

**IMPROVED PERFORMANCE OF ZSI BASED UPFC FOR
ENHANCED POWER FLOW IN INTERCONNECTED
SYSTEM**

A Dissertation

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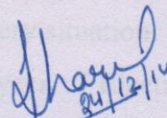
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CERTIFICATE

I hereby certify that the work which is being presented in the thesis entitled, "Improved Performance of ZSI based UPFC For Enhanced Power Flow In Interconnected Power System", in partial fulfilment of the requirements for the award of degree of Master of Engineering in Power System And Electric Drives submitted in Electrical and Instrumentation Engineering Department of Thapar University, Patiala is an authentic record of my own work and carried out under the supervision of Mr. Parag Nijhawan, Assistant Professor.

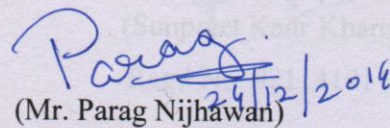
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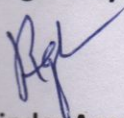


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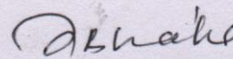
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ABSTRACT

In today's highly complex and interconnected power systems, there is a great need to improve power utilization while still maintaining reliability and security. Reducing the effective reactance of lines by series compensation is a direct approach to increase transmission capability. However, a power transfer capability of long transmission line is limited by stability consideration. Oscillation of generator angle or line angle are generally associated with the transmission system disturbances and can occur due to step changes in load, sudden change of generator output, transmission line switching and short circuit. This low frequency is important to damp as quickly as possible because they cause mechanical wear in power plants and cause power quality problem. If the electromechanical oscillations are not properly controlled in the electric power system operation, it may lead to a partial or total system outage. Instability problems in power systems that can lead to partial or full blackout can be broadly classified into three main categories, namely voltage, phase angle and frequency related problems. In early age this signal instability problem was solved by amortisseurs implemented in generator rotors, later with the application of fast excitation system this was solved by development & utilization of Power System Stabilizer (PSS) and however in modern power system due to the connection of power grids in vast area, for inter area oscillation damping due to the ability of controlling line impedance, power flow and bus voltage, Flexible AC transmission Systems (FACTS) devices implementation offers an alternative solution.

The ZSI employs an impedance network to connect the inverter main circuit to the power circuit thus providing unique features that overcomes the conceptual and theoretical barriers limitations of VSI and CSI. This inverter has unique features in terms of voltage (both buck & boost).

The focus of this research work is on a FACTS device known as Unified Power Flow Controller (UPFC) implemented with Z-Source Inverter (ZSI), which can provide simultaneous control of basic power system parameters like voltage, active power flow, reactive power flow, impedance and phase angle. Employing ZSI in UPFC further improves the performance of UPFC in transmission network. In this research work, simulation models for interconnected power systems are carried out without UPFC, with VSI based UPFC and With ZSI based UPFC. Simulation models have been incorporated into MATLAB based Power System Toolbox (PST). These models were analyzed for active power flow and reactive power flow with and without UPFC. Performance analysis of VSI based UPFC and ZSI based UPFC has been studied under faulty conditions also. The results of the power system without UPFC and with VSI based UPFC and ZSI based UPFC are compared and the conclusion is given at the end under normal and abnormal conditions.

LIST OF ABBREVIATIONS

FACTS	: Flexible Alternating Current Transmission Systems
TCSC	: Thyristor-controlled series compensator
TCPST	: Thyristor-controlled phase shifting transformer
UPFC	: Unified Power Flow Controller
ZSI	: Z-Source Inverter
HVDC	: High Voltage Direct Current
STATCOM	: Static Compensator
SSSC	: Static Synchronous Series Controller
VSI	: Voltage Source Inverter
CSI	: Current Source Inverter
GTO	: Gate turn-off Thyristors
IGBT	: Insulated Bipolar Transistors

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CHAPTER 1

INTRODUCTION

1.1. Introduction

In interconnected power systems, it is important to have control over power transfer. This can improve stability and allow transmission lines to be loaded closer to their thermal limits. In order to have a better use of the transmission capabilities of the transmission lines, different types of FACTS devices have been studied: static compensator (STATCOM), thyristor-controlled series compensator (TCSC), thyristor-controlled phase shifting transformer (TCPST). Among the FACTS devices, the unified power flow controller (UPFC) is a power electronics-based system considered as the most powerful, which can provide full dynamic control of the parameters of a transmission line: bus voltage, line impedance and phase angle.

A number of Flexible Alternating Current Transmission System (FACTS) controllers are available today due to the rapid development in the field of power electronics. Generally, each of these controllers can act only on one of the three parameters (voltage, impedance and angle), that determine the power flow through a transmission line. But Unified Power Flow Controller (UPFC) is such a versatile FACTS device that has the capability of controlling all the three parameters simultaneously. With the rapid development of power electronics, it is possible to design power electronic equipment of high rating for high voltage systems, the voltage stability problem resulting from transmission system may be, at least partly, improved by use of the equipment well-known as FACTS-controllers.

In the transmission area, application of power electronics consists of HVDC power transmission and FACTS. HVDC is an economical way to interconnect power systems, which are situated in different regions and separated by long distances or those which have different frequencies. HVDC involves conversion of ac to dc at one end and conversion of dc to ac at the other end. Also, there is a widespread use of microelectronics, computers and high speed communication for control & protection of present transmission system.

FACTS being a new technology will play the principal role to enhance controllability and power transfer capability in an ac system. FACTS technology is not a single high power controller, but rather a collection of controllers, which can be applied individually or in coordination with others to control one or more of the interrelated system parameters. This technology has opened up new opportunities for controlling power and enhancing the usable capacity of present, as well as new and upgraded lines. Current through a line can be controlled at a reasonable cost enabling a large potential of increasing the capacity of the existing line and the

use of FACTS controllers to enable the corresponding power to flow through such lines under normal and contingency conditions [1-5].

1.2. Basic types of FACTS Controller

FACTS controller can be classified into four categories:

- a) Series Controller (e.g. Static Synchronous Series Controller (SSSC))
- b) Shunt Controller (e.g. STATCOM, D-STATCOM)
- c) Combined Series – Series Controller
- d) Combined Series – Shunt Controller (e.g. Unified Power Flow Converter (UPFC))

FACTS devices are used as power flow controller and the voltage source converter in a line ultimately resulting into oscillation damping. Series controllers are used to control power flow and oscillations damping in a line. Shunt devices are effective to control voltage [1-5].

A voltage in series with the transmission line can be introduced to control the current flow and thereby the power transmissions from the sending end to the receiving end. A series compensator in principle injects a voltage in series with the line. As long as the voltage is in phase quadrature with the line current, the series compensator supplies or consumes variable reactive power only. Therefore, the series compensator could be variable impedance (such as a capacitor or a reactor) or a power electronics-based variable source of main frequency, and subsynchronous and harmonic frequencies (or a combination) to meet the desired control strategy. For example Static Synchronous Series Compensator (SSSC).

In the shunt compensation, a current is injected into the system at the point of connection. This can be implemented by varying shunt impedance, a voltage source, or a current source. As long as the injected current is in phase quadrature with the line voltage, the shunt compensator only supplies or consumes variable reactive power. Power converters using thyristors, gate turn-off thyristors(GTOs) or gate insulated bi-polar transistors (IGBTs) can be used to control the injected current or the compensating voltage. For Example STATCOM, D-STATCOM [6].

A Unified Power Flow Controller (UPFC) is a typical FACTS device capable of instantaneous control of three system parameters. Unified Power Flow Controller (UPFC) is able to control both the transmitted real power and the reactive power flows. The Unified Power Flow Controller (UPFC), with its unique combination of fast shunt and series compensation, is a powerful device which can control three power system parameters [6].

1.3 Orientation of work

The introduction of Power System Stability Problem, Literature Review, Importance of FACTS devices are given in chapter 1.

Chapter 2 Presents the Literature Review, Gap in Literature Review, Problem Formulation and Objective of the thesis work.

Chapter 3 Introduces the Construction, Principle, and Control of Unified Power Flow Controller (UPFC) as shunt converter and as series converter.

Chapter 4 Introduces the Working Principle, Control Methods and Advantages of ZSI.

Chapter 5 Presents the SIMULATION models for performance analysis of Simulink models without UPFC, with VSI based UPFC and with ZSI based UPFC under normal and abnormal (Three phase to ground fault) conditions.

The Results and Discussion of the Thesis work are given in chapter 6.

Conclusions and Future scope of the Thesis work is presented in Chapter 7.

CHAPTER 2

LITERATURE REVIEW

2.1. Overview of the work of other researchers

Xiao-Ping Zhang and Keith R Godfrey [1] presented the mathematical models for eleven new UPFC series control modes. These include direct voltage injection, bus voltage regulation, line impedance compensation and phase angle regulation.

B. Kawkabani, et .al [2] described the modelling of Unified Power Flow Controllers (UPFC) to study the steady-state and transient behaviour of electrical networks equipped with FACTS devices. Detailed time-domain simulations are carried out on four model power systems (single-machine system and multi-machine systems including the IEEE-14 bus test system), to illustrate the control features of these devices and their influence to increase power transfer and improve system stability. The interaction between the UPFC, the network and the machines are analyzed.

Y. Jaganmohan Reddy, et .al [3] focused on the design of an HPS (Hybrid Power System) for the building which is a part of the urban electrification.

Pramod Kumar Gouda, et .al [4] proposed to model and simulate a unified power flow controller (UPFC) in power system computer aided design and electromagnetic transient direct current (PSCAD/EMTDC) environment. The series converter of the UPFC controls the transmission line real/reactive power flow and the shunt converter of the UPFC controls the UPFC bus voltage/shunt reactive power and the DC link capacitor voltage.

Anna Baby, et .al [5] described the works carried out to evaluate the present system requirement and the proposal for the most optimal location for FACTS device to meet the requirement. The criterion used in finding the optimal location is based on the voltage profile of the system; ie the voltage deviation at each bus with respect to its optimum value is minimized.

Muhammad H. Rashid [6] described the different types of compensators and their applications.

Sheng-Huei Lee, et .al [7] presented the hybrid Unified Power-Flow Controllers (UPFCS) models for power flow calculations is developed: an ideal voltage source model is used to represent the series part while an ideal current source model is used to represent the shunt part

N.F. Mailah, et .al [8] deals with the study and simulation of Unified Power Flow Controller at its normal and abnormal conditions using MATLAB software.

Maryam Hashemi Namin [9] presented the monitoring of active power flow in the faulted line for the system with and without UPFC.

J. Dejvices and T.C. Green [10] addressed two issues: enhancement of fault recovery and controller design accounting for filter dynamics. Performance of the Unified Power Flow Controller (UPFC) is improved by a proposed modification of the UPFC into double Static Synchronous Series Compensator (SSSC) in order to double its capability in fault recovery mode.

M.Noroozian, et .al [11] presented the optimal power flow control in electric power systems by use of unified power flow controller (UPFC). Models suitable for incorporation in power flow programs are developed and analysed.

Z.J. Meng and P.L. So [12] presented a current injection model of unified power flow controller (UPFC) that is suitable for use in power system stability studies.

Savinder Malik and Lalit Dalal [13] analysed the Simulink models for voltage, active power flow and reactive power flow, with and without UPFC.

K. Belacheheb and S. Saadate [14] compared the three power flow control approaches.

Amit Shiwalkar and N. D. Ghawghawe[15] described the practical contingency condition of a transmission line, over which a study using UPFC is done without sacrificing the available generation capacity. Simulation were carried out using MATLAB software to overcome the contingency condition by using UPFC.

Fang Zheng Peng [16] presented an impedance-source (or impedance-fed) power converter and its control method for implementing dc-to-ac, ac-to-dc, ac-to-ac, and dc-to-dc power conversion.

Suresh L, et .al [17] presented the Z – source inverters as an alternative power conversion concept as they have both voltage buck and boost capabilities. These inverters use a unique impedance network, coupled between the power source and converter circuit, to provide both voltage buck and boost properties, which cannot be achieved with conventional voltage source and current source inverters.

B.Anvari, et .al [18] presented the Z-source inverter for controlling the speed and reducing the torque ripple of a brushless DC motor.

Byamakesh Nayak and Saswati Swapna Dash [19] analysed the different control techniques for Z-Source inverter.

2.2. Gap in Literature Review

Gaps in the Literature Review are as follows:

- Application of ZSI based UPFC to show the power flow improvement in transmission system.
- Comparison of performance of VSI based UPFC and ZSI based UPFC to reduce the level of Fault current and I^2R losses in the transmission system under three phase to ground fault in transmission system.

2.3. Problem Formulation

In this dissertation, it is proposed to analyse the performance of ZSI based UPFC in power flow improvement. The comparison of VSI based UPFC and ZSI based UPFC has been done in this work. Simulink models are used for this analysis.

Firstly, the performance analysis is done in normal condition and then in abnormal condition i.e. under Three phase fault condition.

The results are compared under different conditions.

2.4. Objective of the Work

Objective of this research work is:

- To improve the performance of transmission line with the application of UPFC.
- To investigate the simulation models of transmission system using VSI based UPFC and ZSI based UPFC to show the improvement of Power Flow and to compare their performances under Normal and Abnormal condition.

CHAPTER 3

UNIFIED POWER FLOW CONTROLLER

3.1. Introduction

The use of power electronic controllers - Flexible AC Transmission Systems (FACTS) - in electric power systems is becoming increasingly widespread due to rapid progress in power electronic technology. The main objectives of FACTS are to increase the useable transmission capacity of lines, to control power flow over designated transmission routes, and to provide voltage support. Better utilization of existing power system capacities by installing new power electronic controllers such as FACTS has become imperative. FACTS devices are able to change, in a fast and effective way, the network parameters in order to achieve a better system performance. FACTS controllers make it possible to control circuit impedance, voltage angle and power flow for optimal operation performance of power systems. Among the converter based FACTS controllers, the UPFC is a versatile FACTS controller.

The Unified Power Flow Controller is a sort of multi-function controller which can play an important role in solving various transmission system problems. UPFC is able to control, simultaneously or selectively, all the parameter effecting power flow in the transmission line i. e. real power, reactive power, voltage, impedance and phase angle. This unique capability is signified by the adjective “UNIFIED” in its name, alternatively it can independently control the real and reactive power flow in the line. The versatility afforded by UPFCs provides an opportunity to solve various problems of large scale power systems in real-time within reasonable costs.

The objective of this chapter is to describe the construction, principles and different modes of operation of the UPFC. For clarity a simple single-phase circuit is considered in this chapter to describe the different modes of the UPFC operation [7-10].

3.2. UPFC Principle

The unified power flow controller consists of two switching converters. These converters are operated from a common dc link provided by a dc storage capacitor shown in Figure. 3.1.

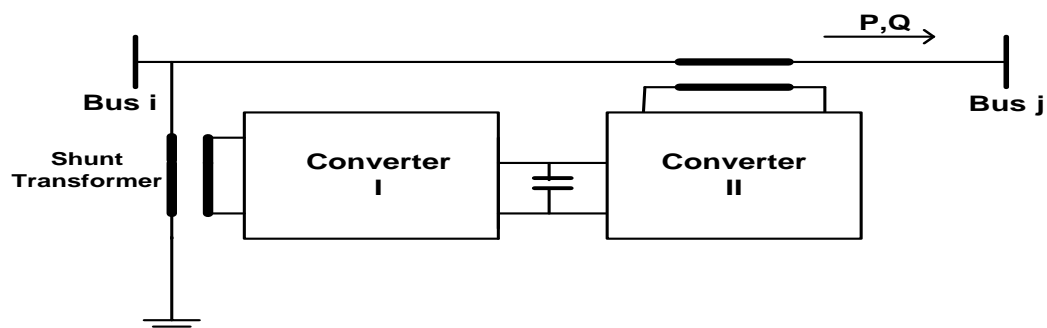


Figure 3.1. Basic Configuration of UPFC

Converter 2 provides the main function of the UPFC by injecting an ac voltage with controllable magnitude and phase angle in series with the transmission line via a series transformer. The basic function of converter 1 is to supply or absorb the real power demand by converter 2 at the common dc link. It can also generate or absorb controllable reactive power and provide independent shunt reactive compensation for the line. Converter 2 supplies or absorbs locally the required reactive power and exchanges the active power as a result of the series injection voltage [11-14].

This arrangement functions as an ideal a.c. to a.c. power converter in which the real power can freely flow in either direction between the a.c. sides of the two inverters. Due to the different functions of the two inverters in the system, inverter 1 is referred to as the exciter and inverter 2 as the booster. The reactive power on the two a.c. sides of the inverters can be controlled independently.

The series inverter (inverter 2) is connected to the transmission line through a booster transformer in a manner similar to the SSSC. The shunt inverter is connected to the system bus through an excitation transformer in the same way as an ASVC. Therefore, the UPFC can be considered as a multi-function controller which is capable of providing the performance of one or two FACTS devices. Because of its structure, the UPFC provides new dimensions of controllability, which have not been achieved with other FACTS controllers.

The UPFC can provide simultaneous control of all basic power system parameters (transmission voltage, impedance and phase angle). The controller can fulfill functions of reactive shunt compensation, series compensation and phase shifting meeting multiple control objectives. From a functional perspective, the objectives are met by applying a boosting transformer injected voltage and a exciting transformer reactive current. The injected voltage is inserted by a series transformer.

Besides transformers, the general structure of UPFC contains also a "back to back" AC to DC voltage source converters operated from a common DC link capacitor, Figure 1. First converter (CONV1) is connected in shunt and the second one (CONV2) in series with the line. The shunt converter is primarily used to provide active power demand of the series converter through a common DC link. Converter 1 can also generate or absorb reactive power, if it is desired, and thereby provide independent shunt reactive compensation for the line. Converter 2 provides the main function of the UPFC by injecting a voltage with controllable magnitude and phase angle in series with the line via a voltage source. Figure 3.2. shows the electric circuit arrangement of UPFC.

