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Combined Operations of SFCL and Optimal Reclosing of Circuit Breakers for Transient Stability Enhancement of Power Systems

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A STUDY ON:

COMBINED OPERATIONS OF SFCL AND OPTIMAL RECLOSING OF CIRCUIT BREAKERS FOR TRANSIENT STABILITY ENHANCEMENT OF POWER SYSTEMS

by

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This thesis is dedicated to my parents Md. Sharif Hossain and ZohraYeasmin and my wife Sayema Khan Tuli for their never ending sacrifices.

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ABSTRACT

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This thesis proposes the coordinated operation of optimal reclosing of circuit breakers and superconducting fault current limiter (SFCL) for enhancing the transient stability of a multi-machine power system. Transient stability performance of the combined operation of optimal reclosing of circuit breakers and SFCL is compared with that of the combined operation of conventional reclosing of circuit breakers and SFCL. Moreover, to see the effectiveness of SFCL in improving the transient stability, its performance is compared with the static var compensator (SVC). Simulation results in Matlab/Simulink environment for permanent balanced and unbalanced faults at different points in the system indicate that the proposed combination of optimal reclosing of circuit breakers and SFCL/SVC can enhance the transient stability of the system well than the combined operation of conventional reclosing of circuit breakers and SFCL/SVC. Furthermore, the SFCL performs better than the SVC for the same operating conditions of the system.

PREFACE

Three papers resulting from my master's research were used as the manuscript of this thesis. Chapter 1 was accepted and presented in *2013 IEEE SoutheastCon conference*. The other articles were submitted to *IEEE Transactions on Applied Superconductivity* and *IEEE Transactions on Power Systems* and are currently under review. Following is a list of the articles used as chapters in this document:

Chapter 1: Mohammad Ashraf Hossain Sadi and Mohd. Hasan Ali, "Overview of the Superconducting Fault Current Limiter Technology in Electric Power and Energy Systems.," submitted to the *IEEE Transactions on Applied Superconductivity*.

Chapters 2,3 and 4: Mohammad Ashraf Hossain Sadi and Mohd. Hasan Ali, "Combined Operation of SFCL and Optimal Reclosing of Circuit Breakers for Power System Transient Stability Enhancement," accepted and presented in 2013 *IEEE SouthEastCon Conference*. Jacksonville, FL, April 4-7, 2013.

Chapters 2, 3 and 4: Mohammad Ashraf Hossain Sadi and Mohd. Hasan Ali, "Power System Transient Stability Enhancement by combined operation of optimal reclosing of circuit breakers and SFCL", submitted to the *IEEE Transactions on Power Systems*.

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LIST OF ABBREVIATIONS

AVR: Automatic Voltage Regulator

CB: Circuit Breaker

GOV: Governor

GPS: Global Positioning System

IEEE: Institute of Electrical and Electronic Engineers

ORCT: Optimal Reclosing Time

RMS: Root Mean Square

SFCL: Superconducting Fault Current Limiter

SVC: Static VAR Compensator

TCR: Thyristor Controlled Reactor

TKE: Total Kinetic Energy

TKED: Total Kinetic Energy Deviation

TSC: Thyristor Switched Capacitor

3LG Fault: Three Phase (line) to Ground Fault

2LG Fault: Two Phase (line) to Ground Fault

1LG Fault: Single Phase (line) to Ground Fault

2LS Fault: Two Phase (line) to Phase Fault

Chapter 1

INTRODUCTION

A. Background

Transient stability of the power system is one of the most important and concerned issue during large and sudden faults in order to maintain acceptable power throughout the system. It is defined as the ability of the power system to regain its stability in the case of large disturbance in the system. The circuit breaker is the most common form of switchgear equipment for power system protection. It has a stationary contact and a moving contact. When the system remains stable then the two contacts remain in connected state to maintain normal power flow. In case of faults on the transmission line, the circuit breakers act to protect the healthy section by opening and maintain continuity of power by reclosing after the fault arc de-ionization. In most of the cases circuit breakers are reclosed with high speed after a fixed time interval. Conventional reclosing technique depicts the reclosing of circuit breakers after a prescribed time period whether the arc between the fixed contact and moving contact still persists or not. However, if the arc still persists, especially in case of a permanent fault, then the circuit breaker would not be able to reclose successfully and will sectionalize the system, which is an indication of the unstable state of the system[1]-[2]. Transient stability is also dependent on the generator state of reclosing. Therefore, to maintain the synchronism and enhance the transient stability, an optimal reclosing time when reclosing of the circuit breakers will enhance the transient stability of the system effectively is needed to be found out [1]-[4].

B. Motivation

As increasing load demands can cause more fault currents on the transmission line, the resistive type superconducting fault current limiter (SFCL) can be used to reduce the effects of the high fault current and also to improve the voltage sag situation in case of a fault in the system. One of the important features of SFCL is that there is essentially no loss and voltage drop at normal operation. The SFCL causes almost no power loss in a steady-state condition and improves the transient stability of power system by suppressing the level of the fault current with the quick operation and auto recovery capability within 0.5s [5]-[9].

Static VAR Compensator (SVC) is a Flexible SC Transmission System (FACTS) device which is connected in shunt with the power system. Although SVC is primarily used for compensating the bus voltage by injecting or absorbing the reactive power, but it also has the capability of improving the transient stability of the power system. SVC with the presence of the power electronic devices can control the unbalanced condition more effectively and can enhance the transient stability of the system by inserting or absorbing instantaneous currents to or from the system[10]-[12]. In this work, SVC is also considered instead of SFCL with the same operating conditions to see how much more effective the SFCL is in improving the transient stability by comparing their performance.

This research uses the optimal reclosing technique described in [13]. The method has an advantage that it uses the kinetic energy of the generators which can be easily obtained in real time. Moreover, for multi-machine power system different generators have different speed characteristics. So, the total kinetic energy technique utilizes the summation of the kinetic energy of every generator in the system. In this method, the time when the total kinetic energy oscillation of the generators without reclosing operation becomes the minimum is determined as optimal reclosing time (ORCT).

C. Literature Review

1) Power System Stability

Power system is very nonlinear in nature. The loads, generator outputs and other operating elements are always changing depending on the system requirements. So when any type of disturbance occurs, the stability of the whole system depends on the initial operating condition as well as on the type of disturbance. In power systems small load change over time in the form of household, commercial and industrial usage of electricity. Power systems should have the ability to sustain such small disturbances and operate normally. Moreover, severe disturbances in the form of line to ground (1LG) fault or the sudden outage of any generator can occur too. So, the robustness of the system should be such that the effect of such disturbances is not significant. Otherwise if the system becomes unstable, it will result in a run-away or run-down situation. An unstable system condition could lead to outages and shutdown of a major portion of the power system [1], [14].

The definition of power system stability is precisely given by a task force, set up jointly by the CIGRE Study Committee 38 and the IEEE Power System Dynamic Performance Committee [14]

"Power system stability is the ability of an electric power system, for a given initial operating condition, to regain a state of operating equilibrium after being subjected to a physical disturbance, with most system variables bounded so that practically the entire system remains intact."

The classification of power system stability suggested by the CIGRE study committee 38 and the IEEE Power System Dynamic Performance Committee task force is represented in figure 1.

2) Classification of Power System Stability

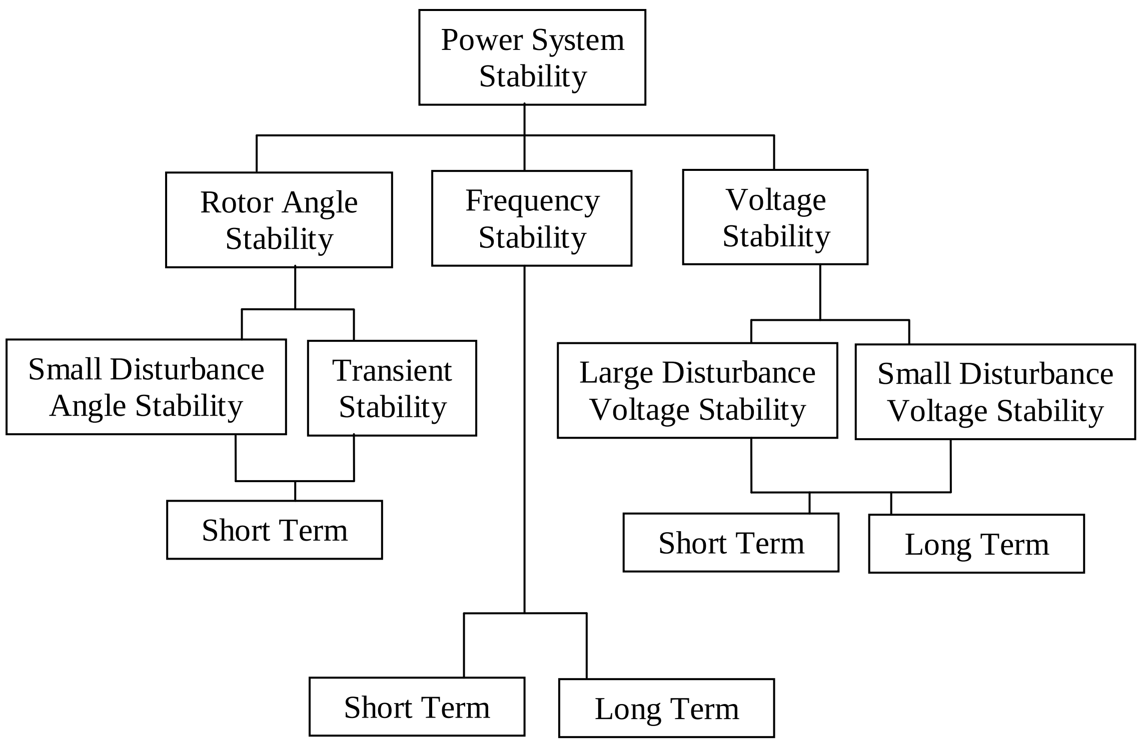


Figure 1: Classification of power system stability.

The time interest for short term stability is 0s to 10s. While the time interest for long term stability is 10's of seconds to few minutes. From the classification it is clear that transient stability is related to rotor angle stability. So, the reason and consequence of rotor angle stability is important to understand **[**1**]**, **[**14**]**.

Rotor angle stability is the ability of synchronous machine in any interconnected power system to remain in synchronism after being subjected to any disturbance. The synchronism depends on the applied mechanical torque and generated electromagnetic torque of the generators which can be represented as

$$T_a = T_m - T_e \tag{1}$$

Where T_a is the accelerated torque, T_m is the mechanical torque, and T_e is the electromagnetic torque.

The stability depends on maintaining the equilibrium between these two torques. In the event of fault the generators rotor speed increases or decreases depending on the system which leads to the instability of the system. Due to the angular difference between generators, load transfer happens between the generators and the system becomes unstable **[**1**]**. With electric power systems, the change in electrical torque of a synchronous machine following a perturbation can be resolved into two components

$$\Delta T_e = T_S \Delta\delta + T_D \Delta\omega \tag{2}$$

Where T_e is the electric torque. $T_S\Delta\delta$ is the component of torque change in phase with the rotor angle perturbation $\Delta\delta$ and is referred to as the synchronizing torque component. T_S is the synchronizing torque coefficient. $T_D\Delta\omega$ is the component of torque in phase with the speed deviation $\Delta\omega$ and is referred to as the damping torque component. T_D is the damping torque coefficient.

Oscillatory instability is due to lack of sufficient damping torque and unstable control action. Non-Oscillatory instability is due to lack of sufficient synchronizing torque **[**1**]**.

3) Transient Stability

Transient stability is a part of rotor angle stability. Transient stability is the ability of the system to maintain stability after the occurrence of severe disturbance. The machines in the power system have to maintain synchronism after such disturbances. These disturbances may be in the form of sudden application of load, loss of generation, loss of large load or a severe fault in the system. Instability is usually due to the insufficient synchronizing torque in the form of aperiodic angular separation. The equal area criterion can be used for quick prediction of the stability **[**1**]**, **[**14**]**. According to equal area criterion, if the system is stable in the first swing then the rotor angle after any disturbance reaches a maximum value. Also, the rotor angle oscillates about the final steady state value **[**1**]**.

