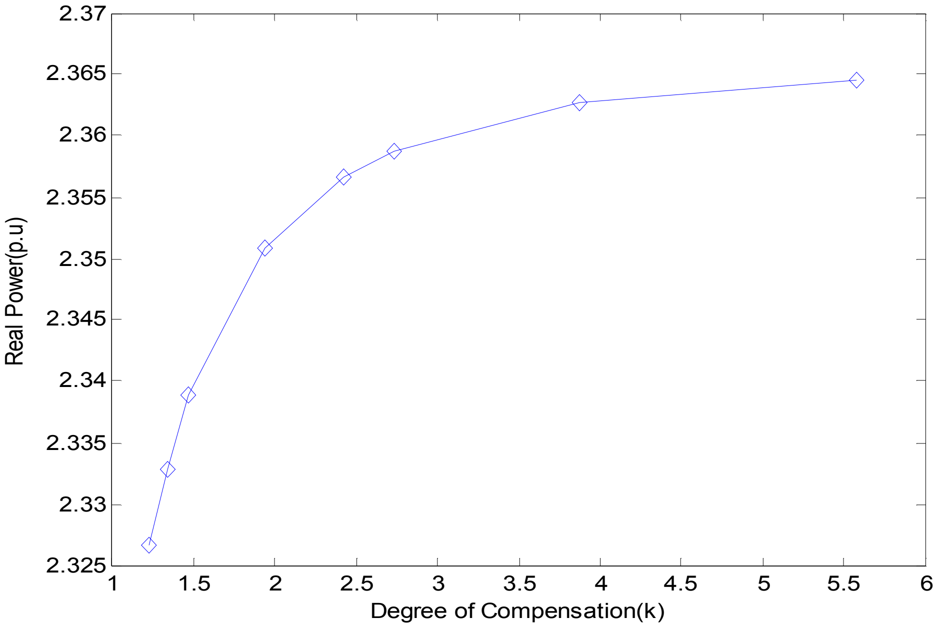


Fig. 5.43 Degree of Compensation vs. Real Power

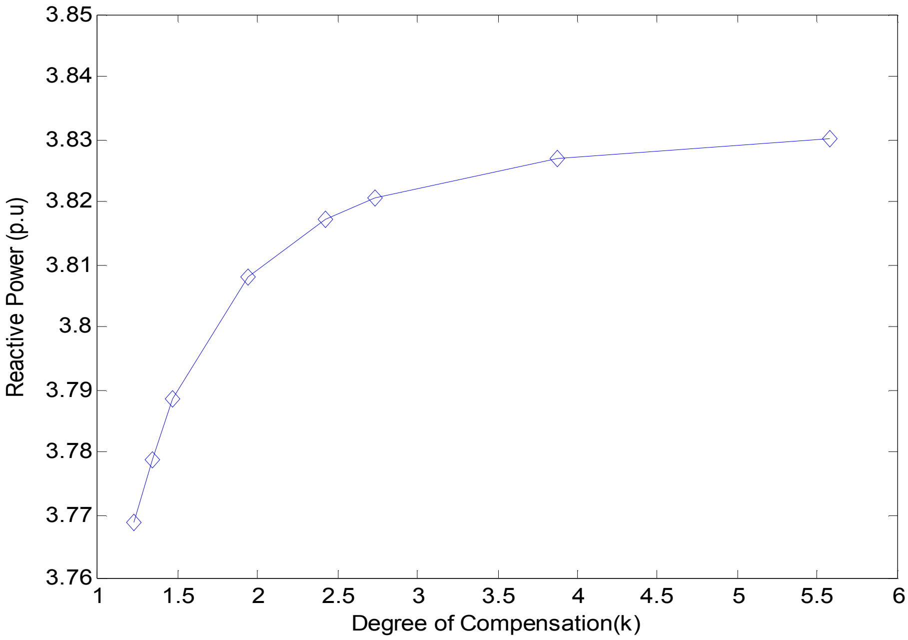


Fig. 5.44 Degree of Compensation vs. Reactive Power

Chapter 6

Conclusion and Future Work

6.1 Conclusion

Modelling of Thyristor Controlled Series Capacitor and case study of it on a transmission system has been carried out using MATLAB7.5/Simulink Power system Blockset. The simulation responses of TCR currents, capacitor currents and capacitor voltages have been presented for firing angle $\alpha=60^{\circ}$. After developing a transmission network for case study, simulation is carried out and the responses for each phases has been presented without TCSC connections and with TCSC. Different faults are created and the responses are analyzed under system disturbances. Further the impact of variation of degree of compensation on power flow is found out.