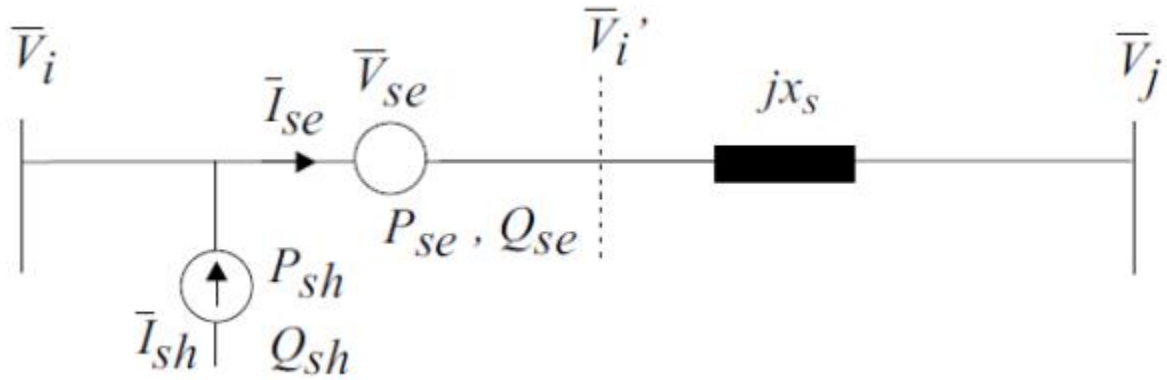


Figure 3.2. The UPFC electric circuit arrangement

3.3. CONTROL OF UPFC

As the UPFC consists of two converters that are coupled on the DC side, the control of each converter is taken up individually.

3.3.1 As the Shunt Converter

The shunt converter draws a controlled current from the system. One component of this current, I_r which is automatically determined by the requirements to balance the real power supplied to the series converter through the DC link. This power balance is enforced by regulating the DC capacitor voltage by feedback control.

The other component of the shunt converter current is the reactive current, I_r which can be controlled as in a STATCOM. There are two operating (control) modes for a STATCOM or the shunt converter. These are:

1. VAR control mode where the reactive current reference is determined by the inductive or capacitive VAR command. The feedback signals are obtained from current transformers (CT) typically located on the bushings of the coupling (step down) transformer.
2. Automatic voltage control mode where the reactive current reference is determined by the output of the feedback voltage controller which incorporates a droop characteristic (as in the case of a SVC or a STATCOM). The voltage feedback signals are obtained from potentials transformer (PT) measuring V_1 at the substation feeding the coupling transformer [1-3].

3.3.2 As the Series Converter

The series converter control is aimed at the injecting a series voltage of the required magnitude and angle. There are different control modes for the series voltage listed below.

1. Direct voltage injection mode where the converter simply generates a voltage phasor in response to the reference input. A special case is when the desired voltage is in quadrature with the line current.
2. Phase angle shifter emulation mode where the injected voltage \widehat{V}_c is phase shifted relative to the voltage V_l by an angle specified by the reference input.
3. Line impedance emulation mode where the series injected voltage is controlled in proportion to the line current. The complex impedance (the injected voltage divided by the line current) seen by the line current is determined by the reference inputs. It is essential to take care (in employing this control mode) to avoid instability or resonance. For example, negative values of the resistance can cause instability. A large value of the capacitive (negative) reactance can result in resonance.
4. Automatic power flow control mode where the reference inputs determine the required real power (P) and the reactive power (Q) at a specified location in the line. Both P and Q can be controlled independently of each other in a feasible region determined by the satisfaction of various constraints that will be discussed later.

In this control mode, series injected voltage is determined by a vector control system to ensure the flow of the desired current (phasor) which is maintained even during system disturbances (unless the system control dictates the modulation of the power and reactive power). Although the normal conditions dictate the regulation of the complex power flow in the line, the contingency conditions require the controller to contribute to system stability by damping power oscillations [3].

CHAPTER 4

ZSI (Z-Source Inverter)

4.1. Introduction

There exist two traditional converters: voltage-source (or voltage-fed) and current-source (or current-fed) converters.

4.1.1. Voltage Source Inverter

Figure 4.1. shows the traditional three-phase voltage-source converter structure. A dc voltage source supported by a relatively large capacitor feeds the main converter circuit, a three-phase bridge. The dc voltage source can be a battery, fuel-cell stack, diode rectifier, and/or capacitor. Six switches are used in the main circuit; each is traditionally composed of a power transistor and an antiparallel (or freewheeling) diode to provide bidirectional current flow and unidirectional voltage blocking capability [16-17].

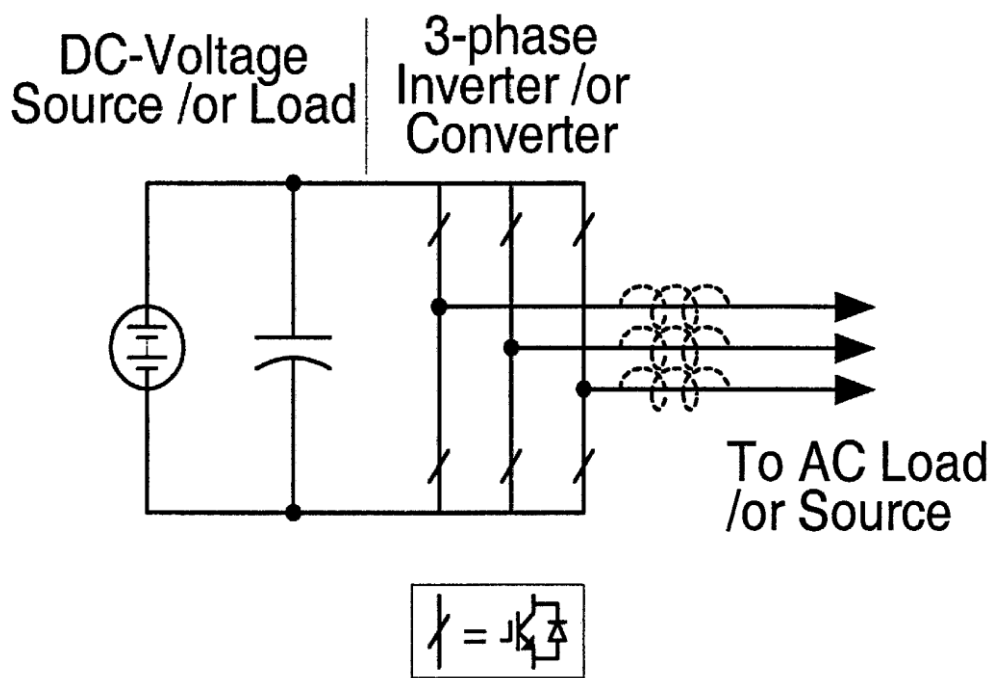


Figure 4.1. Traditional V-Source Converter

The V-source converter is widely used. It, however, has the following conceptual and theoretical barriers and limitations.

- The ac output voltage is limited below and cannot exceed the dc-rail voltage or the dc-rail voltage has to be greater than the ac input voltage. Therefore, the V-source inverter is a buck (step-down) inverter for dc-to-ac

power conversion and the V-source converter is a boost (step-up) rectifier (or boost converter) for ac-to-dc power conversion. For applications where over drive is desirable and the available dc voltage is limited, an additional dc-dc boost converter is needed to obtain a desired ac output. The additional power converter stage increases system cost and lowers efficiency.

- The upper and lower devices of each phase leg cannot be gated on simultaneously either by purpose or by EMI noise. Otherwise, a shoot-through would occur and destroy the devices. The shoot-through problem by electromagnetic interference (EMI) noise's misgating-on is a major killer to the converter's reliability. Dead time to block both upper and lower devices has to be provided in the V-source converter, which causes waveform distortion, etc.
- An output *LC* filter is needed for providing a sinusoidal voltage compared with the current-source inverter, which causes additional power loss and control complexity [16-17].

4.1.2. Current Source Inverter

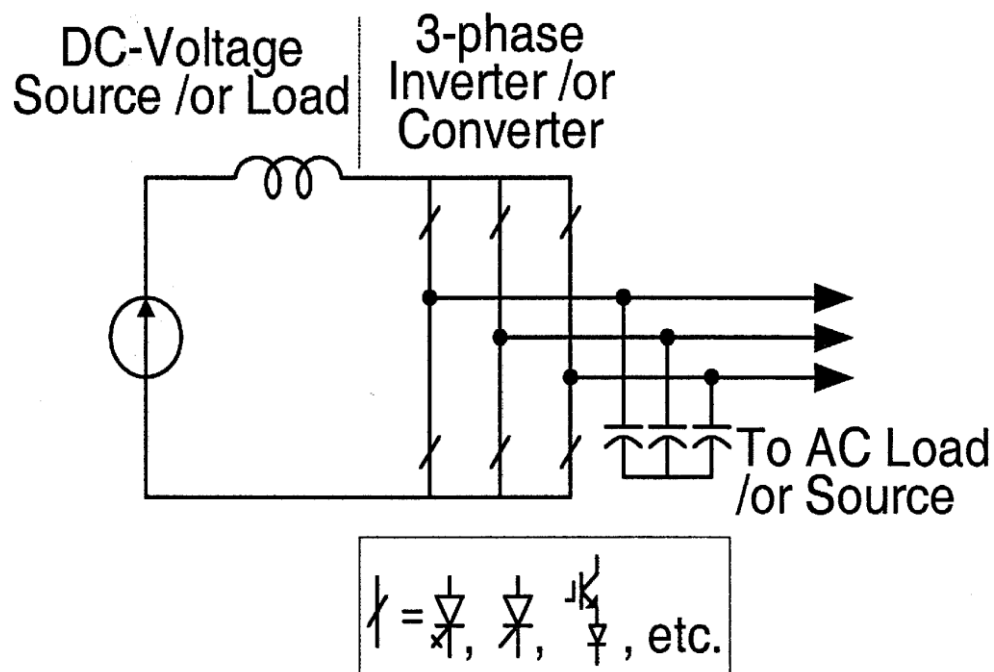


Figure 4.2. Traditional I-Source Converter

Figure 4.2. shows the traditional three-phase current-source converter (I-source converter) structure. A dc current source feeds the main converter circuit, a three-phase bridge. The dc current source can be a relatively large dc inductor fed by a voltage source such as a battery, fuel-cell stack, diode rectifier, or thyristor converter. Six switches are used in the main circuit, each is traditionally composed of a semiconductor switching device with reverse block capability such as a gate-turn-off thyristor (GTO) and SCR or a power transistor with a series diode to provide unidirectional current flow and bidirectional voltage blocking. However, the I-source converter has the following conceptual and theoretical barriers and limitations.

- The ac output voltage has to be greater than the original dc voltage that feeds the dc inductor or the dc voltage produced is always smaller than the ac input voltage. Therefore, the I-source inverter is a boost inverter for dc-to-ac power conversion and the I-source converter is a buck rectifier (or buck converter) for ac-to-dc power conversion. For applications where a wide voltage range is desirable, an additional dc–dc buck (or boost) converter is needed. The additional power conversion stage increases system cost and lowers efficiency.
- At least one of the upper devices and one of the lower devices have to be gated on and maintained on at any time.

Otherwise, an open circuit of the dc inductor would occur and destroy the devices. The open-circuit problem by EMI noise's misgating-off is a major concern of the converter's reliability. Overlap time for safe current commutation is needed in the I-source converter, which also causes waveform distortion, etc.

- The main switches of the I-source converter have to block reverse voltage that requires a series diode to be used in combination with high-speed and high-performance transistors such as insulated gate bipolar transistors (IGBTs).

This prevents the direct use of low-cost and high-performance IGBT modules and intelligent power modules (IPMs).

In addition, both the V-source converter and the I-source converter have the following common problems.

- They are either a boost or a buck converter and cannot be a buck–boost converter. That is, their obtainable output voltage range is limited to either greater or smaller than the input voltage.
- Their main circuits cannot be interchangeable. In other words, neither the V-source converter main circuit can be used for the I-source converter nor vice versa.
- They are vulnerable to EMI noise in terms of reliability [16-17].

4.1.3. Z – Source Inverter

The Z-Source Inverter has been invented by F.G.Peng et al(Peng 2003). The ZSI inverter concept can be applied to all dc-to-dc, dc-to-ac, ac-to-dc, and ac-to-ac power conversion. Figure shows the general ZSI structure. The ZSI employs an impedance network to connect the inverter main circuit to the power circuit thus providing unique features that overcomes the conceptual and theoretical barriers limitations of VSI and CSI. The most unique feature of the ZSI is its low cost [18].

The main objective of static power converters is to produce an AC output waveform from a dc power supply. Impedance source inverter is an inverter which employs a unique impedance network coupled with the inverter main circuit to the power source. This inverter has unique features in terms of voltage (both buck & boost) compared with the traditional inverters. A two-port network that consists of a split-inductor and capacitors that are connected in X shape is employed to provide an impedance source (Z-source) coupling the inverter to the dc source, or another converter. The DC source/load can be either a voltage or a current source/load. Therefore, the

DC source can be a battery, diode rectifier, thyristor converter, fuel cell, PV cell, an inductor, a capacitor, or a combination of those. Switches used in the converter can be a combination of switching devices and anti-parallel diode as shown in figure 4.3.

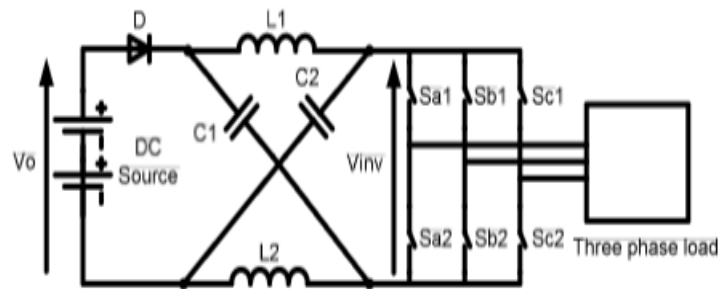


Figure. 4.3. ZSI

Six switches are used in the circuit; each is traditionally composed of a power transistor and an anti-parallel (or freewheeling) diode to provide bidirectional current flow and unidirectional voltage blocking capability. The commonly used switches are Metal Oxide Semi-Conductor Field Effect Transistor (MOSFET), Insulated Gate Bipolar Transistor (IGBT), Bipolar Junction Transistor (BJT), Silicon Controlled Rectifier (SCR), and Gate Turn off Thyristor (GTO) etc. Here we employed IGBT as the switch as it combines the advantages of both BJT and MOSFET [17].

4.2. Impedance Network

ZSI overcomes the above problems of the traditional V-source and I-source converters. The impedance source network includes a combination of two inductors and two capacitors. The combined circuit network works as energy storage or filtering element for the impedance source inverter. The impedance network provides a second order filter. This is more effective to repress voltage and current ripples. The inductor and capacitor requirement should be small than traditional inverters. When the two inductors ($L1$ and $L2$) are small and approach zero, the impedance decreases to two capacitors ($C1$ and $C2$) in parallel and becomes traditional voltage source. Therefore, a traditional voltage inverter's capacitor requirement and physical size are the worst cases for the impedance source inverter. Considering additional filtering and energy storage supplies by the inductors, the impedance source network should needs less capacitance and smaller size compare with the traditional voltage source inverter. Similarly, when two capacitors ($C1$ and $C2$) are small and approach zero, the impedance source network decrease to two inductors ($L1$ and $L2$) in series and become a traditional current source. Therefore a current inverter's inductor requirement and physical size and the worst cases. VSI and CSI are used in only buck or boost operation of inverters while Z-source inverter used in both buck and boost mode operation of the inverter [16-18].

4.3. Working of ZSI

The configuration of 3-phase Z-source inverter is shown in Figure 4.3. It consists of 2 identical inductors and 2 identical capacitors which are composed to form a unique impedance network to avoid short circuit when the devices are in shoot through mode, a diode to block reverse current, and a three phase bridge as in traditional inverter. In 3-phase Z-source inverter, one additional control parameter is introduced, namely the Boost Factor (B), which modifies the AC output voltage equation of traditional 3-phase PWM inverter as following.

$$\hat{v}_{out} = BM V_o/2 \quad (4.1)$$

Where:

\hat{v}_{out} = Maximum sinusoidal inverter output voltage

B = Boost factor

M = Modulation Index

V_o = DC Input voltage

If we replace BM with G, then we may rewrite 4.1 as

$$\hat{v}_{out} = GV_o/2 \quad (4.2)$$

G is the inverter gain,

$$G = BM \quad (4.3)$$

It can be seen that 4.2 has the same form with that of the traditional VSI, i.e.

$$\hat{v}_{out} = MV_o/2 \quad (4.4)$$

Boost Factor is obtained by introducing shoot through of minimally one pare of the inverter arm for a short period of time which called shoot-through time.

$$B = 1/ (1 - 2T_o/T) = 1/(1 - 2D_o) \quad (4.5)$$

Where

T_o = Shoot Through Time 0

T = Switching Period1

D_o = Shoot through Duty Ratio

Thus, in the 3-phase Z-source inverter we have 9 permissible switching states, unlike the traditional 3-phase V source inverter that has eight. They comprise 6 active states, 2 zero states, and 1 additional zero state called shoot through zero states that is forbidden in traditional voltage source inverter.