4) Superconducting Fault Current Limiter (SFCL)

The growth of electricity demand has resulted in more interconnections among existing power system in the past few decades. To cope with the increasing demand there has been an increase of power generation. More parallel paths for power transmission have been added to supply the demanded power. As the existing power system becomes more expanded and interconnected, there is the possibility of an increase in the number of faults in the system as well as an increase in the fault current level. Moreover, with the concept of smart grid, more distributed generators are being connected to the existing power system. The switchgear devices already existing in the power system have a certain life expectancy and short circuit capacity. They were sized in the system depending on their ability to interrupt a certain level of fault current. As the number of faults are increasing and the fault current level of the existing system is increasing, the existing switchgear devices will not be able to protect the system properly. Therefore, the solution of this problem may be to upgrade the existing circuit breakers and switchgear devices in the system to withstand higher fault current. But this task is expensive and will take a lot of time. Hence, a corrective way which will help the existing circuit breakers protect the system at higher fault current levels is needed.

Also, throughout the past few decades distributed generators are being used along with the traditional power generating units because of their environmental friendliness and continuous power supply ability. But when the distributed generators are connected in the system, they increase the fault current level. The most important negative impact is that the distributed generators supply current in the reverse direction in the event of fault. So, there is the false tripping in that situation which ultimately reduces the reliability and flexibility of the power system [15]-[17].

Therefore to protect the switchgear devices and the power grid in these situations a thorough research was carried out. Power engineers were looking for schemes that will detect the fault current correctly and activate the isolating devices in case of over current in the power system. From this view point, the fault current limiters in conjunction with the circuit breakers were introduced in the power system. Fault current limiters introduce fixed impedance in the system. As a consequence, the high fault current level in the tripping switchgear devices becomes lower and they isolate them properly. However, as the impedance introduced by the fault current limiters are continuous in the system, they reduces the system efficiency [6], [18].

The development of high temperature superconductors (HTS) enables the development of fault-current limiters. SFCL were first studied over two decades ago. The earliest designs used low temperature superconductors (LTS) materials that lose all resistance at temperatures a few degrees above absolute zero. LTS materials are generally cooled with liquid helium, a substance both expensive and difficult to handle. The discovery in 1986 of high temperature superconductors, which operate at higher temperatures and can be cooled by relatively inexpensive liquid nitrogen, renewed interest in superconducting fault-current limiters [6],[15]-[27].

SFCL is considered as one of the most promising reliability enhancing devices in the power system to reduce the stress in the isolating devices. The circuit breakers and the SFCL in the power system have a coordinated operation. Circuit Breakers in the power system are connected in series with the SFCL so that the circuit breakers can interrupt the fault current when they are suppressed after the fault by the SFCL. Circuit Breakers must withstand transient recovery voltage without reigniting the arc [9], [28]-[32].

5) Classification of SFCL

The classification of SFCL is represented in figure2.

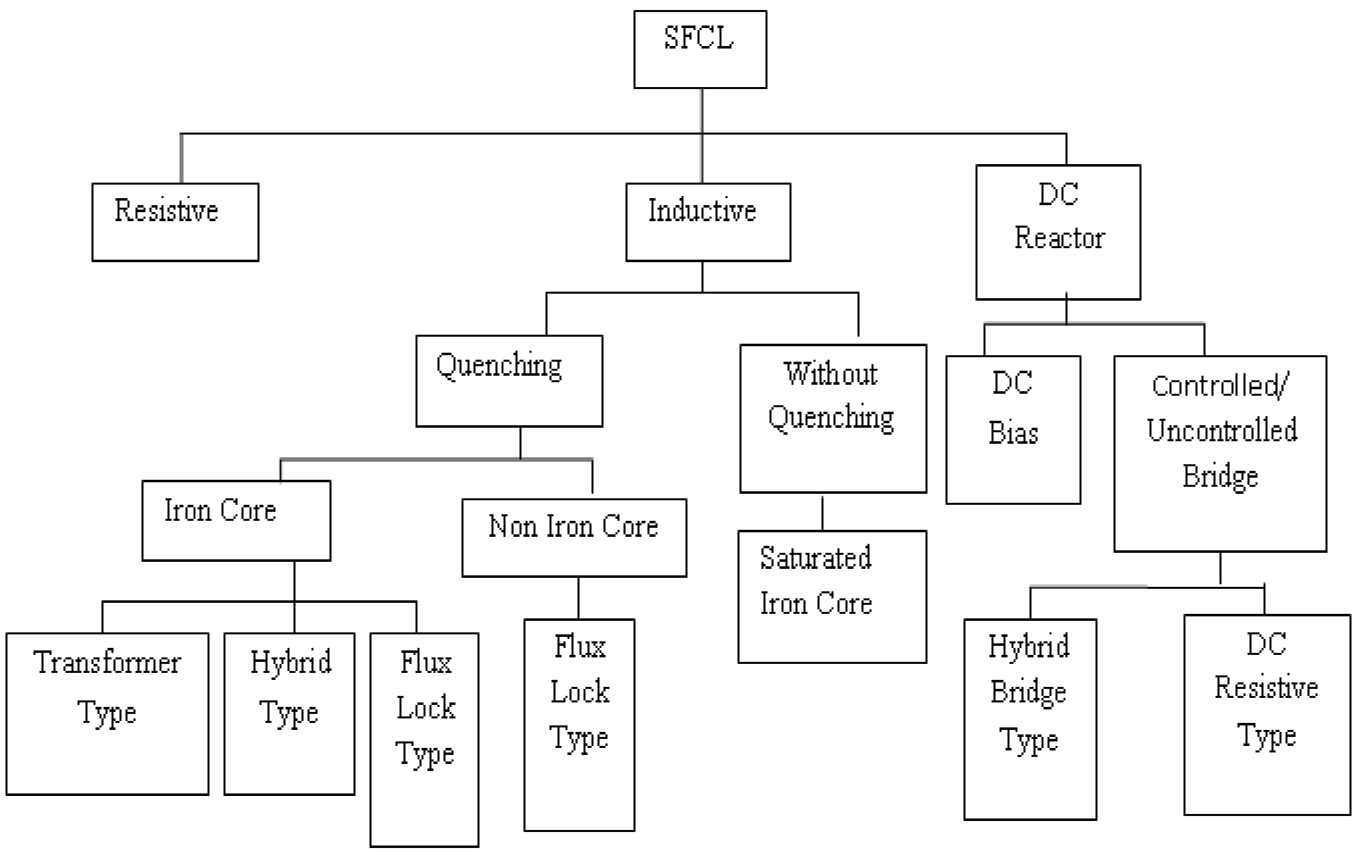


Figure 2: Classification of SFCL.

SFCL can be classified according to their connection into the power system, technology and quenching property. Quenching is the transition from the superconducting state to the current limiting state of the SFCL which is rapid and uncontrolled. Most of the SFCL use this quenching property to limit the fault current **[**7**]**,**[**22**]**-**[**27**]**, **[**33**]**-**[**37**]**.

a) Resistive Type SFCL

In terms of research and application, resistive type SFCL got the most importance in the past decades. There have been a number of resistive SFCL technologies invented up to now **[**5**]**, **[**8**]**, **[**38**]**-**[**40**]**. A common schematic representation of resistive SFCL is presented in figure 3.

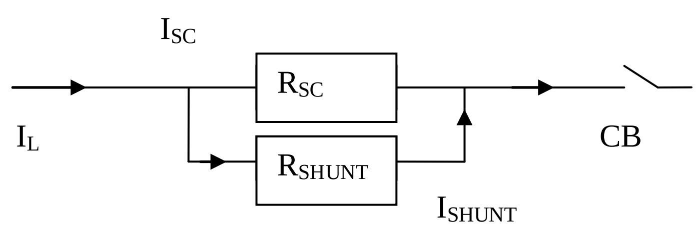


Figure 3: Resistive type SFCL.

In the most common form of resistive type of SFCL superconductor is used as the conducting part of the SFCL. In the steady state condition current passes through the superconductor normally. But when current level increases due to a fault in the system then superconductor quenches. So the resistance of the superconductor increases and as a result voltage level increases in the superconductor that causes the current to pass through the shunt resistance to limit the current level **[**5**]**, **[**8**]**, **[**38**]**-**[**58**]**.

b) Hybrid Type SFCL

The high cost of superconducting element used in resistive type of SFCL hinders its commercialization and application issues. To reduce the use of superconductors, hybrid type SFCL is invented in which the amount of superconductor is reduced. Moreover the superconductor in hybrid SFCL is used only for detecting, triggering and quenching the fault current instead of minimizing the effect of fault current **[**59**]-[**68**]**. Figure 4 shows the schematic diagram of hybrid type SFCL.

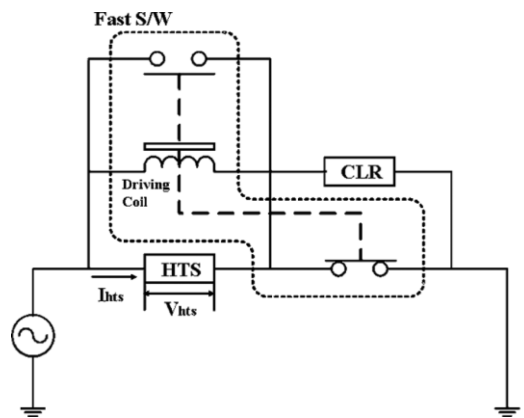


Figure 4: Hybrid Type SFCL.

Hybrid type SFCL can be first half cycle limiting of fault current type or first half cycle non limiting type. The advantage of the non-limiting type is that it helps in proper coordination with the protective relay elements in the system **[**59**]-[**69**]**.

c) Flux Lock Type SFCL

Figure 5 shows the schematic diagram of flux lock type SFCL.

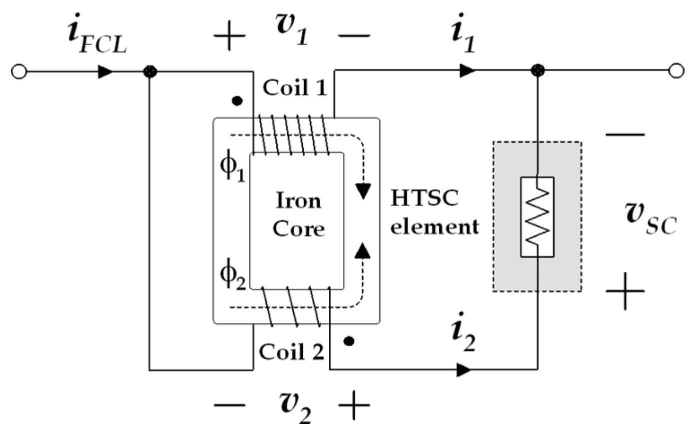


Figure 5: Flux lock type SFCL.

Flux lock type SFCL utilizes the magnetic coupling between two coils connected in series or parallel in an iron core or air core to introduce the current limiting characteristics. The two coils are wound in additive polarity or subtractive polarity direction and the HTSC is connected in series or parallel to the second coil depending on the coil connections **[**70**]-[**77**]**.

d) Transformer Type SFCL

Transformer type SFCL and Flux Lock type SFCL has almost similar design structure but transformer type SFCL has better current limiting capability and the power loss in transformer type SFCL is also low compared to the flux lock type SFCL **[**74**]**,**[**78**]**. Figure 6 shows the schematic diagram of transformer type SFCL.