In this simulation, it is advantageous to have small inductive reactance (X_L) in providing well defined charge reversal and control of the time period of the compensating voltage which is important for handling sub-synchronous resonance. Small X_L increases the magnitude of current harmonics generated by the TCR and circulated through the series capacitor and thus also increases the magnitude of capacitor voltage harmonics injected into the line. The impedance of the TCR reactor does not significantly alter the physical operation of the TCSC; provided that it is sufficiently small in relation to the impedance of the capacitor to facilitate the desired control of the series compensation.

Since system oscillations are greatly influenced by line impedance, TCSC is effective in providing additional power oscillation damping. The harmonics in the system are also damped out in early cycles and there are no disturbances after that. The major benefits of TCSC are the abilities to schedule power flows along desired lines and to rapidly modulate the effective impedance in response to power system dynamics. It has been seen that with the increase in degree of compensation the power flow across the transmission line increases.

6.2 Future Work

The work done can be extended by installing TCSC at multiple sites in the system. Here single module of TCSC is used at the site, more number of modules can be installed. Further it can be coordinated with other FACTS controllers.

References

[1] Acha Enrique, Fuerte-Esquivel, Ambriz-Perez and Angeles-Camacho, *FACTS, Modeling and Simulation in Power Networks*, John Wiley & Sons Publication, IEEE Press, New York, 2004.

[2] Arunachalam M., Lal Ghamandi, CG Rajiv and MM Babu Narayanan, "Performance Verification of TCSC Control and Protection Equipment Using RTDS", *15th PSCC, Liege*, Session 32, Paper 6, pp.1-7, Aug. 2005.

[3] Ghosh Arindam, Chatterjee D., Bhandiwad P. and Pai M.A. , "Trajectory Sensitivity Analysis of TCSC Compensated Power System", *IEEE Power Engineering Society General meeting*, pp.1454-1459,Denver, June 2004.

[4] Grunbaum R. and Pernot Jacques, "Thyristor Controlled Series Compensator: A State of the Art Approach for Optimization of Transmission Over Power Links", *ABB Power Systems*, 2001.

[5] Hingorani NG and Gyugi L, *Understanding FACTS –Concepts and Technology of Flexible Ac Transmission Systems*, Standard Publishers Distributors, IEEE Press, New York, 2001.

[6] Helbing Scott G. and Karady G.G., "Investigations of an Advanced Form of Series Compensation", *IEEE transactions on Power delivery*, vol.9, no.2, pp.939-947, Apr. 1994.

[7] Jovcic Dragan and Pillai G.N., "Analytical Modelling of TCSC Dynamics", *IEEE Transactions on Power Delivery*,vol.20,no.2,pp. 1097-1104, Apr. 2005.

[8] Khederzadeh Mojtaba and SidhunTarlochan S., "Impact of TCSC on the Protection of Transmission Lines", *IEEE Transactions on Power Delivery*, vol.21,no.1, pp. 80-87, Jan. 2006.

[9] Larsen E.V, Clark K., Miske S.A. and Urbanek J., "Characteristics and Rating Considerations of Thyristor Controlled Series Compensation", *IEEE Transactions on Power Delivery*, vol.9, no.2, pp. 992-1000, Apr. 1994

[10] McDonald DJ,Urbanek J,Damsky B.L, “Modelling and Testing of a Thyristor for Thyristor Controlled Series Compensation (TCSC)”, *IEEE Transactions on Power Delivery*, vol.9,no.1,pp.352-359, Jan. 1994.

[11] Mathur RM and Varma RV, *Thyristor-based FACTS Controllers for Electrical Transmission Systems*, John Wiley & Sons Publications, IEEE Press, New York,2002.

[12]Morin Gaston, “Service Restoration Following a Major Failure on the Hydro-Quebec Power System”, *IEEE Transactions on Power Delivery*, vol.2, no.2, pp. 454-463, Apr. 1987.