4.4. Different Control Techniques of ZSI

4.4.1. Simple Boost Control Technique

This control strategy inserts shoot through in all the PWM traditional zero states during one switching period. This maintains the six active states unchanged as in the traditional carrier based PWM. The relation between these two parameters is expressed in equation 4.6. We can see from the equation that shoot-through duty ratio (D_o) decreases with increasing modulation index (M).

$$D_o = 1 - M \quad (4.6)$$

From 4.3 and 4.5 we get

$$G = BM = M / (1 - 2D_o) \quad (4.7)$$

Since $D_o = 1 - M$, thus

$$G = M / (1 - 2D_o) = M / (1 - 2(1 - M)) = M / (2M - 1) \quad (4.8)$$

Equation 4.8 infers that the inverter gain (G) can be controlled by adjusting modulation index (M). If we rearrange 4.1 in the original PWM output voltage equation form, we get

$$\hat{v}_{out} = MBV_o/2 \quad (4.9)$$

BV_o should be the dc input voltage of the traditional VSI which in the case of Z-source inverter is the dc voltage applied to inverter bridge.

Say

$$BV_o = V_{inv} \quad (4.10)$$

From 4.3 and 4.8,

$$B = 2G - 1 \quad (4.11)$$

Substitute 4.11 to 4.10, the voltage stress across the devices is

$$V_{inv} = (2G - 1) V_o = V_o / (2M - 1) \quad (4.12)$$

4.4.2. Maximum Boost Control Method

Maximum boost control method converts all traditional zero states to shoot-through while maintaining the six active states remain unchanged. By this control strategy the shoot-through duty cycle varies each cycle. The inverter gains maximum shoot-through time which in turn gives the inverter higher boost factor, according to equation 4.5. Thus, with the same modulation index as in simple boost control method, we get higher voltage

gain. As the shoot-through duty cycle varies each cycle, what we are interested in is the average value of the duty cycle. In the interval $(\pi/6, \pi/2)$, the average shoot through duty ratio can be expressed as following.

$$\begin{aligned} \frac{\bar{T}_O}{T} &= \frac{\int_{\pi/6}^{\pi/2} (2 - M \sin \theta - M \sin(\theta - 2\pi/3)) d\theta}{2} \\ &= \frac{2\pi - 3\sqrt{3}\pi}{2\pi} \end{aligned} \quad (4.13)$$

From 4.5 and 4.13,

$$B = 3.14 / (5.19M - 3.14) \quad (4.14)$$

The inverter voltage gain (G) is obtained as

$$G = BM = 3.14 M / 5.19M - 3.14 \quad (4.15)$$

Maximum Boost Control Method gives higher Voltage gain for the same modulation index [19].

4.4.3. Third harmonic injection control

This method is opted to use the increased range of modulation indexes. In third harmonic injection constant boost technique the sinusoidal reference signal is merged with third harmonic sinusoidal waveforms with one third amplitude of the fundamental, to generate non-sinusoidal waveforms. Constant shoot-through is introduced in zero states by comparing the triangular carrier wave with a positive, negative constant magnitude and generated non-sinusoidal sinusoidal reference waveforms as in simple boost control. Further, variable shoot-through times are provided considering the third harmonic injected sinusoidal reference waveforms and triangular carriers like maximum boost control.

4.5. Advantages of Z-Source Inverter

The following are the advantages of Z-source inverter when compared to the VSI and CSI:

1. Secures the function of increasing and decreasing of the voltage in the one step energy processing i.e. it works as a buck boost inverter.
2. The main circuit of a ZSI can either be the traditional VSI or the Traditional CSI.
3. Improve resistant to failure switching and EMI distortions.
4. Relatively simple start-up.
5. Provide ride-through during voltage sags without any additional circuits.
6. Improve power factor reduce harmonic current and common-mode voltage.
7. Provides a low-cost, reliable and highly efficient single stage for buck and boost conversions.
8. The load of a ZSC can either be inductive or capacitive or another Z-Source network [17-18].

CHAPTER 5

SIMULATION MODELS FOR PERFORMANCE ANALYSIS OF UPFC

5.1. Overview of system modelling

The benefits of the UPFC and its injection model with several types of control strategies contributing to alleviation of the voltage stability & power transfer capability are explored by analyzing an interconnected system consisting of a combination of a hydro power generating station and Programmable Voltage Source with 4 buses system. The active and reactive power flow is checked. The system model is observed with without UPFC, with VSI based UPFC and with ZSI based UPFC. The work is extended with the Analysis of an interconnected system under Three phase to ground fault without UPFC, with VSI based UPFC and with ZSI based UPFC.

A Unified Power Flow Controller (UPFC) is used to control the power flow in a 500 kV transmission system. It consists of two 100-MVA, three-level, 48-pulse GTO-based converters, one connected in shunt at bus B1 and one connected in series between buses B1 and B2. The shunt and series converters can exchange power through a DC bus. The series converter can inject a maximum of 10% of nominal line-to-ground voltage (28.87 kV) in series with line L2. PI control strategy is used. Different cases are studied under different conditions and results are shown at the end.

5.2. Case I: Power system with programmable Voltage Source

5.2.1. Simulation model without UPFC

SIMULINK model without UPFC for power system with Programmable voltage source of rating 1200MVA to a load via transmission lines is shown in figure 5.1. The ratings of the various components are shown. The active power and reactive power curves with respect to time is shown in figure 5.2.

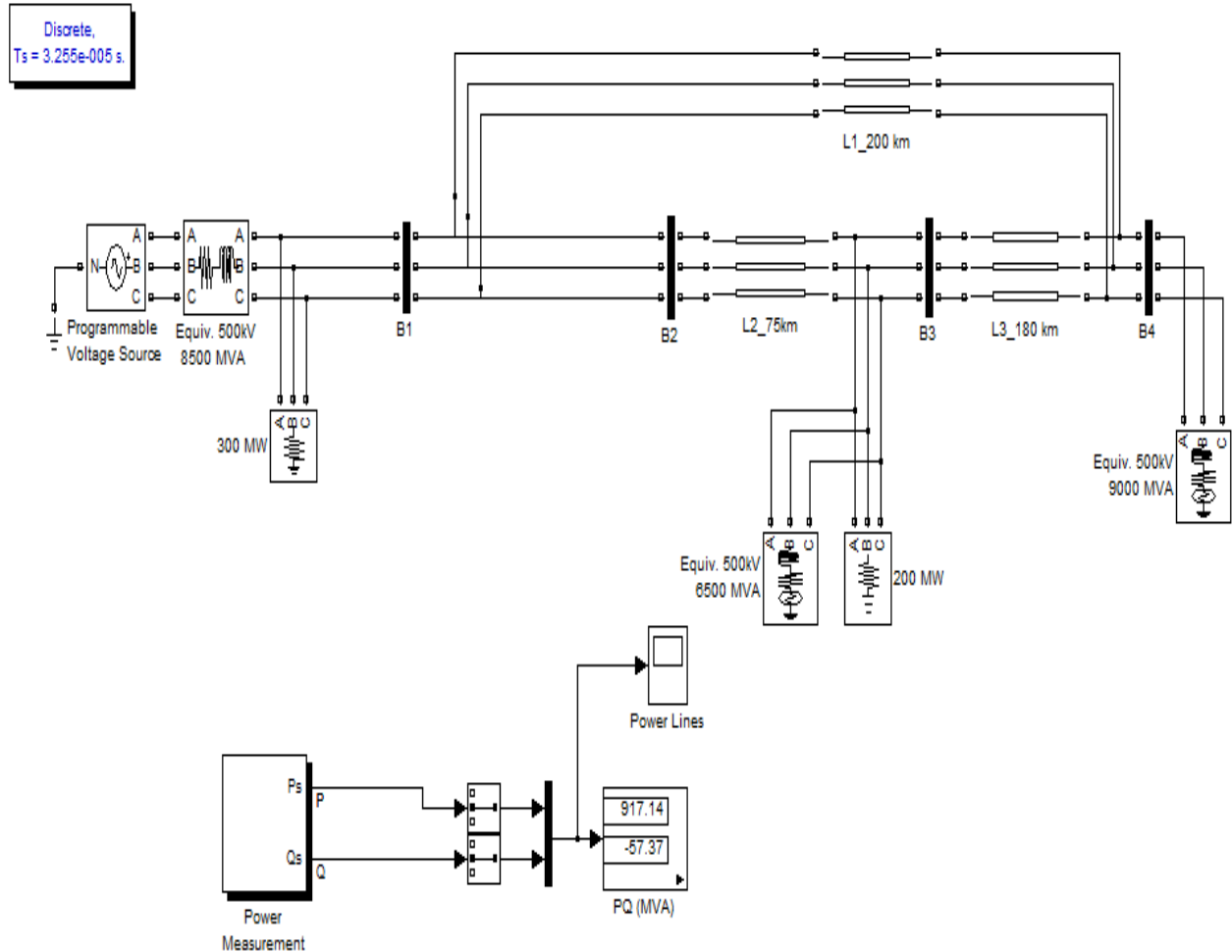


Figure 5.1. Simulation model without UPFC

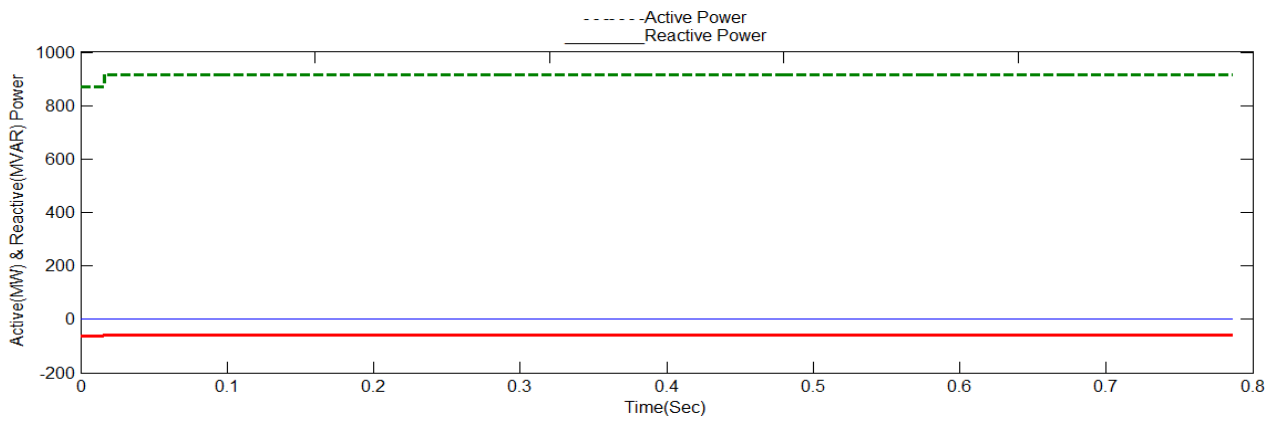


Figure 5.2. Active and Reactive Power Flow

5.2.2. Simulation model with VSI based UPFC

SIMULINK model with VSI based UPFC for power system with Programmable voltage source of rating 1200MVA to a load via transmission lines is shown in figure 5.3. The ratings of the various components are shown. The active power and reactive power curves with respect to time is shown in figure 5.4.

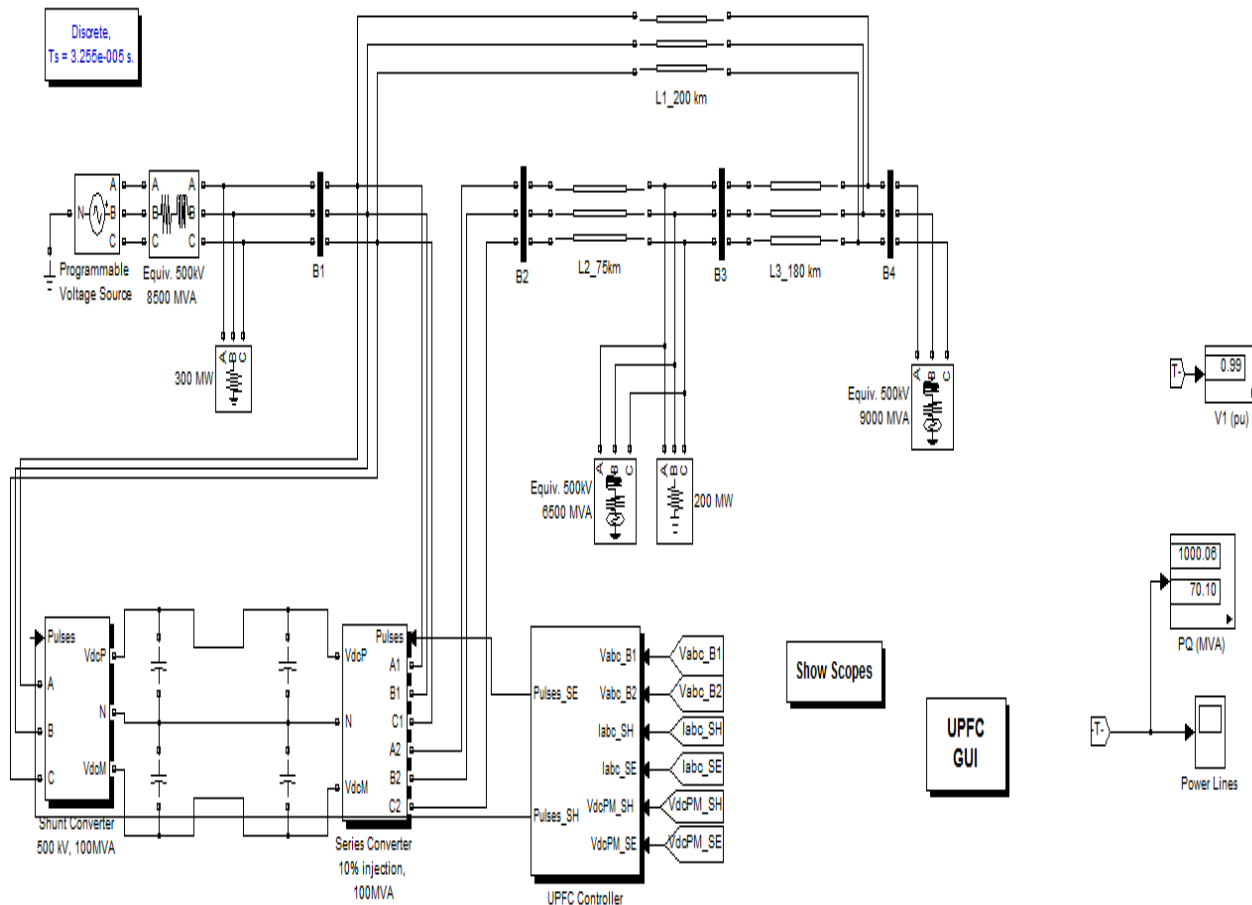


Figure 5.3. Simulation model with VSI based UPFC

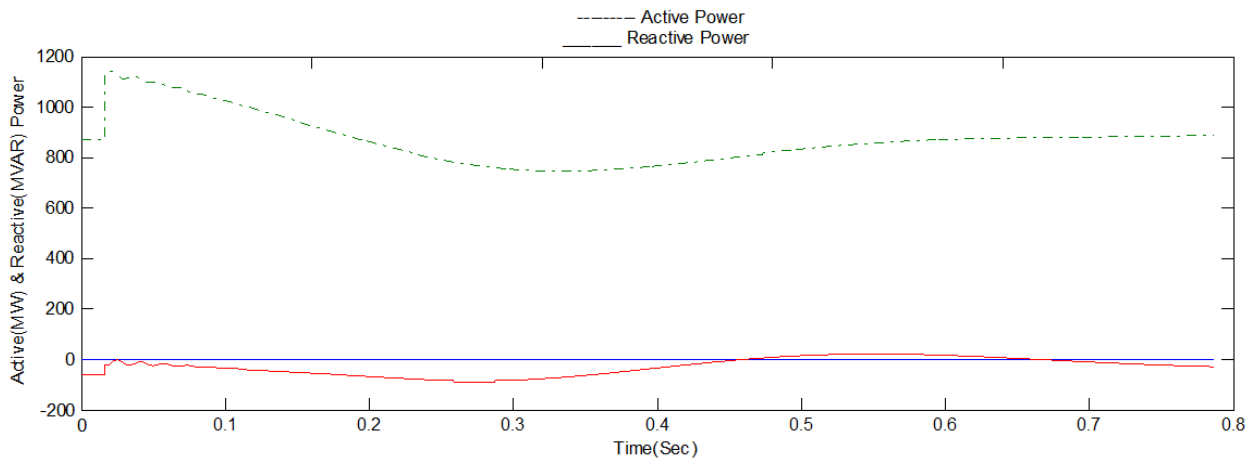


Figure 5.4. Active and Reactive Power Flow

5.2.3. Simulation model with ZSI based UPFC

SIMULINK model with ZSI based UPFC for interconnected power system with Programmable voltage source of rating 1200MVA to a load via transmission lines is shown in figure 5.5. The ratings of the various components are shown. The active power and reactive power curves with respect to time are shown in figure 5.6.