Transformer type superconducting fault current limiter

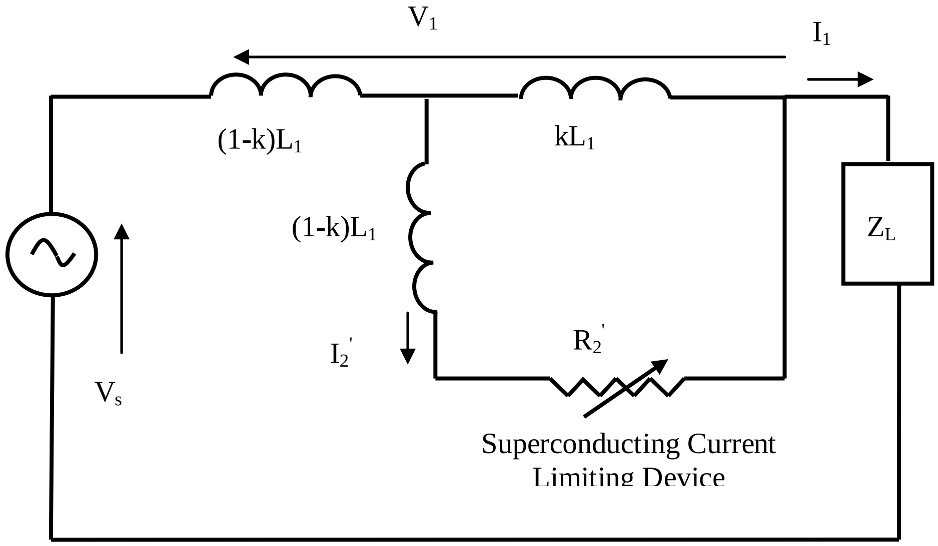


Figure 6: Transformer type SFCL.

Transformer type SFCL has the advantage of design flexibility of the current limiting device and it isolates the current limiting device from the power system. It also reduces the heat loss **[**74**]**,**[**78**]-[**80**]**. Transformer type SFCL is a series transformer whose primary is connected with the transmission line and current limiting device is connected in series with the secondary whereas it is connected in parallel in case of flux lock type SFCL as represented in figure 6 **[**74**]**,**[**78**]-[**87**]**.

e) Saturated Iron Core Type SFCL

Saturated iron Core SFCL is different from the other form of SFCL's in the sense that there is no superconductor quenching requirement in SIC-SFCL **[**88**]**. Figure 7 shows the schematic diagram of saturated iron core type SFCL. SIC-SFCL consists of two iron

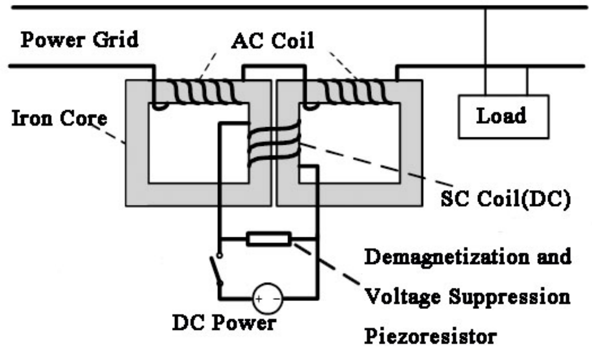


Figure 7: Saturated iron core type SFCL.

cores with ac coil winding which are mainly the power lines. There is a dc superconducting coil connected across the two cores and a dc current supply to the dc superconducting coil for the purpose of saturation of the cores. SIC-SFCL works mainly on the magnetic saturation and desaturation rule [89]-[91].In the saturated state the loss in ac windings is very low and it helps in proper current flow [37], [88]-[101].

f) DC Reactor Type SFCL

The ac loss in the superconducting element introduces the main operational cost in any superconducting fault current limiter element. DC reactor type SFCL has distinct advantage compared to other SFCL's in this issue. In this type of SFCL dc current flows through the superconducting element so there is no ac loss. Moreover there is no quenching in the superconducting element which reduces the damage probability and dc reactor prevents the sudden increase of fault current as is passes through it [102]-[113]. Depending on the presence of the dc bias in the rectifier bridge it can be either dc reactor with dc bias and controlled or uncontrolled type dc reactor.

Figure 8 shows the schematic diagram of dc biased type SFCL.

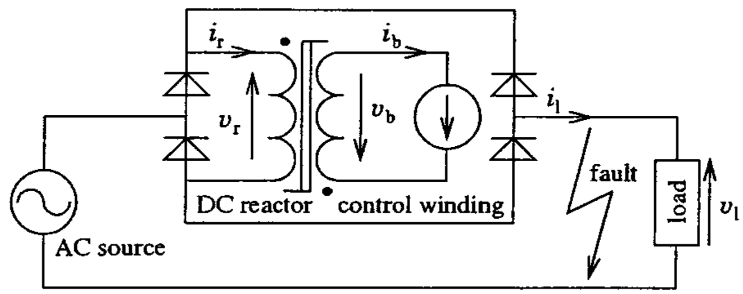


Figure 8: DC biased type SFCL.

DC reactor of the dc bias type utilizes the advantage of reactance winding of iron cores. The iron core has dc reactor and control winding in which the generated fields opposes each other. The dc reactor winding carries the rectified current and the control winding carries the dc bias current. The unsaturated region of the B-H magnetization curve produces high inductance & limits the current. DC saturated reactor type SFCL can limit the fault current before entering into the next saturation region of the magnetization curve [15], [19]-[20], [102] , [107]-[114].

DC resistive SFCL implements the concept of both bridge rectifier type SFCL and resistive type SFCL. In this type of SFCL, an inductance and a superconducting resistance which may be stacked together or separately are used within a bridge. Figure 9 shows the schematic diagram of dc resistive bridge type SFCL. In fault condition the transition property of the superconductor introduces proper limiting operation **[**108**]-[**110**]**, **[**114**]-[**115**]**.

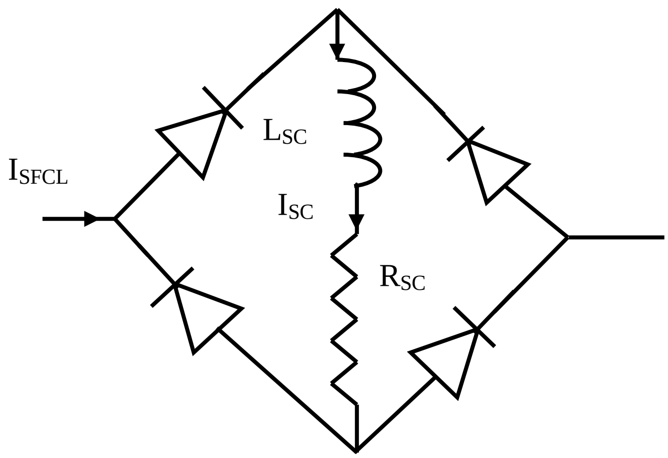


Figure 9: DC resistive bridge type SFCL.

Hybrid bridge type SFCL introduced due to the difficulty of introducing dc bias in the bridge of a dc reactor type SFCL. Figure 10 shows the schematic diagram of hybrid bridge type SFCL. In a hybrid bridge type SFCL combination of thyristor and diode is used along with a superconducting inductor without any dc bias.

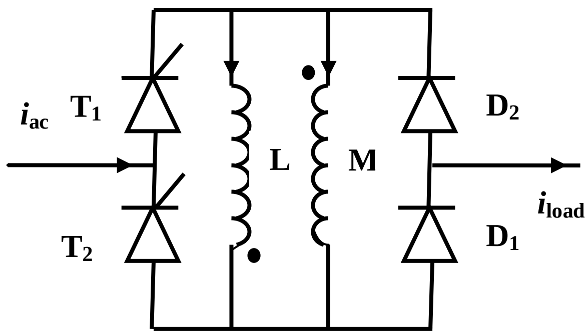


Figure 10: Hybrid bridge type SFCL.

There is no problem in case of normal operation and current limiting operation but in the event of load increase voltage sag happens [116]-[120].

g) Reasons for Choosing Resistive Type SFCL in this work

Among the several types of SFCL, resistive type SFCL has the most simple and unsophisticated construction. The quenching operation of resistive type SFCL is fast, and it can reduce the fault current level effectively within very little time. Although it requires cooling mechanism, but in substation level it can be installed. Moreover, for our MATLAB/SIMULINK model it is very easy to represent in the secondary of the transformers.

h) Application of SFCL

SFCL is a trending technology and so far there is a number of practical installations and application of that technology in the power grid throughout the world. The up-to-date applications of the different type SFCLs is presented in this section.

In 1997 ABB installed a 10.5KV/1MVA resistive SFCL in the Swiss hydro power plant. That SFCL was in the grid for six months [121]. In September 2009, a 12 kV/16 MVA Nexans resistive SFCL was installed into a large power plant located in Boxberg, Germany. Applied Superconductor Limited (ASL) purchased a 12 kV/2 MVA resistive

SFCL from Nexans and installed the device at a distribution substation located in Lancashire, UK. The device can limit a prospective peak fault current of 50 KA to 6 KA. That SFCL is still in operation from 2010[122]. From 2011 a 9 KV/15 MVA resistive SFCL developed by CESI is in operation in North Italian power grid [55]. In October 2011, a 115 KV, 0.9 KA resistive SFCL was successfully installed in the Southern California Edison's high-voltage transmission grid, and it can reduce the fault current about 50%[123].

In January 2009 Zenergy Power Inc. installed a three-phase saturable-core reactor type SFCL at Southern California Edison's (SCE) Shandin substation in San Bernardino, California. It is a 15KV 1.5 KA rating SFCL. This SFCL is still in operation, and according to the manufacturers it can reduce about 30% of the fault current. In the end of 2011 Zenergy Power Inc. installed a three-phase saturable-core reactor type SFCL at American Electric Power's (AEP) Ohio grid. It is a 138KV 1.3 KA rating SFCL. This SFCL is still in operation, and according to the manufacturers it can reduce more than 40% of the fault current[116],[124]. In December 2007 a three-phase 35 kV/90 MVA saturable-core FCL was installed by InnoPower Superconductor Cable Co. Ltd. at the Puji substation, within the Southern China power grid[125]-[126].

In 2007-2008 a 22.9/6.6 kV, 2 MVA transformer type SFCL exhibiting the principal of both resistive and transformer type SFCL was installed in Tokyo, Japan. That research was carried out by Researchers at Nagoya University and installed by Toshiba [**127**].

From 2009 in KEPCO's sub transmission grid a 22.9 KV/630 A hybrid type SFCL manufactured by KEPRI and LSIS is in full operation [61]-[62],[128]-[129].

6) Static VAR Compensator

Static VAR Compensator in this thesis is considered as an auxiliary transient stability enhancing device. By proper controlling it can improve the transient stability of power system. In this work SVC is also considered instead of SFCL with the same operating conditions to see how much effective the SFCL is in improving the transient stability by comparing their performance. Their performance is compared using responses after fault and index values.

SVC is a FACTS family device for fast and proper control of reactive power in the power system. SVC was first developed in the early 1970's for fast controlling the power factor of changing loads but now a days they are used mainly for regulating the transmission voltage and improving the power quality situation. By proper using the first swing stability limit of generators, SVC can also improve the transient stability of power system **[**10**]-[**12**]**. The other applications of SVC are damping of low frequency oscillations, damping of sub synchronous frequency oscillations, control of dynamic over voltages, etc. They are connected in parallel with the transmission line **[**130**]-[**131**]**.

There are three basic types of SVC in the literature **[**130**]-[**131**]**. They are:

a) Variable Impedance Type SVC
b) Voltage Source Type SVC
c) Current Source Type SVC

Figure 11 shows the schematic diagram of TCR and TSC for variable impedance type SVC.

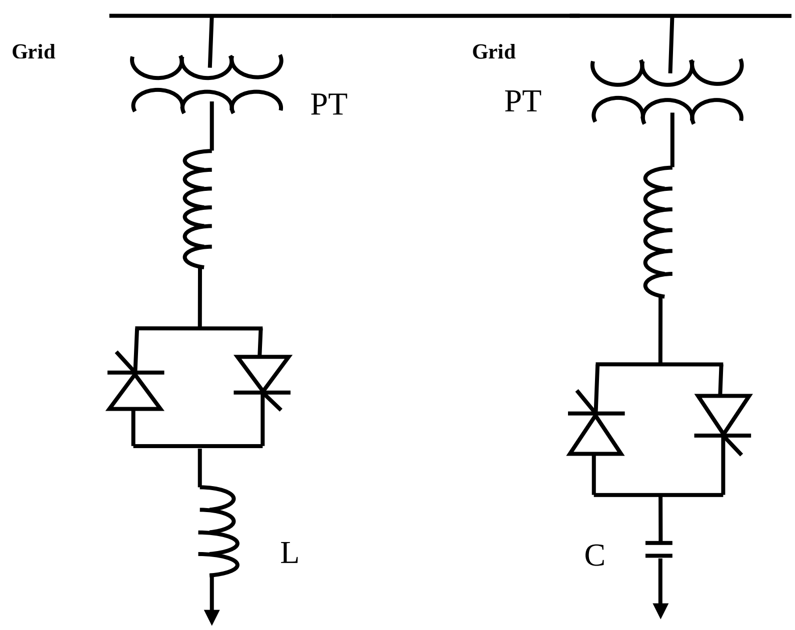


Figure 11: Schematic diagram of TCR and TSC for variable impedance type SVC.