[13] Nyati S., Wegner C.A., Delmerico R.W., Piwko R.J.,Baker D.H and Edris A., “Effectiveness of Thyristor Controlled Series Capacitor in Enhancing Power System Dynamics: An Analog Simulator Study”, *IEEE Transactions on Power Delivery*, vol. 9, no. 2, pp. 1018-1027, Apr. 1994.

[14] Othman Hisham A. and Angquist lennart, “ Analytical Modelling of Thyristor Controlled Series Capacitors for SSR studies”, *IEEE Transactions on Power Systems*, vol.11,no.1, p. 119-127, Feb. 1996.

[15] Padiyar K.R. and Prabhu Nagesh, “A Comparative Study of SSR Characteristics of TCSC and SSSC” *15th PSCC, Liege*, Session 34, Paper 2, pp. 1-7, Aug. 2005.

[16] Parks Owen C., Girgis AdlyA. and Frick Marion E., “Simulating Ferroresonance in a Series Compensated Distribution Network”, *IEEE Proceedings of Ninth International Conference on Harmonics and Quality of Power,* vol.1, pp.162-167, 2000.

[17] Paserba John J., Miller Nicholas W., Larsen Einar V. and Piwko Richard J. , “A Thyristor Controlled Series Compensation Model for Power System Stability Analysis”, *IEEE Transactions on Power Delivery* ,vol.10, no.3, pp.1471-1478, July 1995.

[18] Panda Sidharth, Padhy N.P. and Patel R.N, “ Genetically Optimized TCSC Controller for Transient Stability Improvement”, *International Journal of Computer, Information and System Science and Engineering* ,vol.1,no.1, pp.19-25.

[19] Panda Sidharth, Patel R.N and Padhy N.P., “Power System Stability Improvement by TCSC Controller Employing Multi-objective Genetic Algorithm Approach”, *International Journal of Intelligent technology*, vol.1, no.4 pp.266-273, Aug. 2006.

[20] Panda Sidharth and Padhy N.P, “Thyristor Controlled Series Compensator-based Controller Design Employing Genetic Algorithm: A Comparative Study”, *International Journal of Electronics, Circuits and systems*, vol.1, no.1, pp.38-47, 2007.

[21] Panda Sidharth and Padhy N.P, ‘Power System with PSS and FACTS Controller: Modelling, Simulation and Simultaneous Tuning Employing Genetic Algorithm”, *International Journal of Electrical, Computer and Systems Engineering*, vol.1, no.1, pp.9-18, 2007.

[22] Perkins Brian K. and Iravani M.R, “Dynamic Modeling of a TCSC with Application to SSR Analysis”, *IEEE Transactions on Power Systems*, vol. 12, no. 4, pp. 1619-1625, Nov. 1997.

[23] Singh J.G, Singh S.N. and Srivastava S.C., “Enhancement of Power System Security through Optimal Placement of TCSC and UPFC”, *IEEE Power Engineering Society General Meeting*, pp.1-6,June 2007.

[24] Sybille Gilbert and Le-Huy Hoang, “ Digital Simulation of Power Systems and Power Electronics Using the MATLAB/Simulink Power System Blockset”, *IEEE Power Engineering Society-Winter Meeting* 2000, Special Technical Edition Session, pp.2973-2982, 2000.

[25] Venegas T. and Fuerte-Esquivel C.R., “Steady State Modelling for Thyristor Controlled Series Compensator for Phase Domain Load Flow Analysis of Electric Networks”, *IEEE International Conference on Electric Utility Deregulation and Restructuring and Power Technologies*, pp.191-195, 2000.

[26] Xuequiang Zhao and chen chen,“Circuit Analysis of a Thyristor Controlled Series Compensation”, *IEEE*, *Power Engineering Society 1999 Winter Meeting*,vol.2, pp. 1067-1072, 1999.

[27] X.Zhou and J.Liang "Overview of Control Schemes for TCSC to Enhance the Stability of Power Systems" *IEE Prceedings Generation Transmission and. Distribution*, vol. 146, no. 2, pp. 125-130, Mar. 1999.

[28] Zhu W., Spee R., Mohler R.R., Alexander G.C., Mittlelsladt W.A and Maratukulam D., "An EMTP study of SSR Mitigation Using the Thyristor Controlled Series Compensator", *IEEE Transactions on Power Delivery*,vol.10,no.3, pp.1479-1485, July 1995.

[29] http://www.mathworks.com

[30] http://www.abb.com/FACTS

[31] http://www.siemens.com/energy