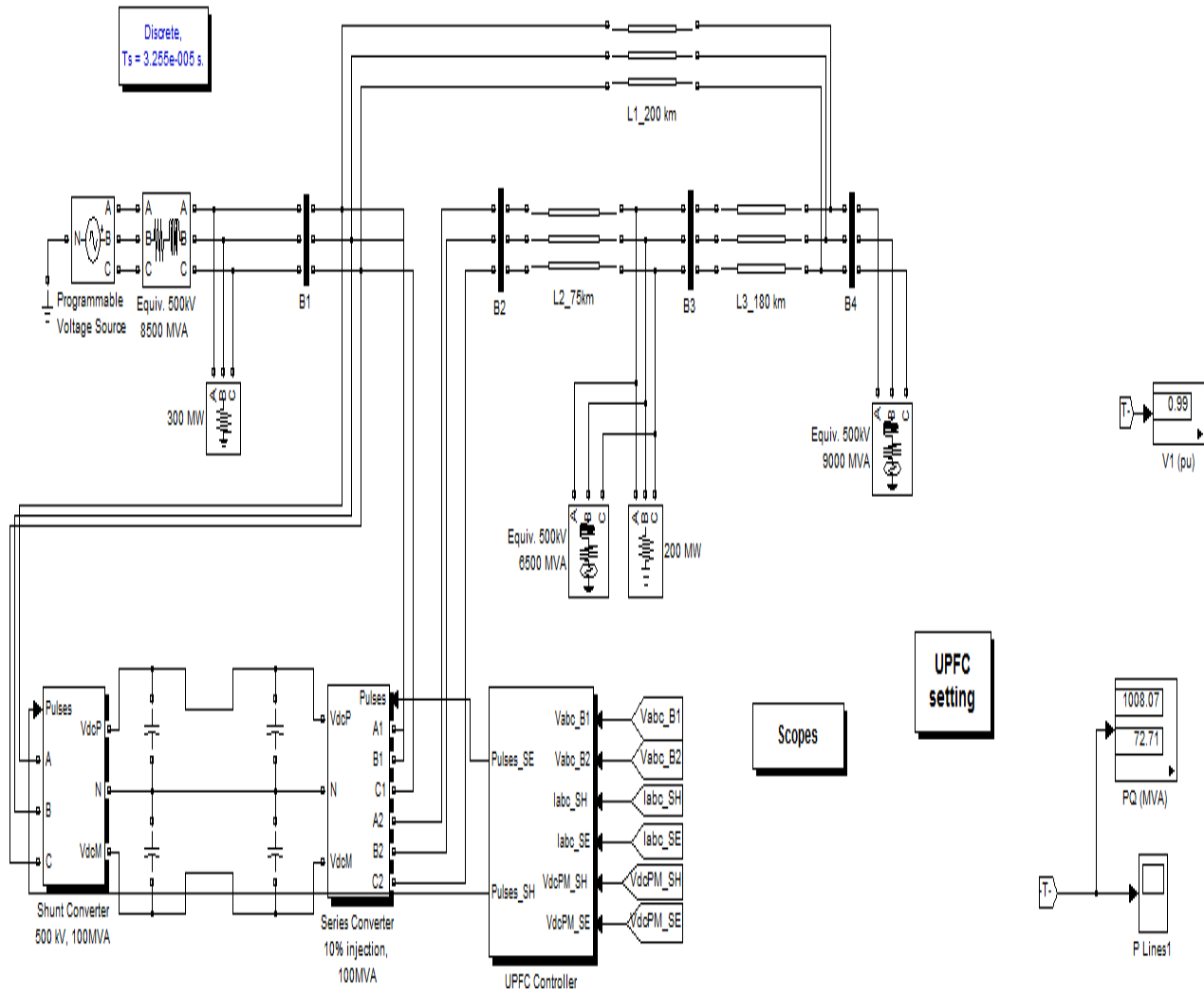


Figure 5.5. Simulation model with ZSI based UPFC

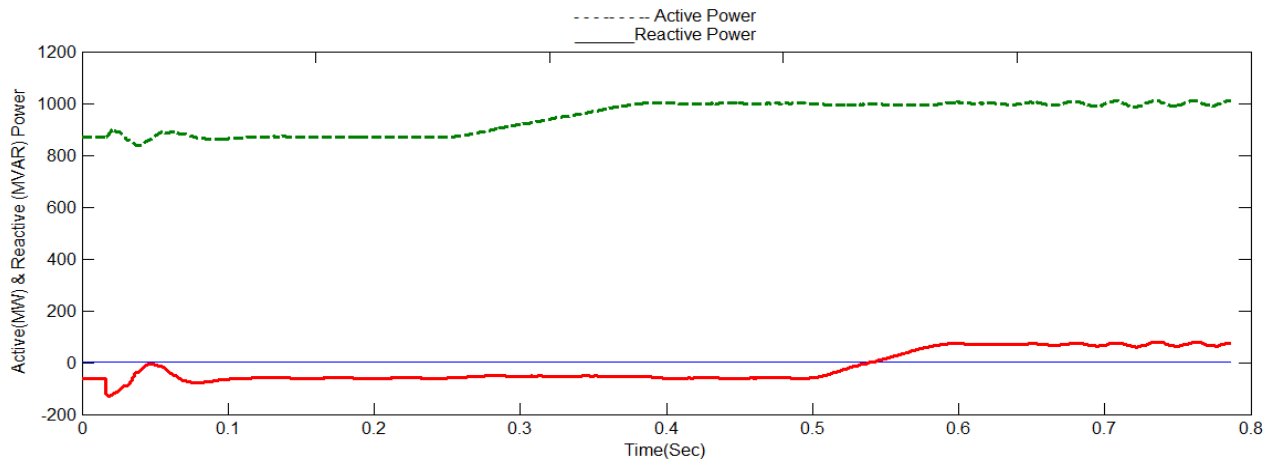


Figure 5.6. Active and Reactive Power Flow

5.2.4. Simulation model Under Three phase to ground fault condition without UPFC

SIMULINK model without UPFC for power system with Programmable voltage source of rating 1200MVA to a load via transmission lines is shown in figure 5.7. The ratings of the various components are shown. The active power and reactive power curves with respect to time, Fault current w.r.t time and I^2R w.r.t. Time are shown in figures 5.8, 5.9 and 5.10 respectively.

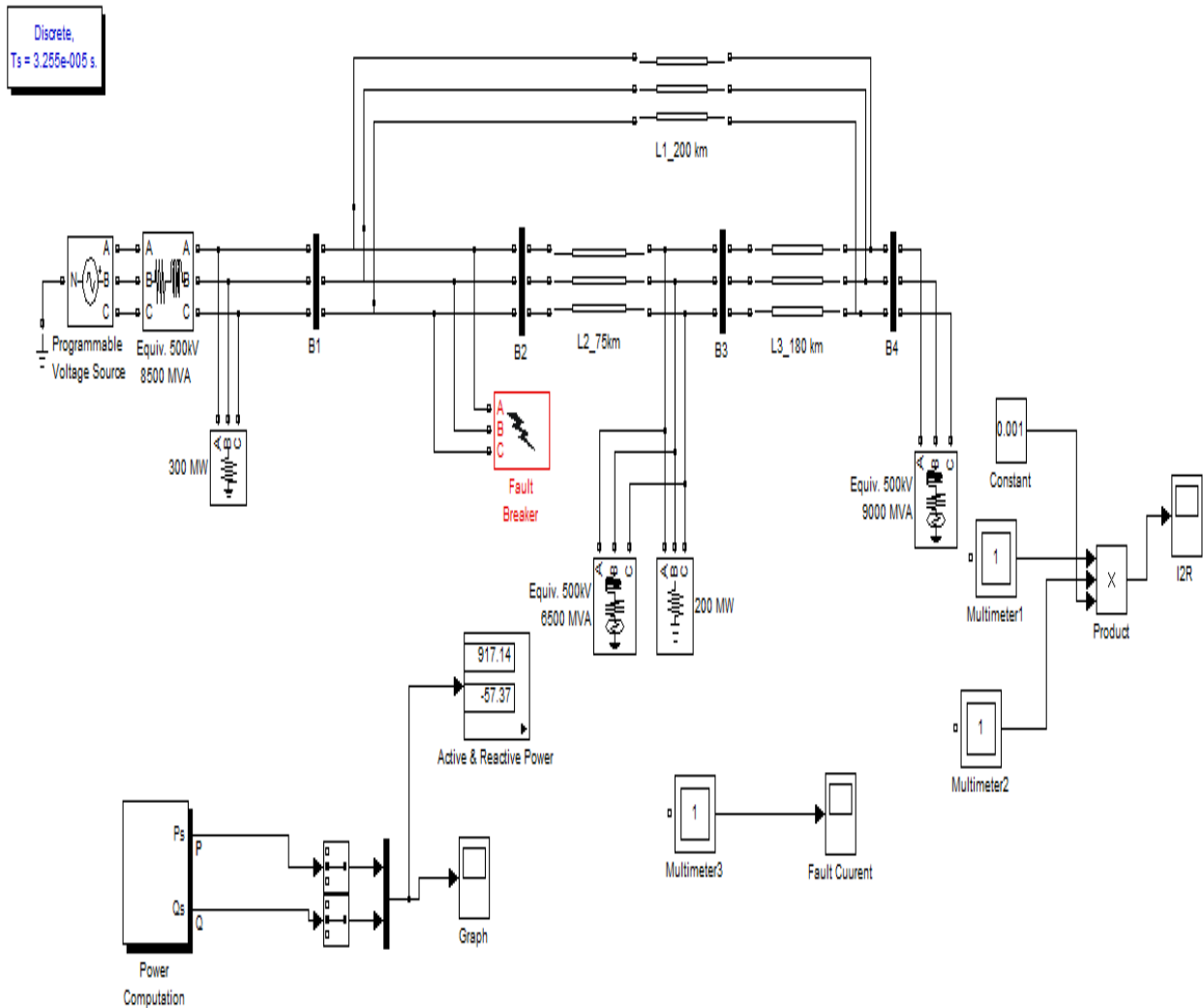


Figure 5.7. Simulation Model without UPFC under Three phase to Ground Fault Condition

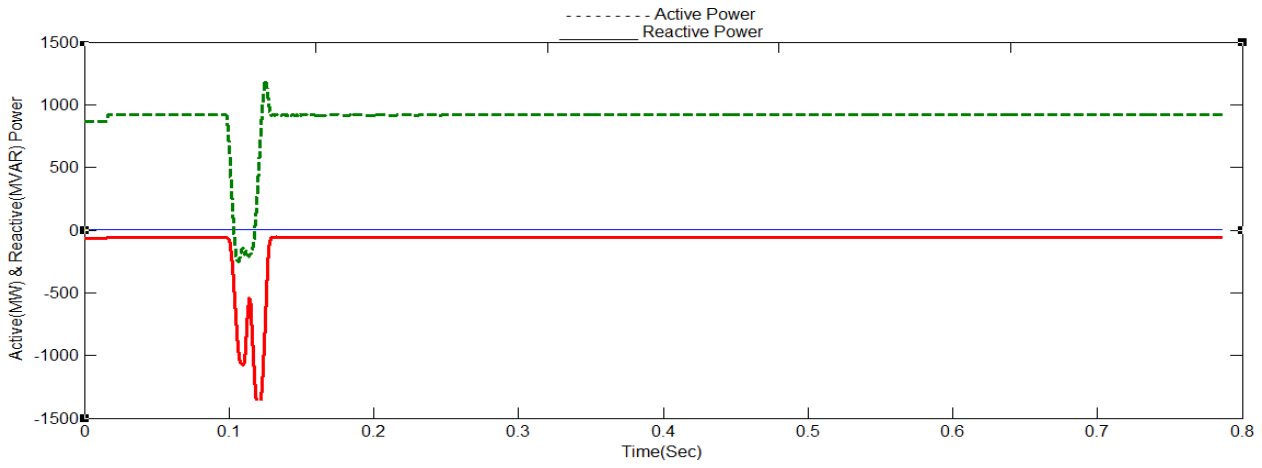


Figure 5.8. Active and Reactive power flow

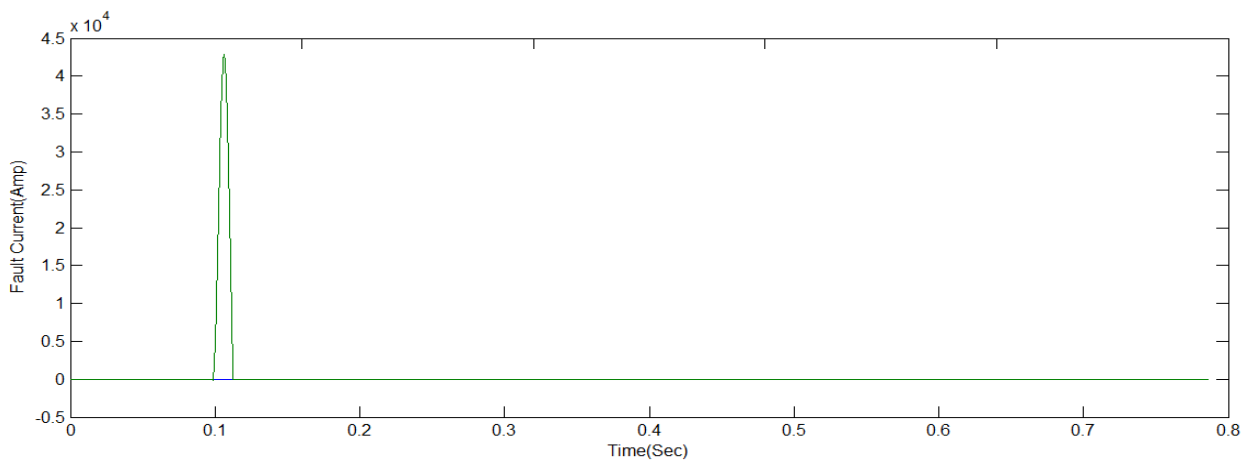


Figure 5.9. Fault Current w.r.t. Time

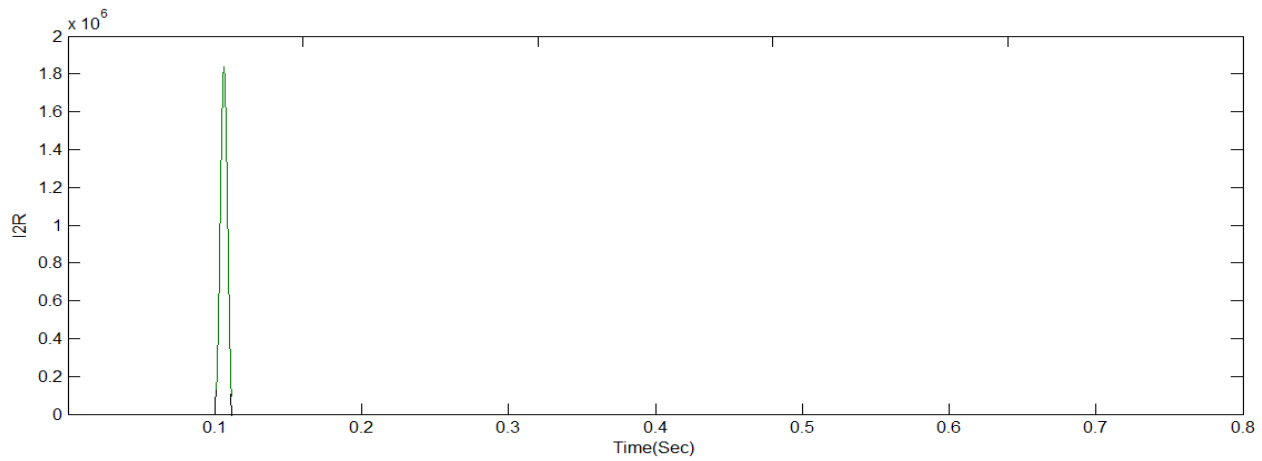


Figure 5.10. I^2R w.r.t. Time

5.2.5. Simulation model Under Three phase to ground fault condition with VSI based UPFC

SIMULINK model with VSI based UPFC under three phase fault condition for power system with Programmable voltage source of rating 1200MVA to a load via transmission lines is shown in figure 5.11. The ratings of the various components are shown. The active power and reactive power curves with respect to time, Fault current w.r.t time and I^2R w.r.t. Time are shown in figures 5.12, 5.13 and 5.14 respectively.