The variable impedance type SVCs are mainly made of Thyristor Controlled Reactor (TCR) in parallel with Fixed Capacitor (FC) or Thyristor Switched Capacitor (TSC). They mainly regulate the voltage in the transmission line. If the power system is capacitive, then TCR's absorb VAR's from the system to maintain proper stability. On the other hand, if the power system is inductive in nature, then the FC or TSC automatically switched on and provides reactive power to the system for stabilizing the voltage. Both TCR and TSC are supplied from a step down transformer and the thyristors are controlled by controlling the firing angle range from 90 degree to 180 degree **[**130**]**-**[**131**]**. TCR and TSC are made of power electronic devices. So there is the presence of harmonics in the system.

To prevent the grid from the harmonics generated in the TCR and TSC, the step down transformers are connected in star-delta formation. To suppress the remaining harmonics from the system, filters are used along with TCRs and TSCs.

Figure 12 shows the schematic diagram of a voltage source type SVC.

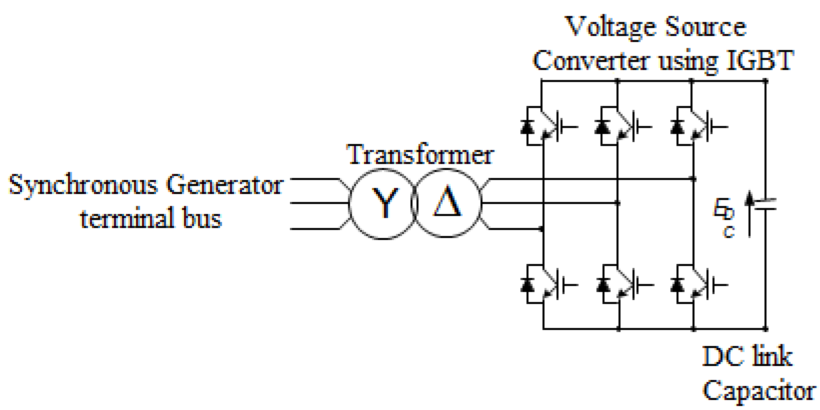


Figure 12: Voltage Source type SVC.

Voltage Source type SVC uses a Voltage Source Converter (VSC) and a dc link capacitor in the terminal of VSC for proper controlling the reactive power of the system. The three phase VSC is made of six IGBT's for proper controlling the voltage. The voltage from the grid is stored in the capacitor through VSC in normal operating condition. Moreover, in the event of disturbance three phase ac voltage is produced from the dc link capacitor voltage through VSC **[**130**]-[**131**]**.

Figure 13 shows the schematic diagram of a current source type SVC.

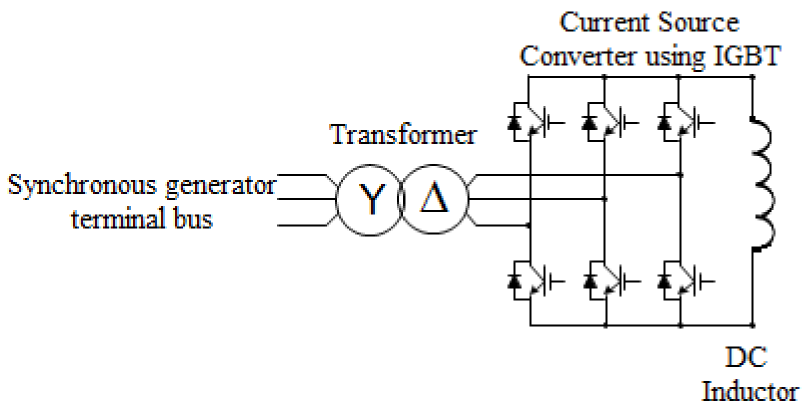


Figure 13: Current Source type SVC.

Current Source type SVC uses a Current Source Converter (CSC) with a dc inductor instead of a dc link capacitor in VSC. A dc inductor is used with IGBT bridge in the CSC. In the CSC the dc current is kept constant with small ripples and thus it forms a current source working on the dc side. In a CSC the direction of current always remains in the same direction **[**130**]-[**131**]**.

a) Application of SVC

SVC is mainly a reactive power controlling FACTS device. With fast acting voltage regulation control it can enhance both transient and steady state stability. SVC improves power transfer in long transmission line by reducing the disturbances caused by changes in reactive power and voltage fluctuations in the normal operation of transmission lines. That action consequently improves the power factor. It easily dampens out the low frequency oscillations. Dynamic overvoltage in the system can also be reduced by using variable impedance type SVC. Another application of SVC is that can also reduce the harmonics **[**130**]-[**131**]**.

7) Novelty

This thesis proposes the combined operation of SFCL and optimal reclosing of circuit breakers to enhance the transient stability of the power network. In order to evaluate the effectiveness of the proposed methodology in more detail, its performance is compared with that of the combined operation of conventional reclosing of circuit breakers and SFCL. Moreover, in order to see the effectiveness of SFCL in improving the transient stability, its performance is compared with the static var compensator (SVC). The effectiveness of the proposed methodology is tested considering permanent balanced and unbalanced faults at different fault locations of the IEEE nine bus power system model[13],[132]-[134]. The total kinetic energy (TKE) of the generators in the system is used to determine the transient stability enhancement index. In this work, simulations are performed through Matlab/Simulink software.

Chapter 2

METHODOLOGY

B. Test System

For the simulation of the transient stability, the IEEE nine bus **[**13**]**,**[**132**]-[**134**]** power system model shown in Figure 14 is used. The model system consists of two generators (G1 and G2) with capacities of 200 MVA and 130 MVA, respectively, and an infinite bus. Generators are connected to one another through transformers and double circuit transmission lines. The line parameters have the form R+jX (jB/2), where R, X and B represent resistance, reactance and susceptance per phase with two lines respectively. F1, F2 and F3 are considered as fault positions. Various generator parameters as well as automatic voltage regulator (AVR) and governor (GOV) control system models used in this simulation are given in Table I and figure 17. The AVR and GOV are the primary control means of the generators to maintain the system stability in case of any faults **[**1**]**, **[**13**]**, **[**132**]-[**134**]**. They are the generator feedback system used for regulating the generators terminal voltage and input mechanical power. V_{to} and E_{fdo} present the reference terminal voltage and field excitation constant of the AVR, respectively. Similarly, ω_{mo} and P_o presents the reference speed of the generator and reference input mechanical power, respectively. The system was implemented in the MATLAB/SIMULINK environment. The per unit transmission line parameters were converted into normal values using the base MVA and base KV values of the system. At first the system was stabilized in the MATLAB/SIMULINK environment comparing with some stabilizing indexes, and the auxiliary transient stability enhancing devices (SFCL and SVC) were implemented. SFCLs are connected in the secondary side of the transformer 1 and transformer 2 as shown in figure 15 and SVCs (SVC 1 and SVC 2) are connected in shunt at the terminals of generators G1 and G2 as shown in figure 16.These two auxiliary transient stability enhancing devices are inserted in the system separately.

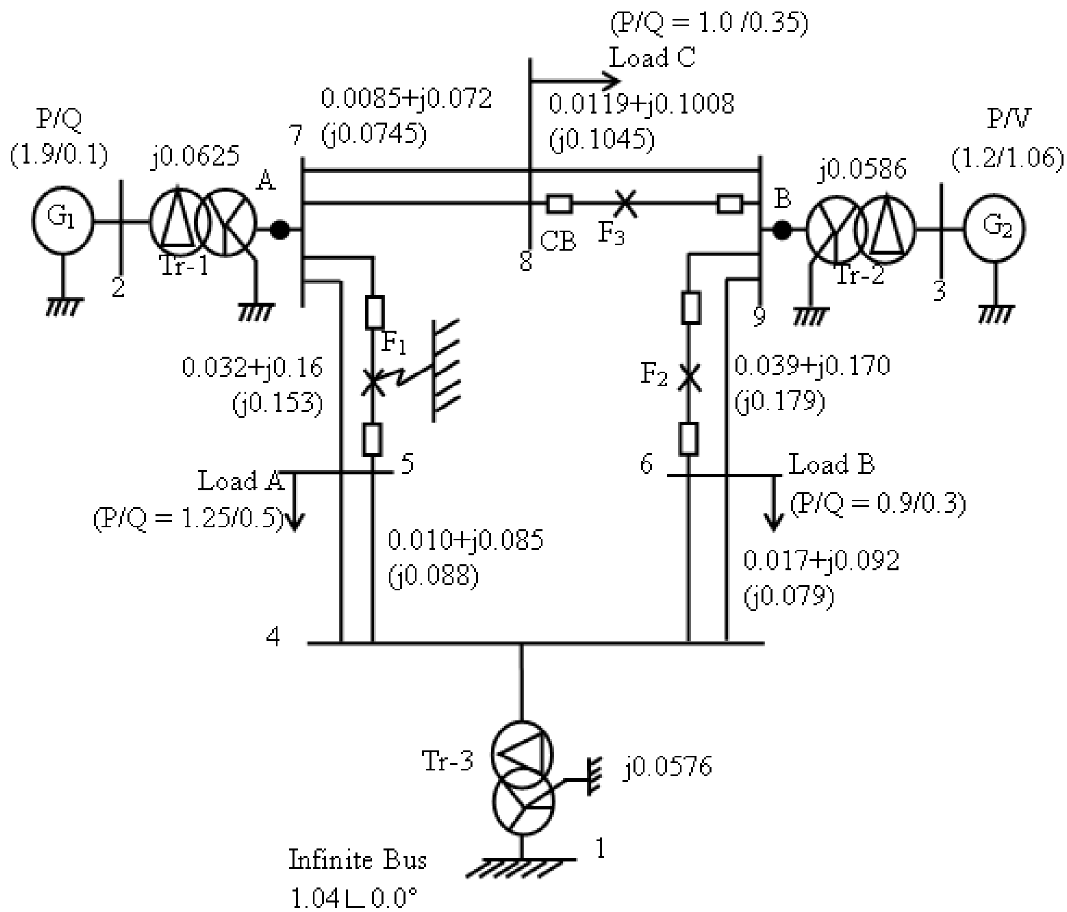


Figure 14: IEEE nine bus system.

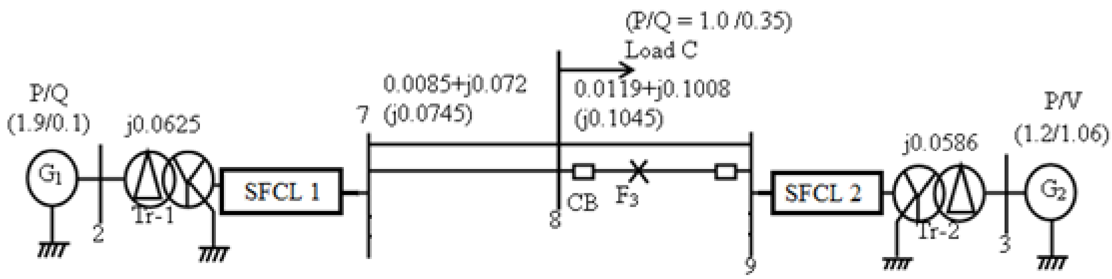


Figure 15: IEEE nine bus system with SFCL.