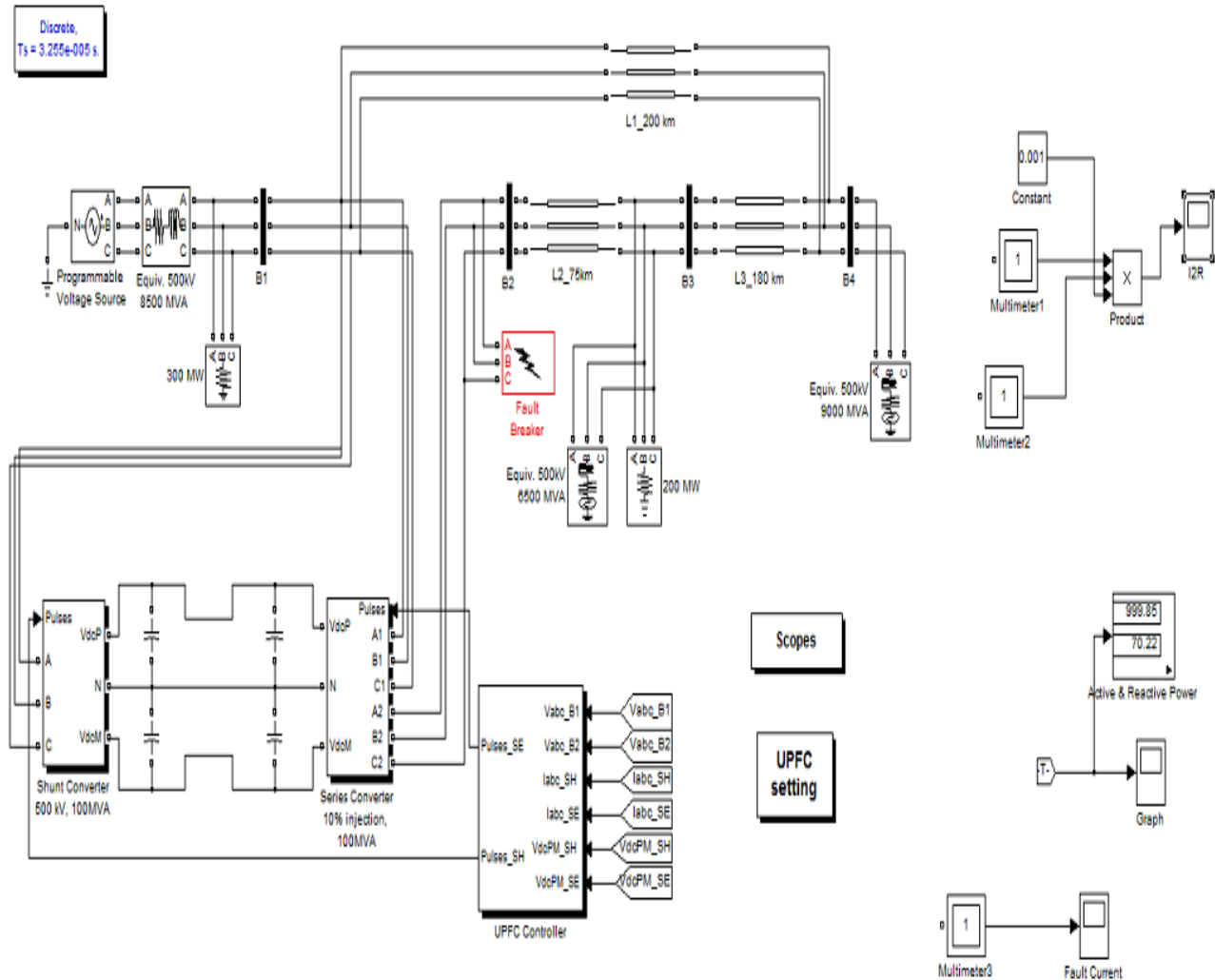


Figure 5.11. Simulation Model using VSI based UPFC under Three phase to Ground Fault Condition

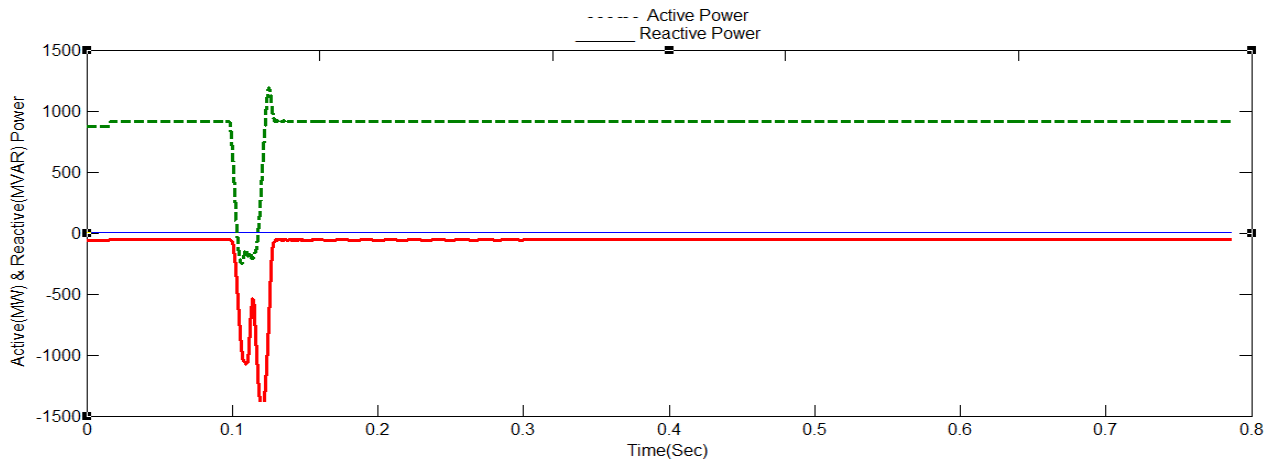


Figure 5.12. Active and Reactive Power Flow

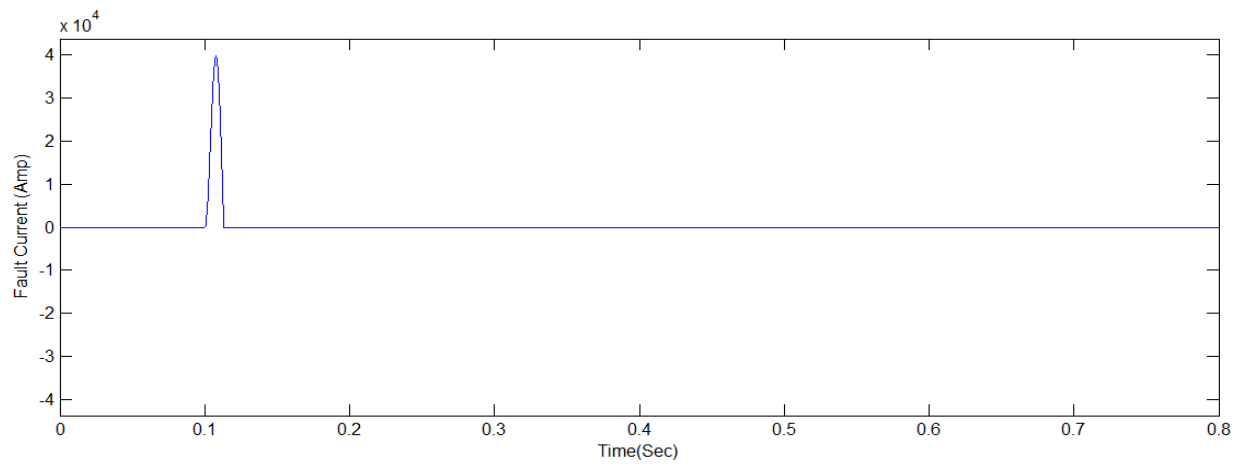


Figure 5.13. Fault Current w.r.t. Time

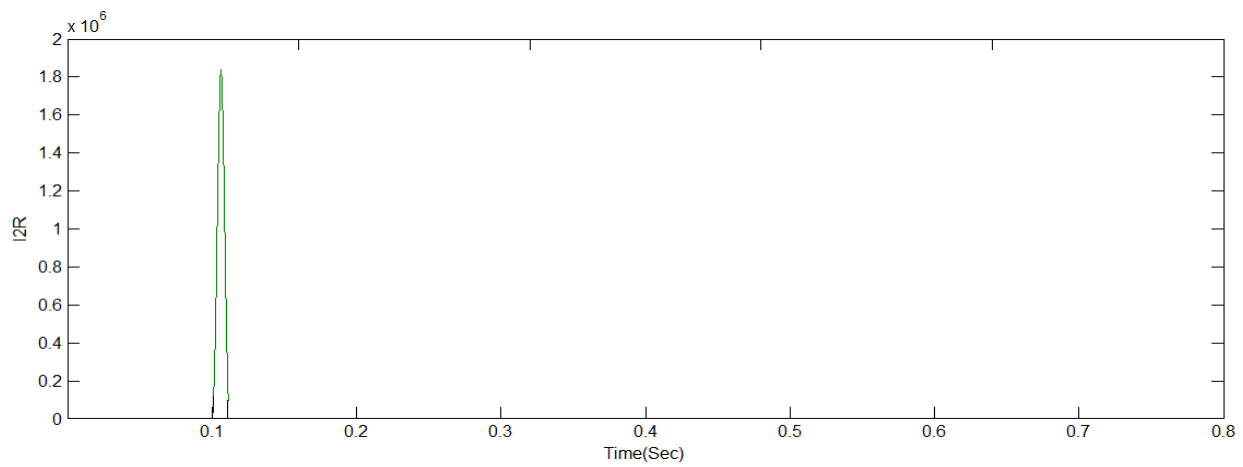


Figure 5.14. I^2R w.r.t. Time

5.2.6. Simulation model Under Three phase to ground fault condition with ZSI based UPFC

SIMULINK model with ZSI based UPFC for power system with Programmable voltage source of rating 1200MVA to a load via transmission lines is shown in figure 5.15. The ratings of the various components are shown. The active power and reactive power curves with respect to time, Fault current w.r.t time and I^2R w.r.t. Time are shown in figures 5.16, 5.17 and 5.18 respectively.

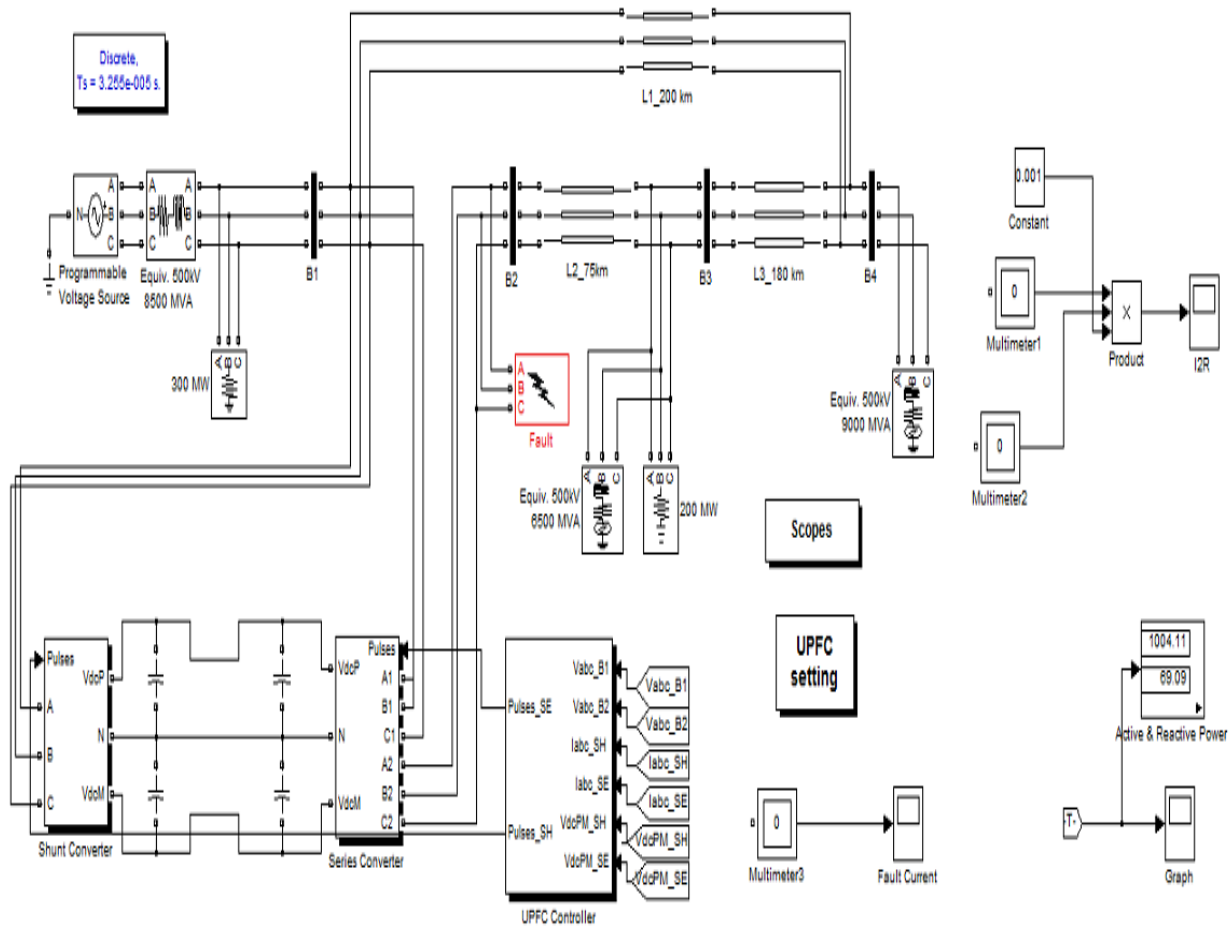


Figure 5.15. Simulation Model using ZSI based UPFC under Three phase to Ground Fault Condition

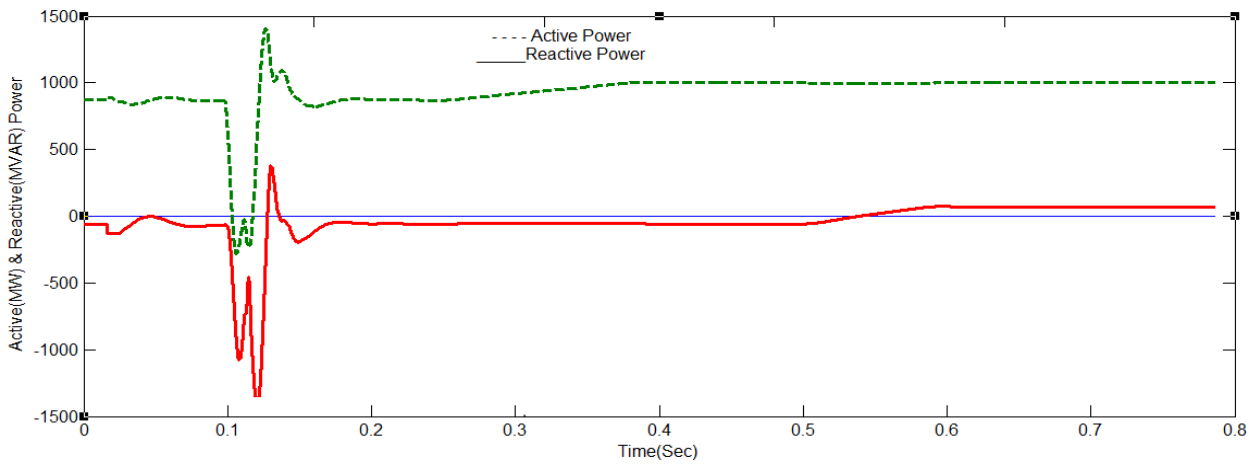


Figure 5.16. Active and Reactive Power Flow

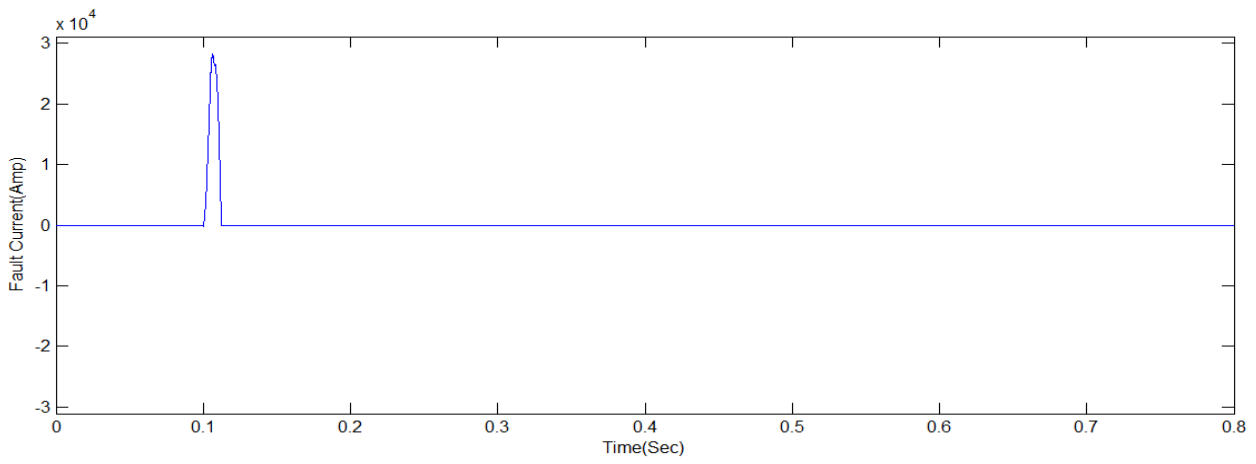


Figure 5.17. Fault Current w.r.t. Time

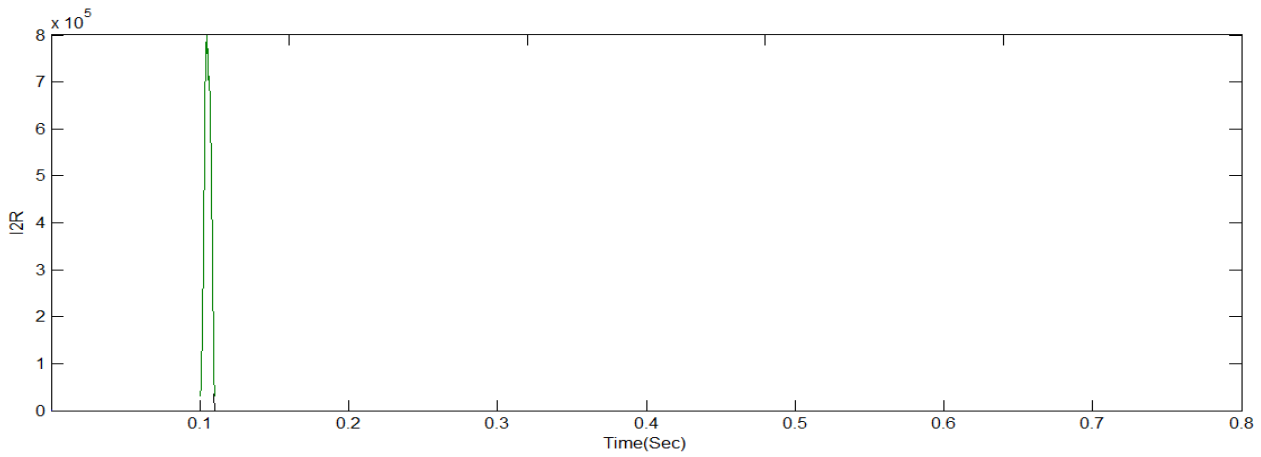


Figure 5.18. I^2R w.r.t. Time

5.3. Case II: Power system with Programmable Voltage Source and Hydro Power Station

5.3.1. Simulation Model without UPFC

SIMULINK model for interconnected power system with hydro power plant and Programmable voltage source of rating 1200MVA and 500KV respectively connected to a load via transmission lines is shown in figure 5.19. The ratings of the various components are shown. The active power and reactive power curves with respect to time are shown in figure 5.20.

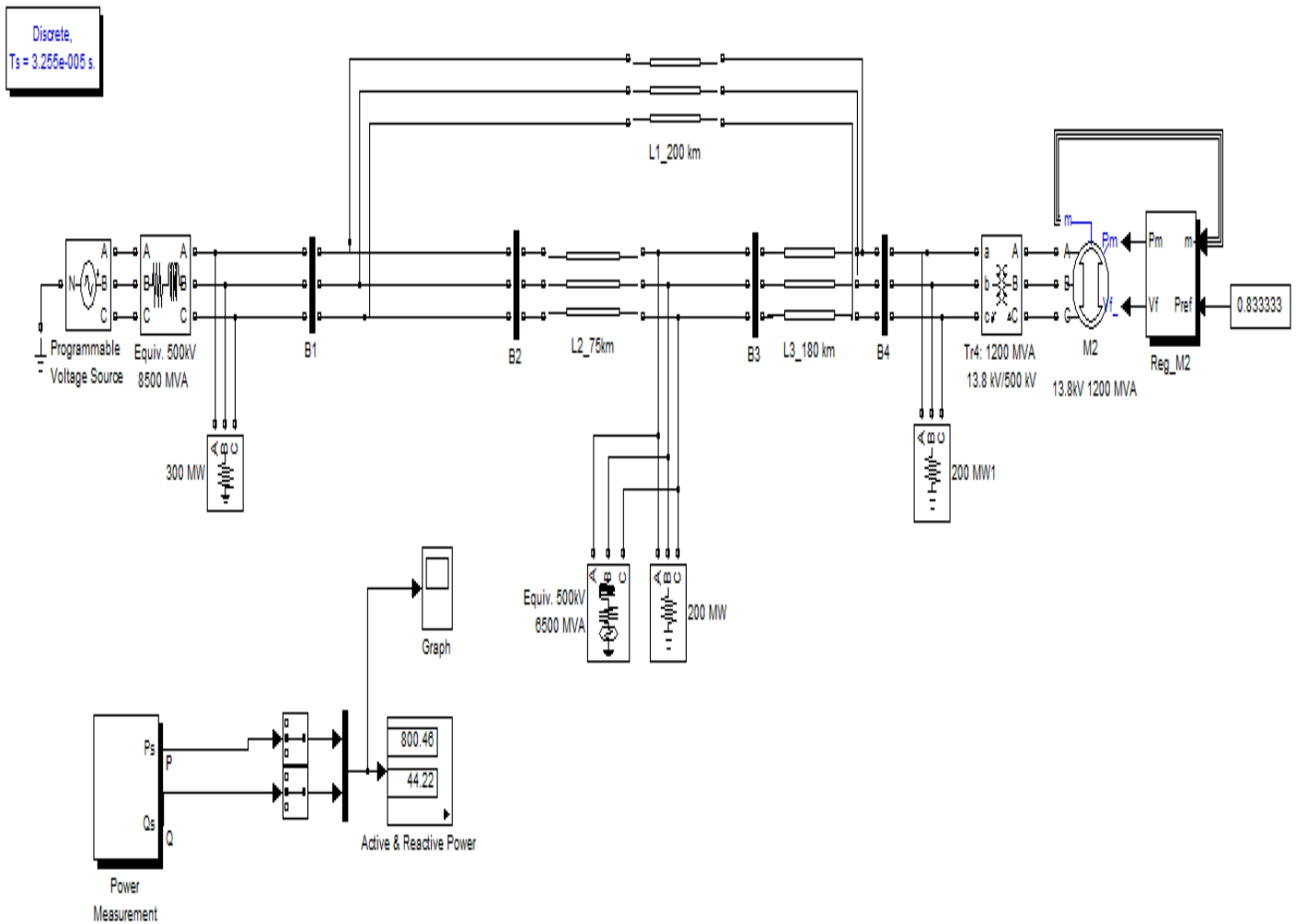


Figure 5.19. Simulation model without UPFC

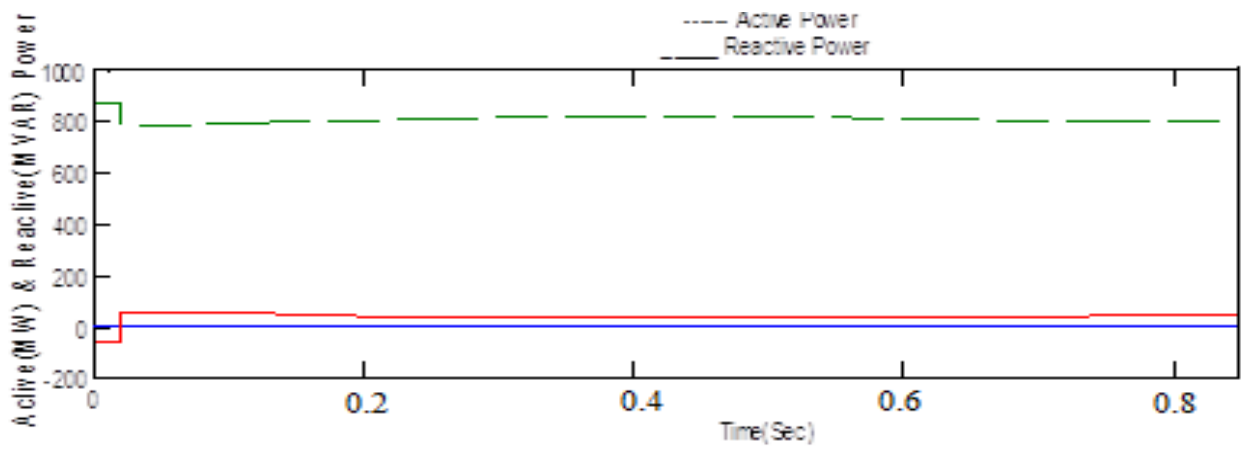


Figure 5.20. Active and Reactive power flow

5.3.2. Simulation model with VSI based UPFC

SIMULINK model for interconnected power system with hydro power plant and Programmable voltage source of rating 1200MVA and 500KV respectively connected to a load via transmission lines is shown in figure 5.21. The VSI based UPFC is implemented in the simulation model for the improvement of power flow in the system. The ratings of the various components are shown. The active power and reactive power curves with respect to time are shown in figure 5.22.

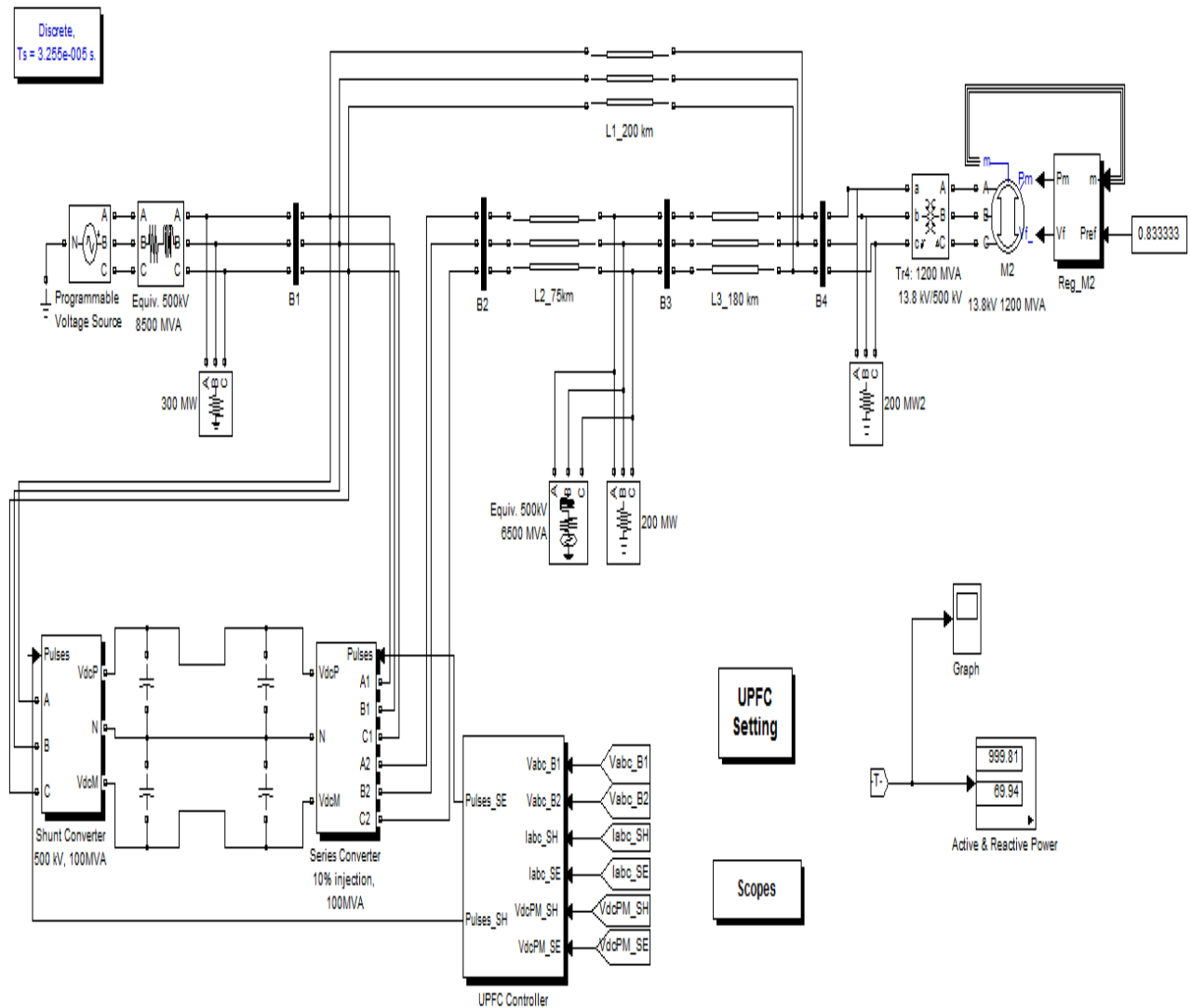


Figure 5.21. Simulation model using VSI based UPFC

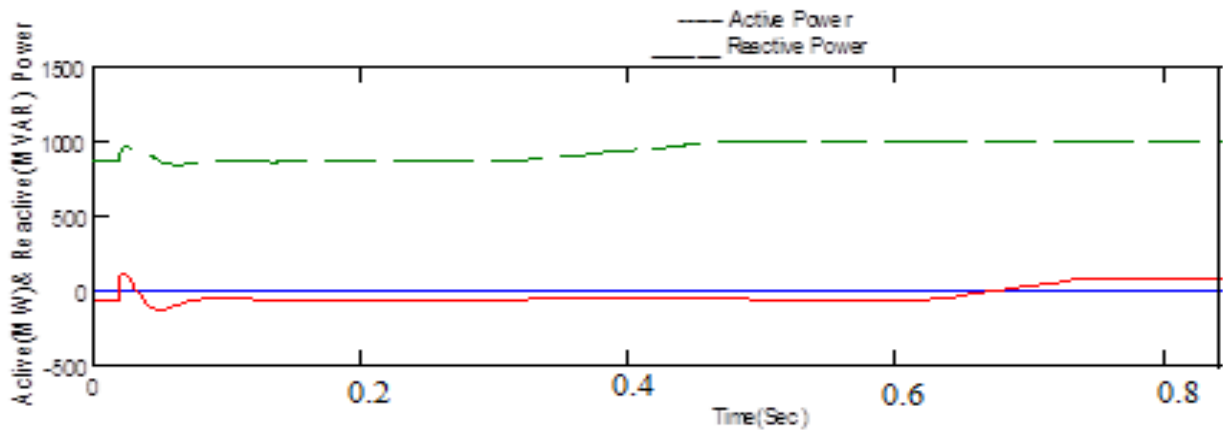


Figure 5.22. Active and Reactive power flow

5.3.3. Simulation model With ZSI based UPFC

SIMULINK model for interconnected power system with hydro power plant and Programmable voltage source of rating 1200MVA and 500KV respectively connected to a load via transmission lines is shown in figure 5.23. The ZSI based UPFC is implemented in the simulation model for the improvement of power flow in the system. The ratings of the various components are shown. The active power and reactive power curves with respect to time are shown in figure 5.24.

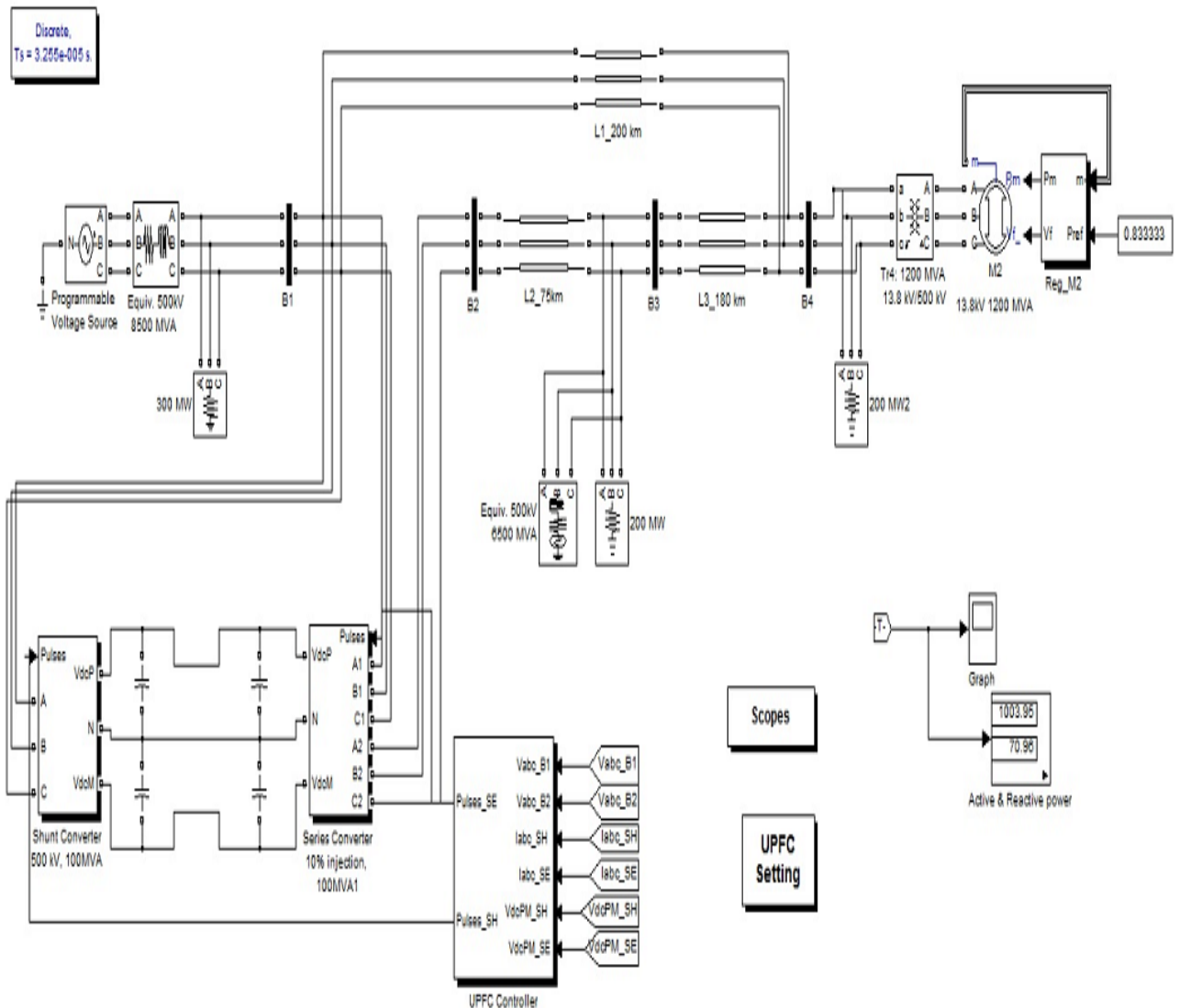


Figure 5.23. Simulation model using ZSI based UPFC

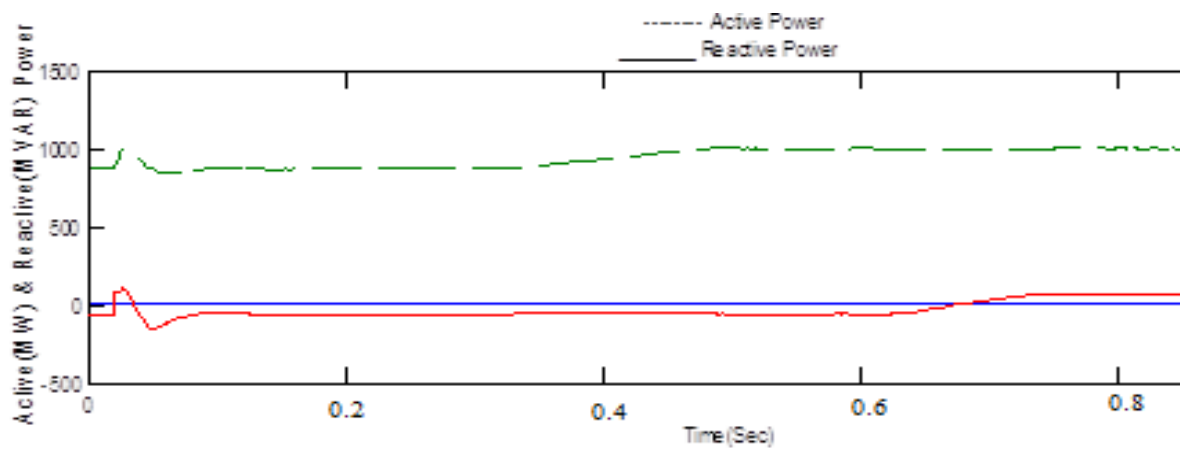


Figure 5.24. Active and Reactive power flow

5.3.4. Simulation model without UPFC under Three Phase To Ground Fault

SIMULINK model for interconnected power system with hydro power plant and Programmable voltage source of rating 1200MVA and 500KV respectively connected to a load via transmission lines is shown in figure 5.25. The ratings of the various components are shown. A three phase to ground fault is created at t=0.1 sec for 0.01 sec at bus 2 as shown in figure. 5.25. The active power, reactive power curves with respect to time, Fault current w.r.t time and I^2R w.r.t. Time are shown in figure 5.26, 5.27 and 5.28 respectively.