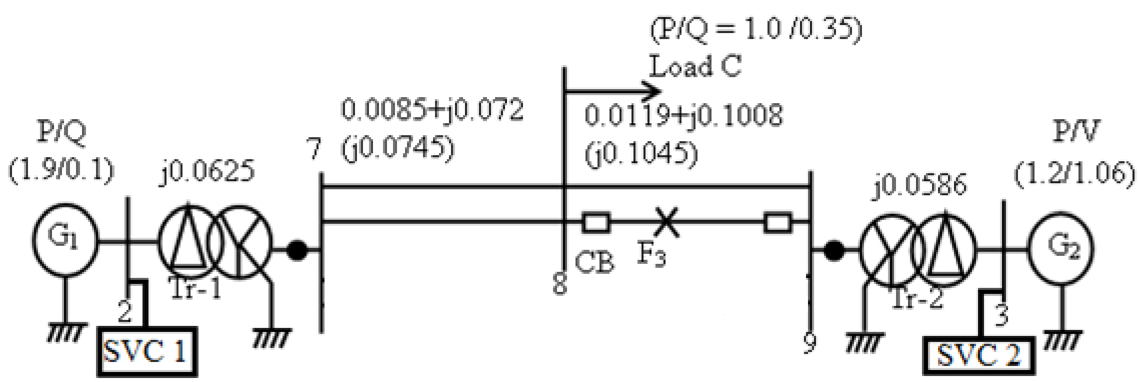
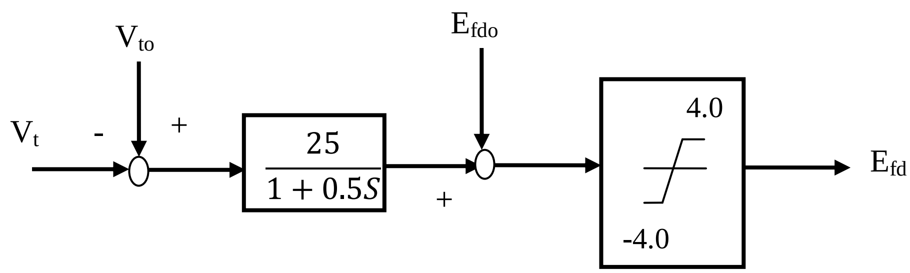


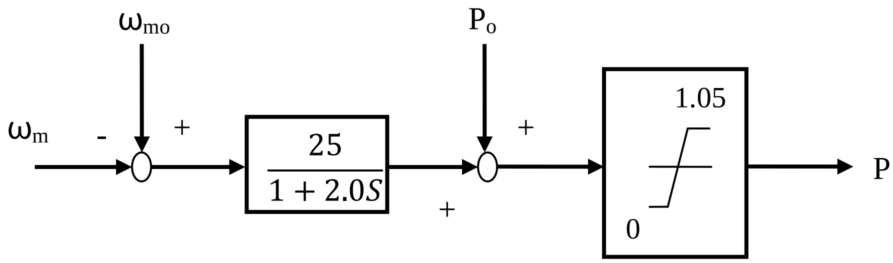
Figure 16: IEEE nine bus system with SVC.

Table 1: Generator Parameters

	G1	G2
MVA	200	130
r_a (pu)	0.003	0.004
x_a(pu)	0.102	0.078
X_d(pu)	1.651	1.220
X_q(pu)	1.590	1.160
X'_d(pu)	0.232	0.174
X'_q(pu)	0.380	0.250
X''_d(pu)	0.171	0.134
X''_q(pu)	0.171	0.134
T'_{do}(pu)	5.900	8.970
T'_{qo}(pu)	0.535	1.500
T''_{do}(pu)	0.033	0.033
T''_{qo}(pu)	0.078	0.141
H (sec)	9.000	6.000



a) AVR.



b) GOV.

Figure 17: AVR and GOV for the generators.

C. Optimal Reclosing Technique

Conventional auto-reclosing of circuit breakers can affect the stability, as it is dependent on the generator state of reclosing instances. So, to enhance the transient stability, circuit breakers should be closed at an optimal reclosing time (ORCT), when the system disturbance has no effect after reclosing operation.

The optimal reclosing technique using total kinetic energy of the participating generators in the system as described in **[**13**]** is used in this work. In this method, the time when the total kinetic energy oscillation of the generators without reclosing operation becomes the minimum is determined as ORCT.

In multi-machine power system different generators have different rotor speed characteristics. Therefore, rotor speed cannot be implemented directly for optimal reclosing of circuit breakers. But the participation of all generators in the system is necessary in determining the optimal reclosing time. In the total kinetic energy technique for determining the optimal reclosing time, the rotor speed and the power rating of each generator in the whole system is taken into account. The total kinetic energy, $W_{total,}$ can be calculated easily by knowing the rotor speed of each generator and can be expressed as

$$Wtotal = \sum_{i=1}^{N} Wi\ (J) \tag{3}$$

$$\text{where} \quad W_i = 1/2 * J_i * w_{mi}^2\ (J) \tag{4}$$

denotes kinetic energy in joules for a generator, *i* is the generator number, *N* is the total number of generators, *J* is the moment of inertia in kg.m^2 and w_{mi} is the rotor angular velocity in mechanical rad/s. Moment of inertia *J* for each generator can be expressed as

$$J = \frac{(H * MVArating)}{(5.48 * 10^{-9} * Ns^2)}$$

Where H denotes the Inertia constant of the generator and N_s denotes the synchronous angular speed in rpm.

ORCT of the circuit breakers is determined without reclosing operation of the circuit breakers after the opening of breakers. After the occurrence of the fault circuit breakers are opened at 0.1 sec, they remain in open position for determining the optimal reclosing time (ORTC). In figure 18 the optimal reclosing times $ORCT_1$ and $ORCT_2$ are indicated for three phase to ground (3LG) fault at fault position 1 in the nine bus system at which kinetic energy becomes the minimum. Figures 19-23 represents the ORCTs for 3LG and single line to ground (1LG) fault at different fault positions of the system. These ORCT values along with the double line fault (2LS) are represented in table 2.

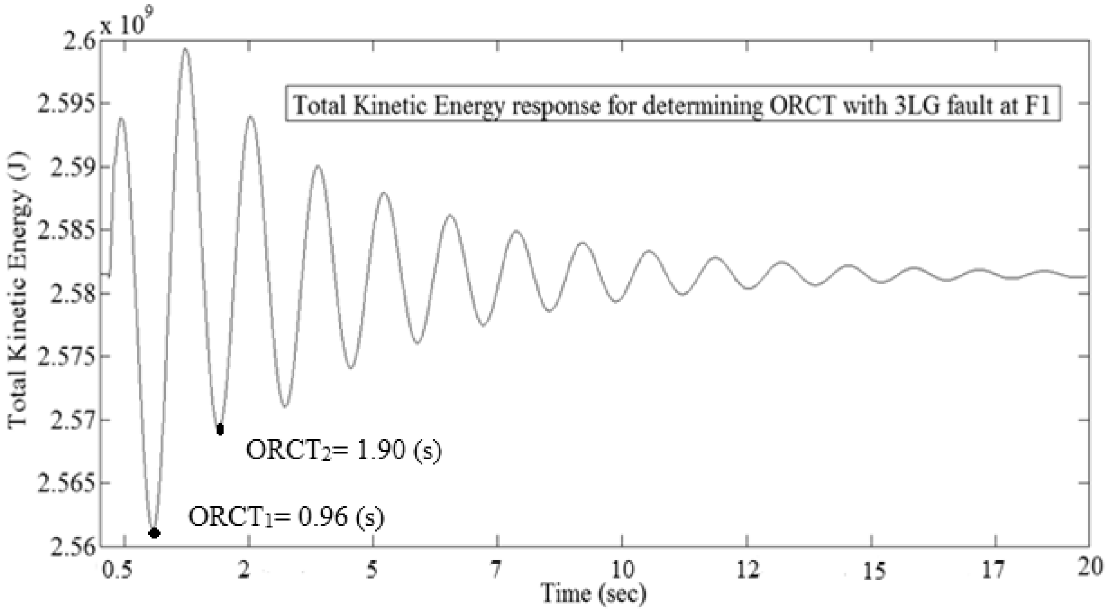


Figure 18: Optimal reclosing time for 3LG permanent fault at F1.

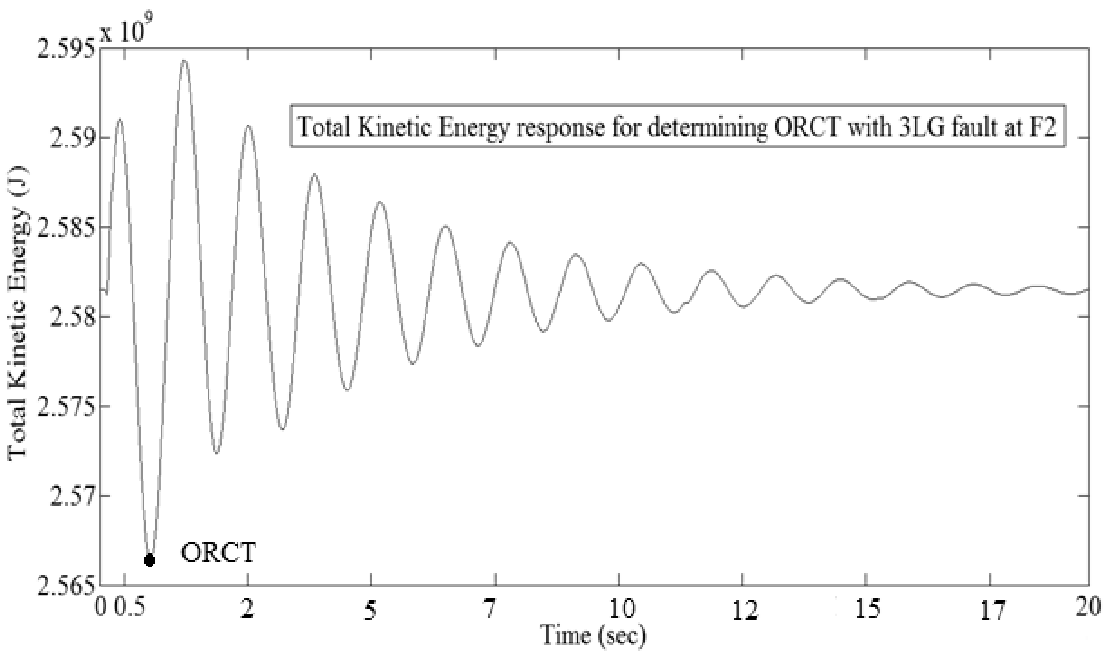


Figure 19: Optimal reclosing time for 3LG fault at F2.

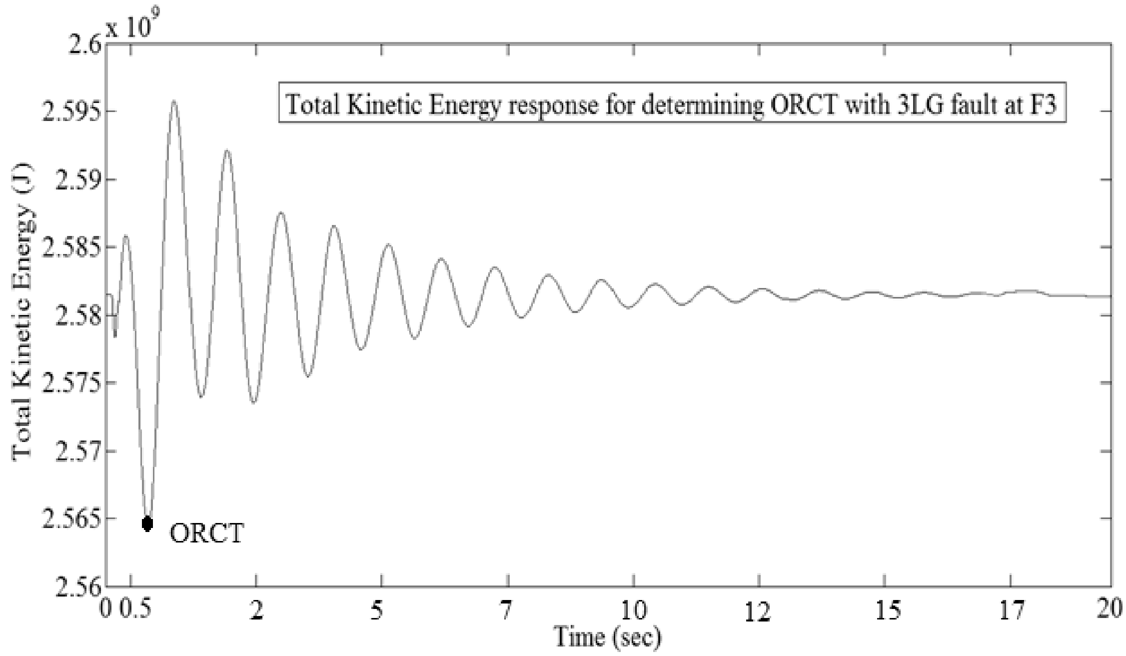


Figure 20: Optimal reclosing time for 3LG fault at F3.

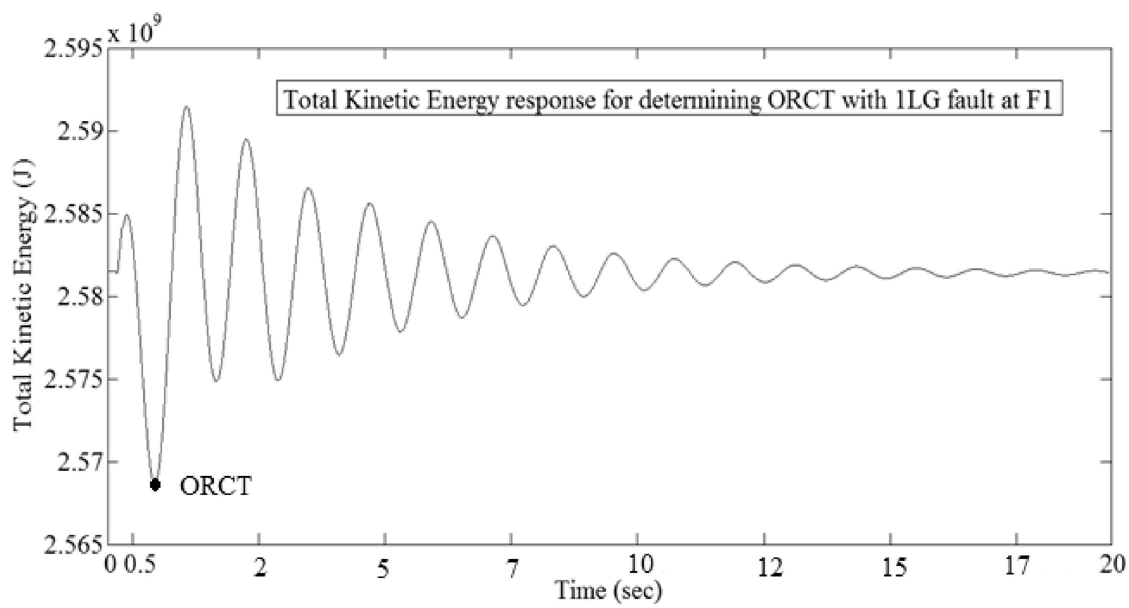


Figure 21: Optimal reclosing time for 1LG fault at F1.

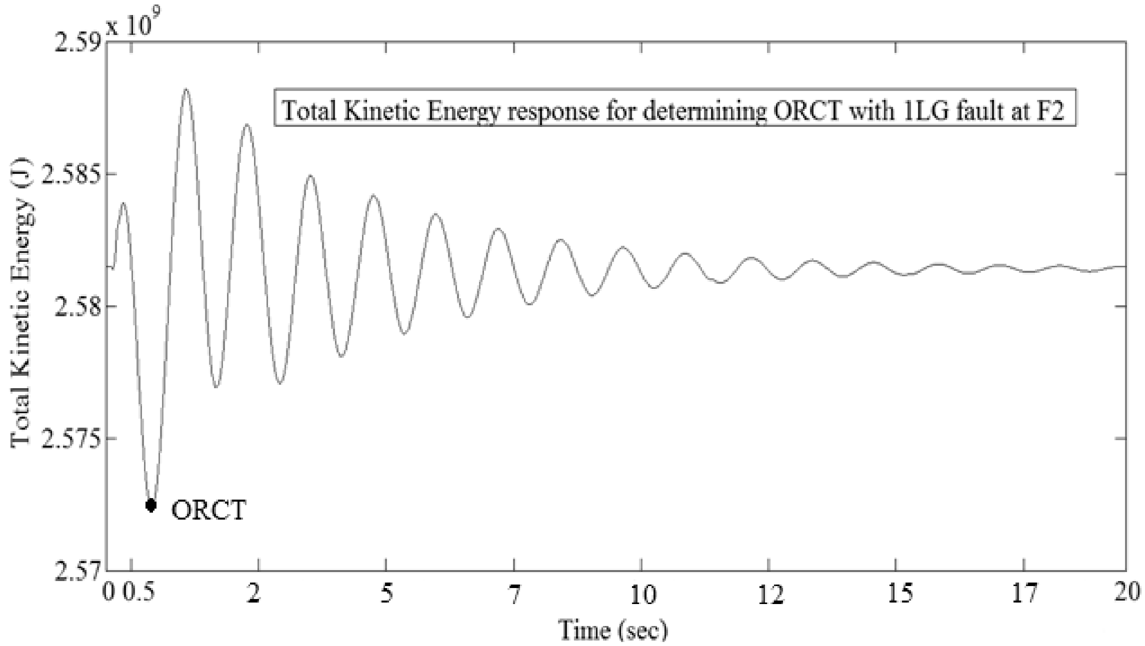


Figure 22: Optimal reclosing time for 1LG fault at F2.

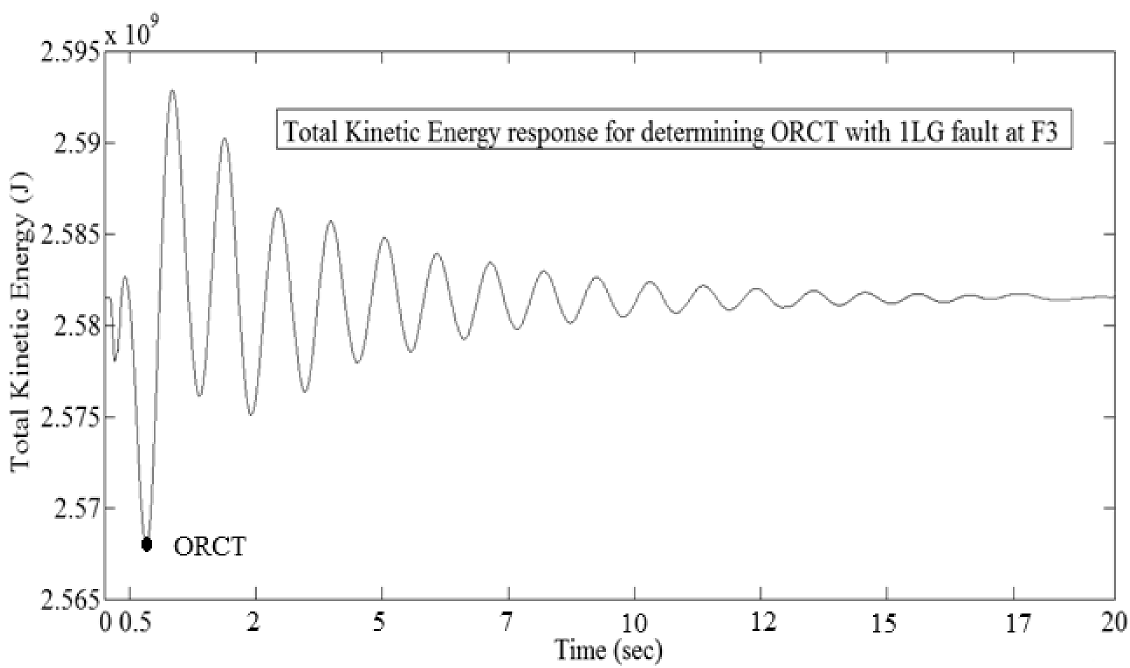


Figure 23: Optimal reclosing time for 1LG fault at F3.

In determining the ORCT between the $ORCT_1$ and $ORCT_2$, consideration of the dead time is important. It is the time between arc interruption by the circuit breaker contacts and the reclosing of the same contacts. ORCT must not be less than this dead time. This deionization time of the arc is dependent on the type of fault, line voltage magnitude and the fault duration. So, optimal reclosing should happen when the deionization time $T_r <$ ORCT. The deionization time **[**13**]** T_r can be expressed as T_r= (10.5+ KV/34.5) cycles. Where KV indicates the line to line rms voltage of the system.

Using the proposed optimal reclosing technique, the values of ORCT for different permanent faults at different locations are calculated from the total kinetic energy responses and represented in the Table 2. These responses are also presented from figures 18 to 23 for different faults and operating conditions.

Table 2: Optimal Reclosing Time

Fault Type	Fault Location	ORCT
3LG	F1	0.960
	F2	0.955
	F3	0.850
2LG	F1	0.920
	F2	0.915
	F3	0.850
1LG	F1	0.890
	F2	0.880
	F3	0.860
2LS	F1	0.950
	F2	0.940
	F3	0.840

D. Implementation of Superconducting Fault Current Limiter

A power system has many interconnections and bulk power transmissions over long distances. So, there is the high possibility of short circuit faults and consequently high short circuit currents. A resistive type superconducting fault current limiter as mentioned above has the ability to limit the effect of high short circuit current. In case of fault, the resistive type SFCL can enhance the transient stability by absorbing the active power of the accelerating generator. The advantage of the resistive type SFCL is that it introduces almost a lossless superconductor in case of the steady state operation and turns out to form a series resistance in the event of fault in power system [5],[16],[26].

The simple structure of the resistive SFCL unit as shown in figure 24 was used in this work. The unit consists of the stabilizer resistance of the n-th unit, R_{ns}, the superconductor resistance of the n-th unit, $R_{nc}(t)$ which is connected with R_{ns} in parallel, and the coil inductance of the n-th unit, L_n. The subscript, n denotes the number of connected units [4]. The value of R_{ns} is not zero. However, the total resistance of parallel connection becomes zero because the value of R_{nc} is zero in the steady-state condition. The value of $R_{nc}(t)$ becomes non-zero time-varying parameters during a fault depending on its unique characteristic. The value of total resistance of the SFCL during a fault depends on the total number of units in figure 24, which are connected in series. The value of L_n is so small that its effect can be ignored [16].

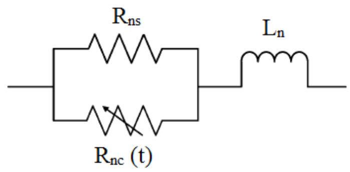


Figure 24: Structure of resistive SFCL unit.

For analyzing the effect of SFCL in the IEEE nine bus systems, the simplified version of resistive SFCL used in this work is shown in figure 25, and they are connected in the secondary of each generators transformer as shown in figure 15.

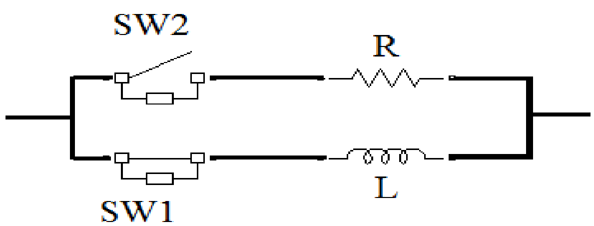


Figure 25: Resistive SFCL control circuit.

For steady state operation the switch remains closed so that the continuity of power supply never hampers. The inductance, L has a very low value so that under normal condition there is negligible loss. The switching of the switch is controlled through the rms current rating of the generators. As soon as the fault occurs, the rms current rating of the generators becomes high. If the current rating in the switch goes beyond the fault current level, then the switch will operate in the open mode and the SFCL resistance will come in series with the system. The values for the resistance and the fault current level have been determined by careful study in order to obtain the best system performance. Depending on the fault nature generators have different fault level current. The value of the SFCL resistance is kept within the 2 pu value of the system parameters.

E. Implementation of Static VAR Compensator

Due to many interconnections and bulk power transmissions over long distances in power system there are inter area low frequency oscillation possibilities. FACTS devices have the ability to damp the inter area oscillation. SVC is a reactive power compensating FACTS device but SVC has the ability to improve the transient stability **[**11**]**, **[**135**]-[**137**]**. Figure 26 and figure 27 represents the schematic diagram of SVC and its control system for this work.