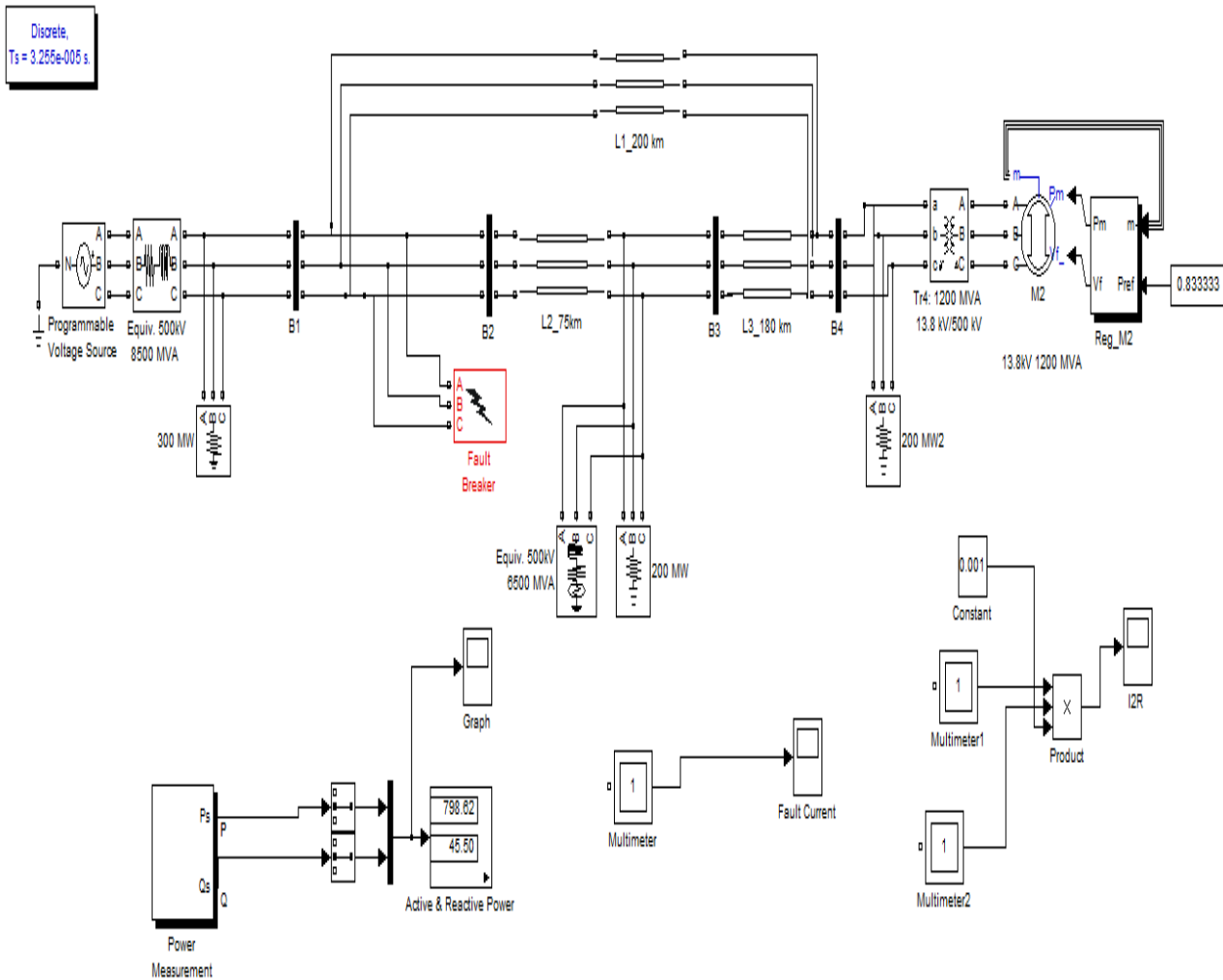


Figure 5.25. Simulation Model without UPFC under Three phase to Ground Fault Condition

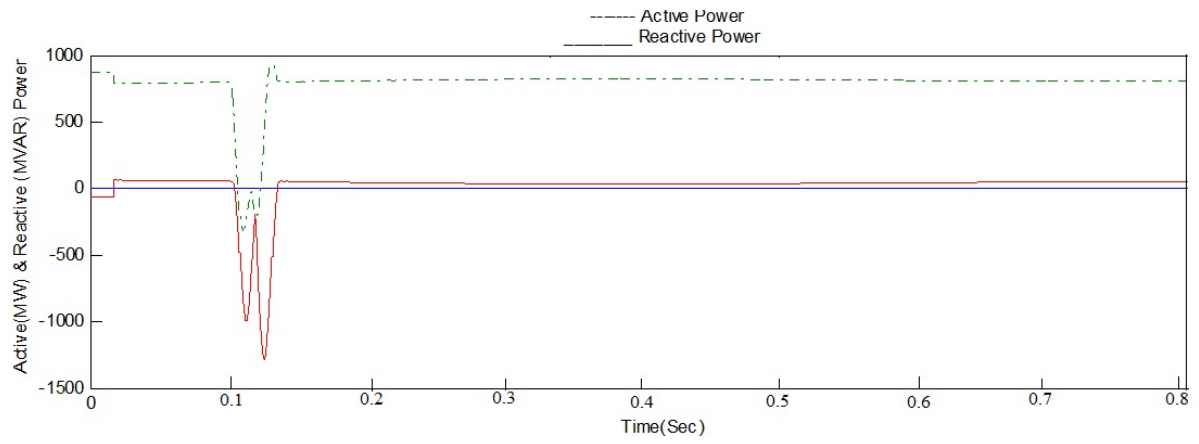


Figure 5.26. Active and Reactive power flow

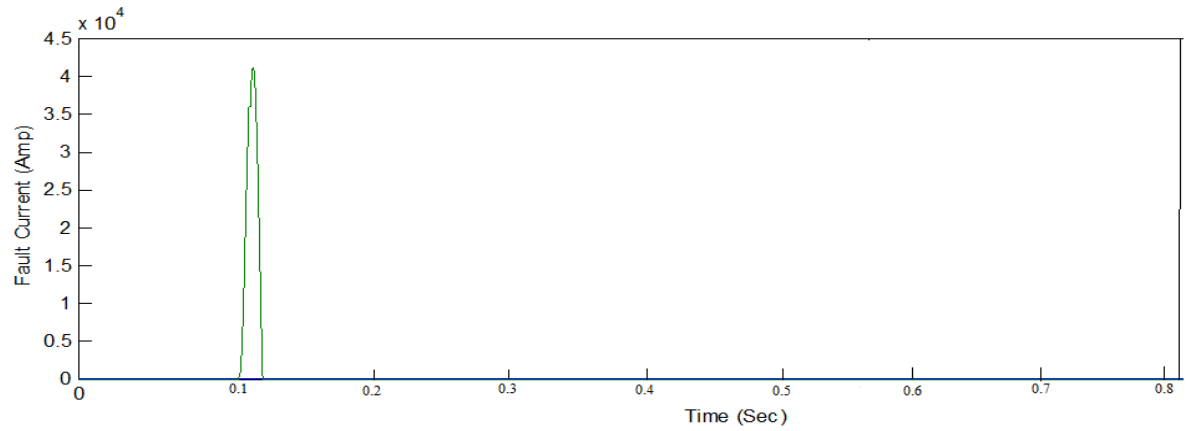


Figure 5.27. Fault current w.r.t. Time

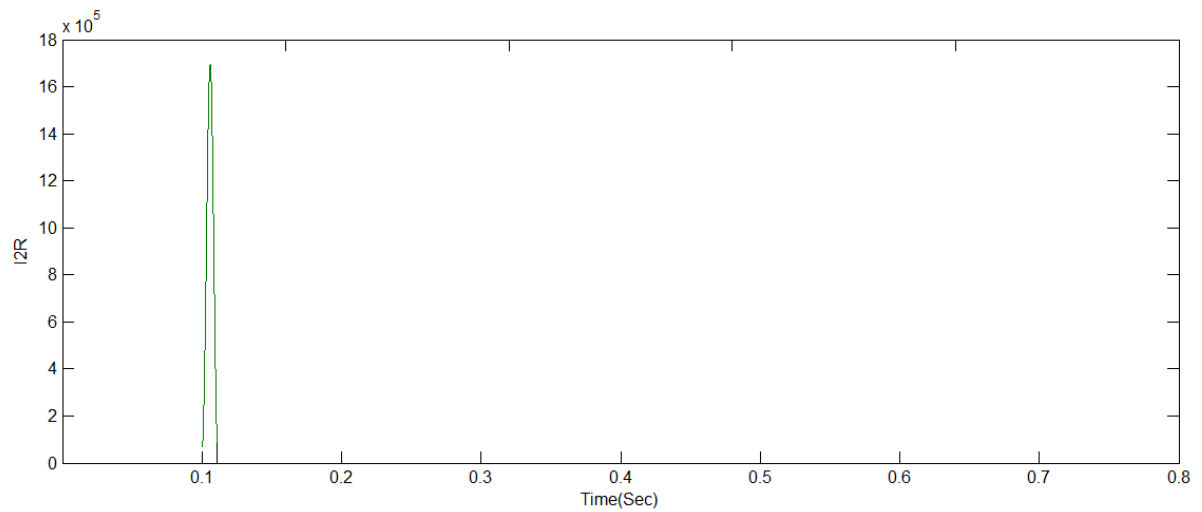


Figure 5.28. I^2R w.r.t. Time

5.3.5. Simulation model using VSI based UPFC under Three Phase To Ground Fault

SIMULINK model with VSI based UPFC for interconnected power system with hydro power plant and Programmable voltage source of rating 1200MVA and 500KV respectively connected to a load via transmission lines is shown in figure 5.29. The ratings of the various components are shown. A three phase to ground fault is created at t=0.1 sec for 0.01 sec at bus 2 as shown in figure 5.29. The active power, reactive power curves, Fault Current w.r.t. Time and I^2R w.r.t. Time are shown in figure 5.30, 5.31 and 5.32 respectively.

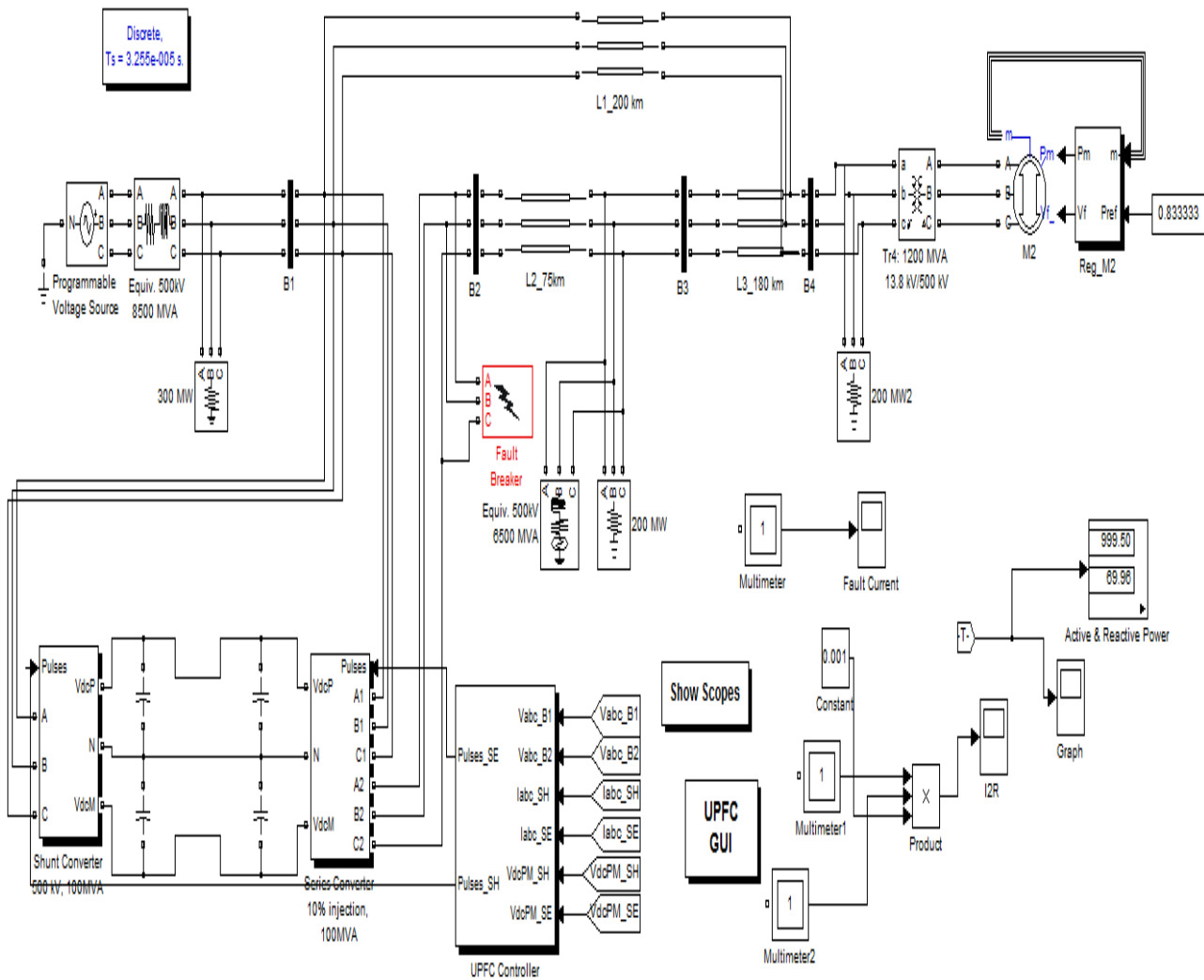


Figure 5.29. Simulation model with VSI based UPFC under 3 Phase to Ground Fault condition