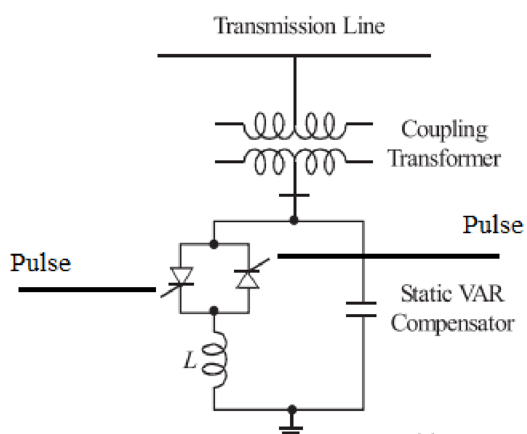


Figure 26: SVC connected to transmission line.

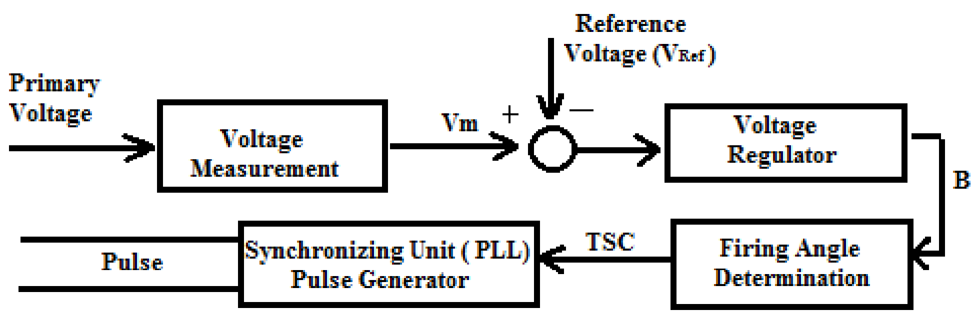


Figure 27: Control System of SVC.

In this work, SVC is connected in shunt with each terminal of the P/Q (G1) and P/V (G2) generator as shown in figure 16. SVC is connected as Fixed Capacitor-Thyristor Controlled Reactor (FC-TCR) as shown in figure 26. Firing angle of the thyristor is controlled in such a way that the capacitor bank will be connected with the generator terminals during the fault periods.

The FC-TCR is supplied from the step down coupling transformer. The variation in reactive power is performed by switching the FC-TCR by controlling the firing angle α, which is in the range 0 degree to 90 degrees. For keeping the system voltage constant, SVC susceptance B is measured using the voltage regulator as shown in figure 27 of the SVC control system. The equivalent susceptance, B_{eq} as mentioned in (5) is determined by the firing angle α of the thyristors that is defined as the delay angle measured from the peak of the capacitor voltage to the firing instant **[**10**]-[**12**]**, **[**138**]**.

$$B_{eq} = B_L(\alpha) + B_C \tag{5}$$

Here $B_L(\alpha) = -1/\omega L\left(1 - \frac{2\alpha}{\pi} - \frac{sin(2\alpha)}{\pi}\right)$

and $B_C = \omega C$ & $0° \leq \alpha \leq 90°$.

If the real power consumed by the SVC is assumed to be zero then

$$P_{SVC} = 0$$

$$Q_{SVC} = - B_{SVC} * V^2 \quad (6)$$

where V is the bus voltage magnitude.

As the reactive power demand at the bus varies, the susceptance is varied subject to the limit. However, the reactive power as shown above in equation (6) is a function of the square of the bus voltage, so reactive power generation decreases if the bus voltage decreases. The equivalent susceptance in the SVC control system is used to determine the firing angle. The phase locked loop (PLL) in the synchronizing system is used in the secondary voltage side and produces pulse using pulse generator for thyristor switching.

Chapter 3

SIMULATION RESULTS AND DISCUSSIONS

In this work, simulations are performed through Matlab/Simulink software. Simulations have been carried out considering both balanced (3LG: three-phase-to-ground) and unbalanced (1LG: single-phase-to-ground, 2LG: double-phase-to-ground fault, 2LS: phase-to-phase fault) permanent faults. F1, F2 and F3 are considered as the fault locations in the system model as shown in figure 14. The simulation time and time step are considered as 20s and 50 µs, respectively.

For the evaluation of transient stability in this work we have used the stability index W_c [13],[132] which is given by

$$W_c\,(\text{sec}) = \int_0^T \left| \frac{d}{dt}(Wtotal) \right| dt \,/\, systembasepower \qquad (7)$$

where T is the simulation time and W_{total} is the total kinetic energy.

The value of W_c is a representation of universal stability of the system. The lower the value of W_c, the better the system's performance.

Stability index values for conventional and optimal reclosing situations considering both SFCL and SVC will illustrate the effectiveness of these two auxiliary stability enhancing devices. Tables 3 and table 4 represent these values.

Table 3: Values of W_c for conventional reclosing with and without SFCL/SVC.

Fault Type	Fault point	W_c values (Conventional Reclosing without SFCL)	W_c values (Conventional Reclosing with SFCL)	Improvement with SFCL	W_c values (Conventional Reclosing without SVC)	W_c values (Conventional Reclosing with SVC)	Improvement with SVC
3LG	F1	0.4332	0.1938	55.26%	0.4332	0.2123	50.99%
	F2	0.5267	0.1517	71.19%	0.5267	0.1772	66.35%
	F3	0.5517	0.1836	66.72%	0.5517	0.2115	61.02%
2LG	F1	0.3707	0.1702	54.08%	0.3707	0.2011	45.75%
	F2	0.4014	0.1565	61.01%	0.4014	0.1696	57.74%
	F3	0.4905	0.1824	62.81%	0.4905	0.2201	55.21%
2LS	F1	0.2904	0.1546	46.76%	0.2904	0.1946	32.98%
	F2	0.2213	0.1614	27.06%	0.2213	0.1714	22.54%
	F3	0.2302	0.1982	13.90%	0.2302	0.2182	5.21%
1LG	F1	0.2245	0.1912	14.83%	0.2245	0.1912	14.83%
	F2	0.2123	0.1395	34.29%	0.2123	0.1421	33.06%
	F3	0.2359	0.2107	10.68%	0.2359	0.2279	3.39%

Table 4: Values of W_c for optimal reclosing with and without SFCL/SVC.

Fault Type	Fault point	W_c values (Optimal Reclosing without SFCL)	W_c values (Optimal Reclosing with SFCL)	Improve-prove-ment with SFCL	W_c values (Optimal Reclosing without SVC)	W_c values (Optimal Reclosing with SVC)	Improve prove-ment with SVC
3LG	F1	0.2540	0.1308	48.50%	0.2540	0.1518	40.23%
	F2	0.2880	0.1195	58.50%	0.2880	0.1362	52.70%
	F3	0.2123	0.1601	24.58%	0.2123	0.1687	20.53%
2LG	F1	0.1881	0.1354	28.01%	0.1881	0.1445	23.17%
	F2	0.1908	0.1042	45.38%	0.1908	0.1204	36.89%
	F3	0.2191	0.1563	28.66%	0.2191	0.1667	23.91%
2LS	F1	0.1625	0.1452	10.64%	0.1625	0.1543	5.04%
	F2	0.1506	0.1097	27.15%	0.1506	0.1182	21.64%
	F3	0.1821	0.1388	23.77%	0.1821	0.1521	16.74%
1LG	F1	0.1260	0.1057	16.11%	0.1260	0.1170	7.14%
	F2	0.1458	0.09963	31.66%	0.1458	0.1086	25.51%
	F3	0.1767	0.1441	18.44%	0.1767	0.1544	12.62%

F. Effect of Coordinated Operation of Conventional Reclosing of Circuit Breakers and SFCL/SVC.

For conventional reclosing of the circuit breakers, it is considered that the fault occurs at 0.1s at any of points F1, F2 and F3. Circuit breakers are opened at 0.2s and reclosed at 1.0s. As the fault considered is permanent in type, the circuit breakers are reopened at 1.1 s. It is assumed that the circuit breakers clear the line when the current through it crosses the zero level. The SFCLs connected at the transformer secondary come into operation as soon as the fault occurs and circuit breakers open. Similarly, SVCs connected at the terminal of the generators come into operation as soon as the fault occurs and circuit breakers open. Tables 3 shows the index values for 3LG, 2LG, 1LG and 2LS faults at different fault positions with and without the presence of SFCL and SVC for conventional reclosing of circuit breakers. The values of the indexes indicate the effectiveness of the combined operation of conventional reclosing and SFCL/SVC for enhancing the transient stability during unsuccessful reclosing instead of only conventional reclosing of circuit breakers.

It is noteworthy that the index values in Table 3 for any particular fault position and fault type with SFCL are less compared with the index values of the same fault position and fault type with SVC. This fact demonstrates that the performance of SFCL in enhancing the power system transient stability is better than that of the SVC.

The responses of the total kinetic energy in case of conventional reclosing with no SFCL/SVC, in case of conventional reclosing with SFCL and conventional reclosing with SVC are presented in Figures 28 and 29.

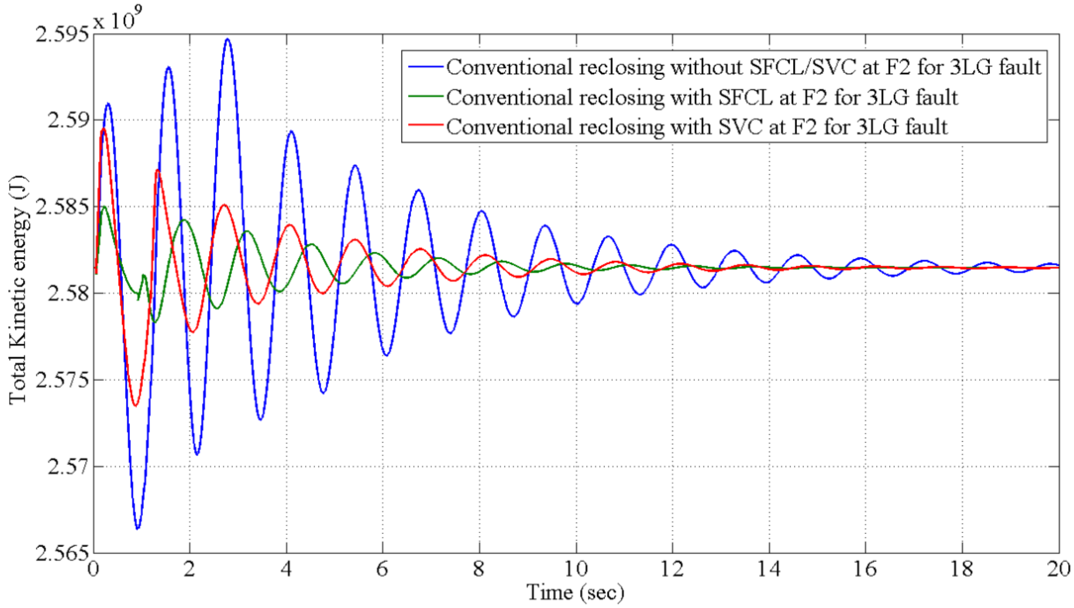


Figure 28: Total kinetic energy response for conventional reclosing without SFCL/SVC, with SFCL and with SVC for 3LG fault at F2.

From figure 28 the effectiveness of SFCL and SVC in stabilizing the total kinetic energy oscillation after the occurrence of fault is very clear. In this case a 3LG fault at fault position 2 was considered. For conventional reclosing of circuit breakers, the system without any SFCL/SVC takes more time to stabilize. But the presence of SFCL/SVC in the same situation with conventional reclosing of circuit breakers can stabilize the system more quickly. Moreover, from the response it is clear that the SFCL is stabilizing more quickly than the SVC. This fact is also reflected in the stability index value of table 3.