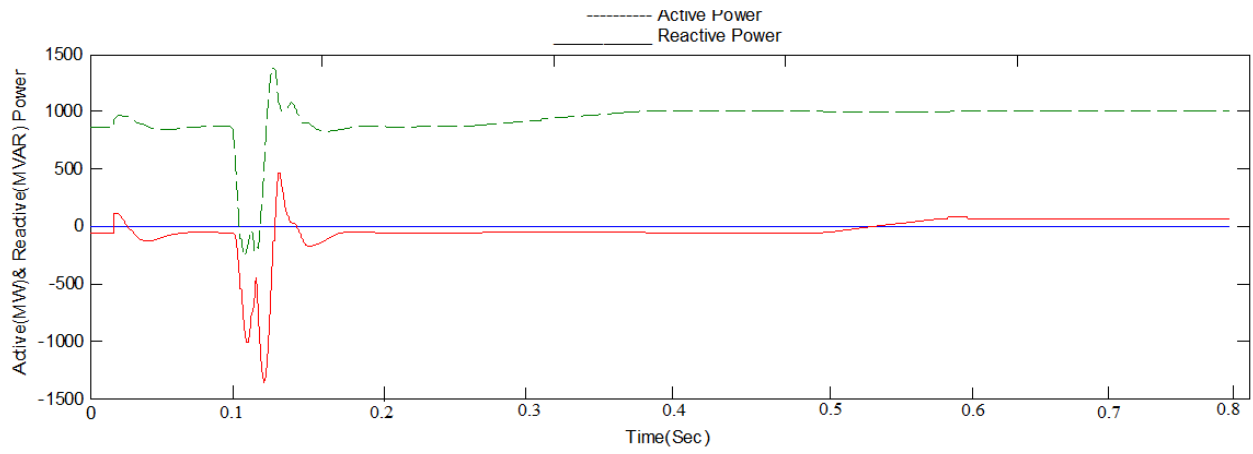


Figure 5.30. Active and Reactive power flow under Three Phase fault

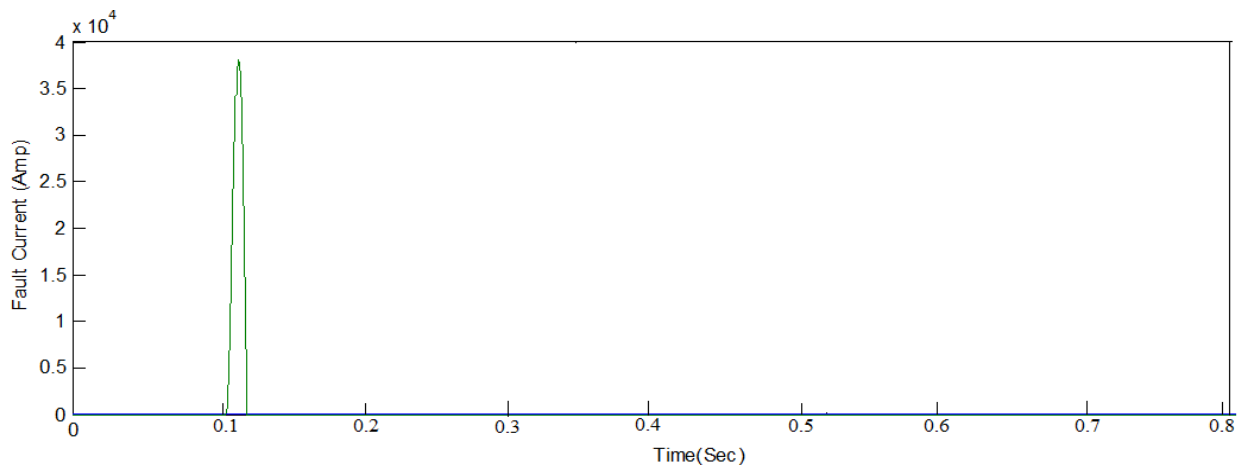


Figure 5.31. Fault Current w.r.t. Time

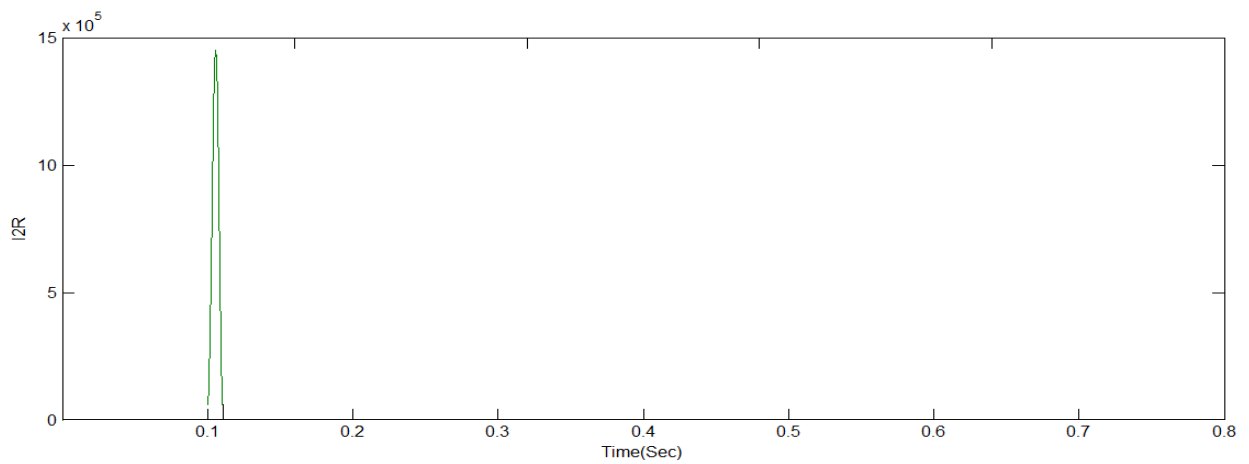


Figure 5.32. I^2R w.r.t. Time

5.3.6. Simulation model using ZSI based UPFC under Three phase To Ground Fault

SIMULINK model with ZSI based UPFC for interconnected power system with hydro power plant and Programmable voltage source of rating 1200MVA and 500KV respectively connected to a load via transmission lines is shown in figure 5.33. The ratings of the various components are shown. A three phase to ground fault is created at t=0.1 sec for 0.01 sec at bus 2 as shown in figure 5.33. The active power, reactive power curves, Fault Current w.r.t. Time and I^2R w.r.t. Time are shown in figure 5.34, 5.35 and 5.36 respectively.

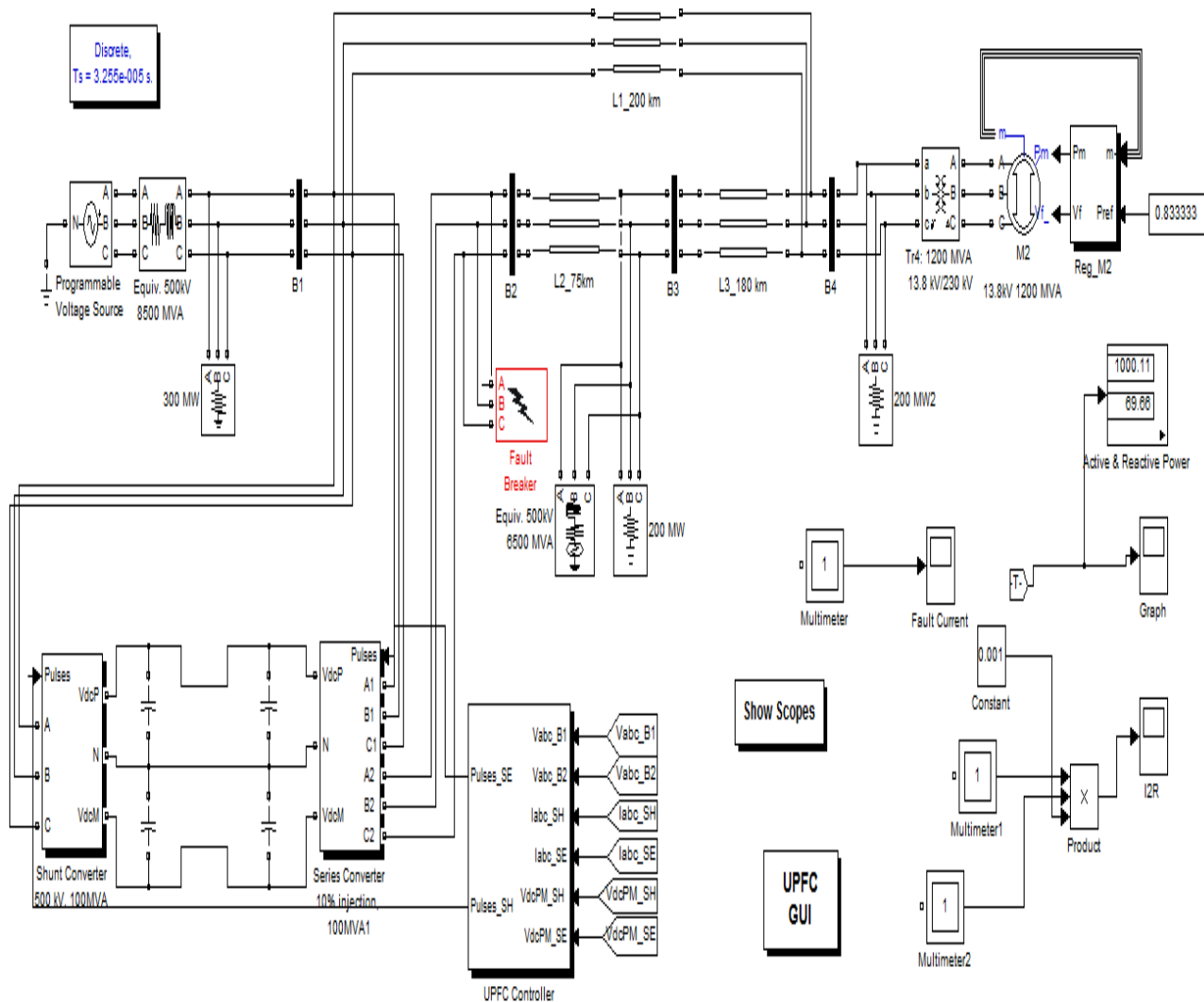


Figure 5.33. Simulation model using ZSI base UPFC under Three Phase fault

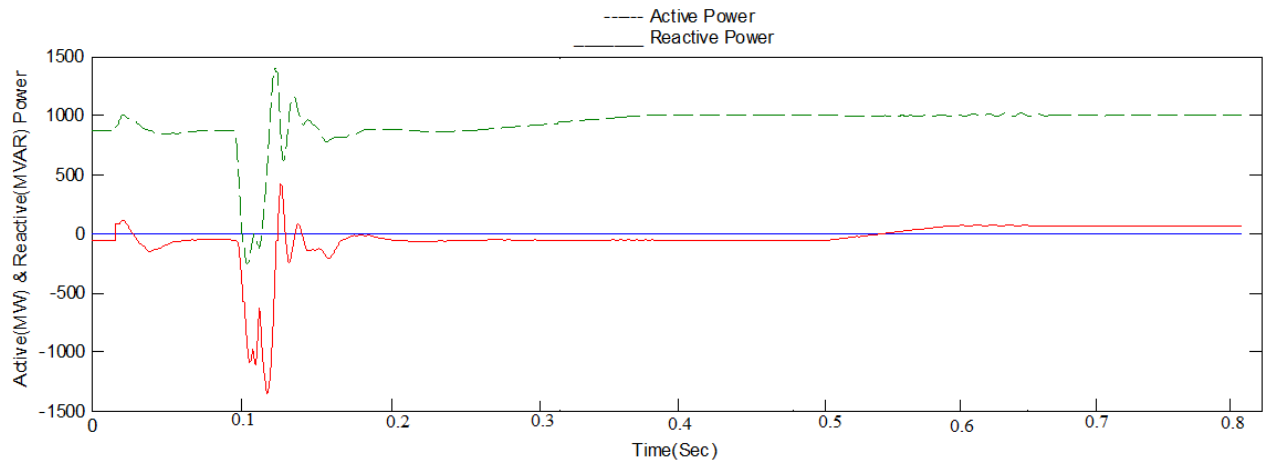


Figure 5.34. Active and Reactive power flow under Three phase fault

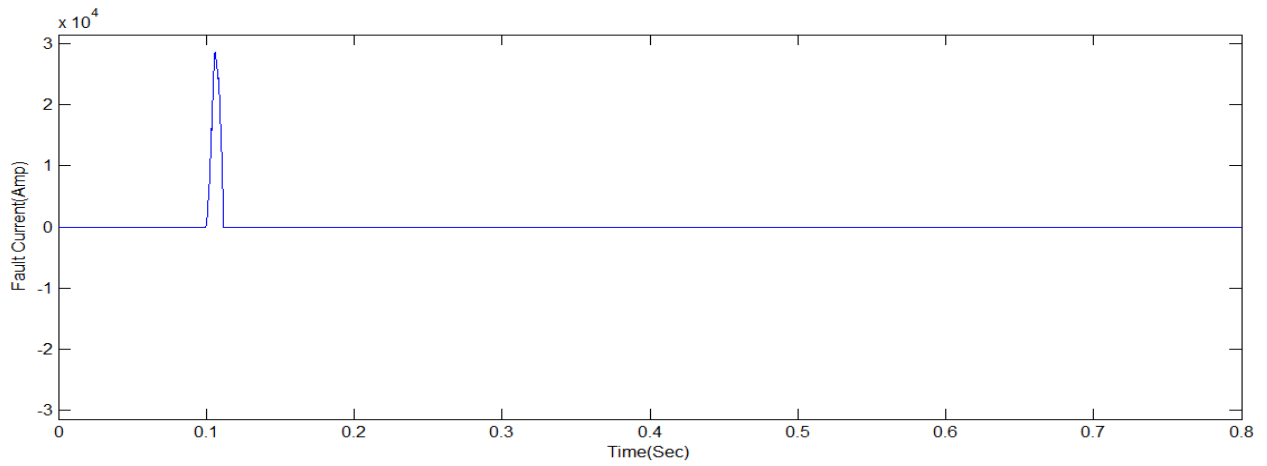


Figure 5.35. Fault Current w.r.t. Time

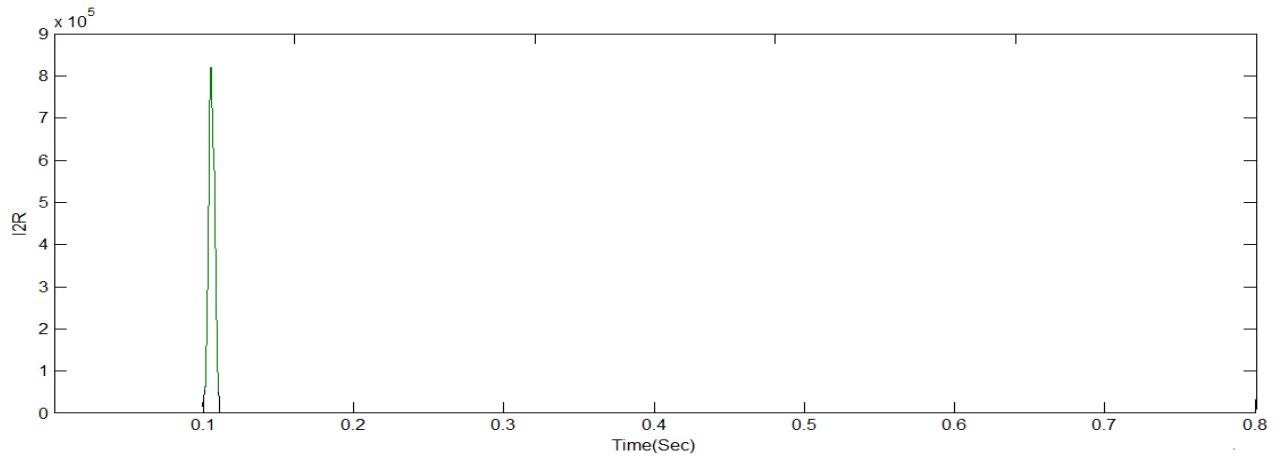


Figure 5.36. I^2R w.r.t. Time

CHAPTER 6

RESULTS AND DISCUSSIONS

6.1. Results

6.1.1. Case I: Simulation model of power system with Programmable Voltage Source

The result for simulation models under normal condition is given in table 6.1 and under abnormal condition (Three phase to Ground fault Condition) is given in table 6.2. The Value of I^2R loss under different conditions is given in table 6.3.

(A) Under Normal Condition

Power Flow	Without UPFC	With VSI based UPFC	With ZSI based UPFC
Active Power(MW)	917.14	1000.06	1008.07
Reactive Power(MVAR)	-57.37	70.10	72.71

Table 6.1. Results for Simulation model under Normal Condition

(B) Under Three Phase To Ground Fault Condition

Power Flow	Without UPFC	With VSI based UPFC	With ZSI based UPFC
Active Power(MW)	917.14	999.85	1004.11
Reactive Power(MVAR)	-57.37	70.22	69.09

Table 6.2. Results for Simulation model under Three Phase to Ground Fault Condition

(C) I^2R Loss (With Three Phase to Ground Fault Condition)

I^2R Loss (Watt)	Without UPFC	With VSI based UPFC	With ZSI based UPFC
	9183	7866	4000

Table 6.3. Results for I^2R Loss under Three Phase to Ground Fault Condition

6.1.2. Case II: Simulation model of power system with Programmable Voltage Source and Hydropower Plant

The result for simulation models under normal condition is given in table 6.4 and under abnormal condition (Three phase to Ground fault Condition) is given in table 6.5. The Value of I^2R loss under different conditions is given in table 6.6.

(A) Under Normal Condition

Power Flow	Without UPFC	With VSI based UPFC	With ZSI based UPFC
Active Power(MW)	800.46	999.81	1003.95
Reactive Power(MVAR)	44.22	69.94	70.98

Table 6.4. Results for Simulation model under Normal Condition

(B) Under Three Phase To Ground Fault Condition

Power Flow	Without UPFC	With VSI based UPFC	With ZSI based UPFC
Active Power(MW)	798.62	999.50	1000.11
Reactive Power(MVAR)	45.50	69.96	69.66

Table 6.5. Results for Simulation model under Three Phase to Ground Fault Condition

(C) I^2R Loss (With Three Phase To Ground Fault Condition)

I^2R Loss (Watt)	Without UPFC	With VSI based UPFC	With ZSI based UPFC
	8470	7273.5	4100

Table 6.6. Results for I^2R Loss under Three Phase to Ground Fault Condition

6.2. Discussions

In Case I, It has been observed that the active and reactive power flow has been improved by 82.92 MW and 12.73 MVAR respectively with the use of VSI based UPFC and active and reactive power has been further improved by 90.93 MW and 15.34MVAR respectively with the use of ZSI based UPFC.

It has been observed that Under abnormal condition, the effect on power flow is very less but the magnitude of fault current has been reduced greatly with the use of VSI based UPFC and the magnitude is further reduced with the use of ZSI based UPFC.

The I^2R loss without using UPFC is 9183 Watt. By using VSI based UPFC it has been reduced by 1317 Watt and it is further reduced by 5183 Watt by using ZSI based UPFC.

In Case II, It has been observed that the active and reactive power flow has been improved by 199.35 MW and 25.72 MVAR respectively with the use of VSI based UPFC and active and reactive power has been further improved by 203.49 MW and 26.76 MVAR respectively with the use of ZSI based UPFC.

It has been observed that Under abnormal condition, the effect on power flow is very less but the magnitude of fault current has been reduced greatly with the use of VSI based UPFC and the magnitude is further reduced with the use of ZSI based UPFC.

The I^2R loss without using UPFC is 8470 Watt. By using VSI based UPFC it has been reduced by 1196.5 Watt and it is further reduced by 4370 Watt by using ZSI based UPFC.

CHAPTER 7

CONCLUSIONS AND FUTURE SCOPE OF WORK

7.1. Conclusions

In this research work, simulation models for performance analysis in a transmission system without UPFC, with VSI based UPFC and with ZSI based UPFC have been made. The system models are observed with Programmable Voltage Source and with the combination of Hydro power plant and programmable Voltage source. The analysis is done on the basis of active power flow and reactive power flow of the system, Fault level during Three phase to Ground Fault condition and I^2R Loss in the system during Three phase to Ground Fault condition. From the results, following conclusions are obtained:

- It is observed that with the help of the unified power flow controller, the active power flow has been improved although UPFC has significant effect on reactive power flow. The Active and Reactive power has been further improved when ZSI based UPFC has been used.
- VSI based UPFC and ZSI based UPFC plays an important role even when the fault has occurred.
- It is also observed that the magnitude of oscillations is less when the system is provided with VSI based UPFC and the magnitude of oscillations has been further reduced by using ZSI based UPFC.
- The I^2R Loss in the system is greatly reduced in case of VSI based UPFC and ZSI based UPFC as compared to the system without UPFC.

7.2. Future Scope of Work

The work can be extended:

- To develop better control techniques for ZSI.
- To show the performance of ZSI based UPFC in hybrid power system.
- To use with artificial neural network and the combination of fuzzy-neural to improve the dynamic performance of ZSI based UPFC.

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