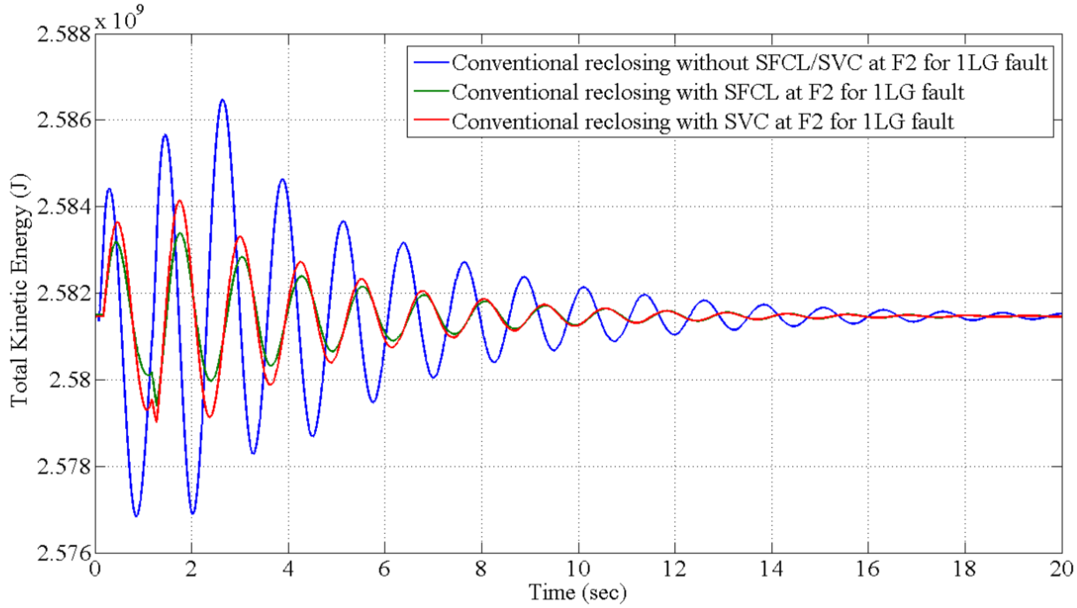


Figure 29: Total kinetic energy response for conventional reclosing without SFCL/SVC, with SFCL and with SVC for 1LG fault at F2.

From figure 29 the effectiveness of SFCL and SVC in stabilizing the total kinetic energy oscillation after the occurrence of fault is very much clear. In this case a 1LG fault at fault position 2 was considered. For conventional reclosing of circuit breakers, the system without any SFCL/SVC takes more time to stabilize. But the presence of SFCL/SVC in the same situation with conventional reclosing of circuit breakers can stabilize the system more early. Moreover, from the response it is clear that the SFCL is stabilizing more early than the SVC. This fact is also reflected in the stability index value in table 3.

G. Effect of Coordinated Operation of Optimal Reclosing of Circuit Breakers and SFCL/SVC

In case of optimal reclosing, circuit breakers are opened at 0.1s after the occurrence of the fault and reclosed according to the ORCT given in Table 2 for different fault points and different fault types. The other simulation conditions are the same as the case of conventional reclosing described above.

Table 4 shows the index values for 3LG, 2LG, 1LG and 2LS faults at different fault positions with and without the presence of SFCL and SVC for optimal reclosing of circuit breakers.

Now by comparing table 4 with table 3, it can be noticed that for any particular fault position and fault type the index value for optimal reclosing with either SFCL/SVC is lower than the index value for conventional reclosing with either SFCL/SVC. This fact proves the effectiveness of the proposed optimal reclosing of circuit breakers with SFCL/SVC in improving the transient stability of the power system.

Moreover, it is noteworthy that the index values in Table 4 for any particular fault position and fault type switch SFCL are less compared with the index values of the same fault position and fault type with SVC in the same table. This fact demonstrates that the performance of the proposed combination of optimal reclosing of circuit breakers and SFCL is better than that of the combination of optimal reclosing of circuit breakers and SVC.

The responses of the total kinetic energy in case of optimal reclosing with no SFCL/SVC, in case of optimal reclosing with SFCL and conventional reclosing with SVC are presented in Figures 30 and 31.

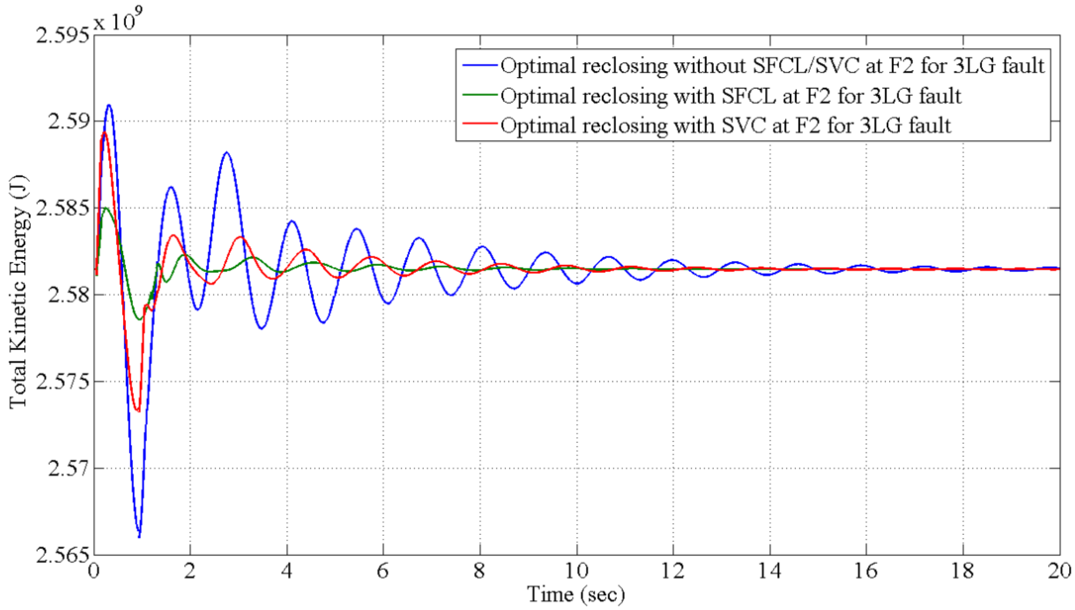


Figure 30: Total kinetic energy response for optimal reclosing without SFCL/SVC, with SFCL and with SVC for 3LG fault at F2.

From figure 30 the effectiveness of SFCL and SVC in stabilizing the total kinetic energy oscillation after the occurrence of fault is very much clear. In this case a 3LG fault at fault position 2 was considered. For optimal reclosing of circuit breakers, the system without any SFCL/SVC takes more time to stabilize. But the presence of SFCL/SVC in the same situation with optimal reclosing of circuit breakers can stabilize the system more early. Moreover, from the response it is clear that the SFCL is stabilizing more early than the SVC. This fact is also reflected in the stability index value in table 4.

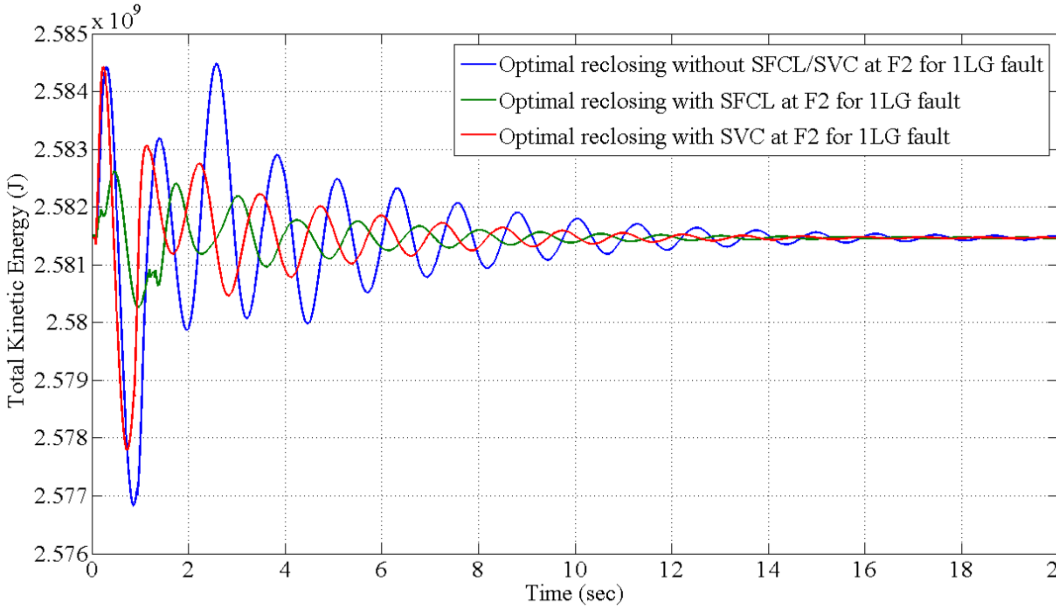


Figure 31: Total kinetic energy response for optimal reclosing without SFCL/SVC, with SFCL and with SVC for 3LG fault at F2.

From figure 31 the effectiveness of SFCL and SVC in stabilizing the total kinetic energy oscillation after the occurrence of fault is very much clear. In this case a 1LG fault at fault position 2 was considered. For optimal reclosing of circuit breakers, the system without any SFCL/SVC takes more time to stabilize. But the presence of SFCL/SVC in the same situation with optimal reclosing of circuit breakers can stabilize the system more early. Moreover, from the response it is clear that the SFCL is stabilizing more early than the SVC. This fact is also reflected in the stability index value in table 4.

As SFCL has the ability to compensate active power, so it is important to observe the generators active power and rms current responses with the presence of SFCL. These responses are presented in figures 32 to 37, which indicate the better stability responses with the presence of SFCL. For both the generators the active power response and rms current responses are presented with and without the presence of the SFCL.

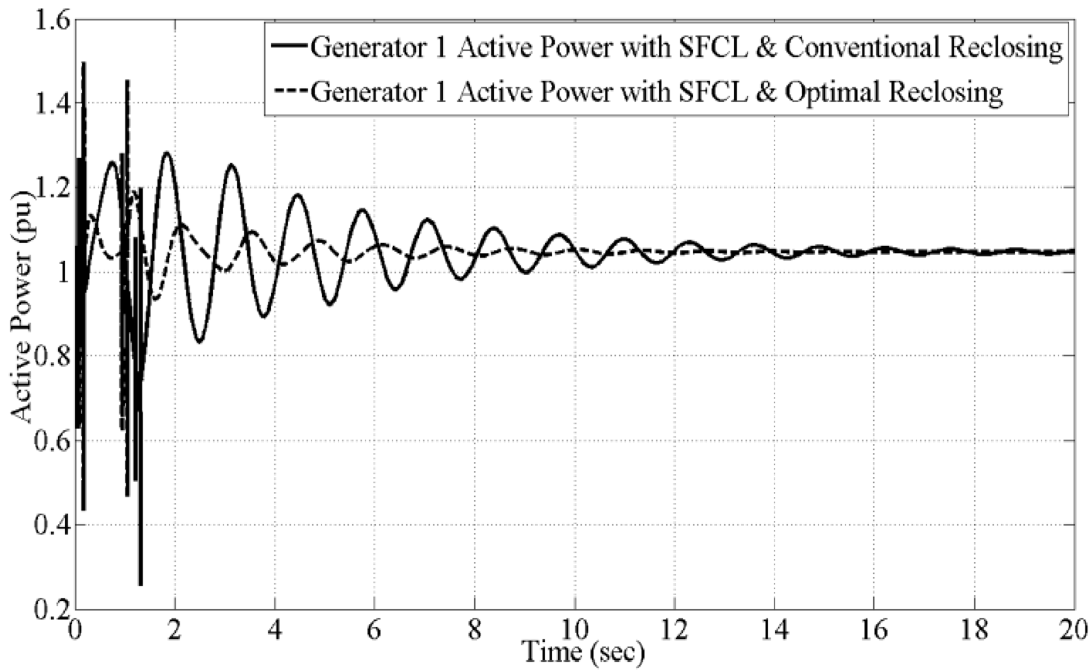


Figure 32: Generator 1 active power response with SFCL for 3LG fault at F2.

For 3LG at fault position 2, the active power response of the generator 1 in the presence of SFCL for both conventional reclosing and optimal reclosing of circuit breakers is shown in figure 32. That response indicates the generator active power is stabilized more quickly to its steady state value in case of optimal reclosing of circuit breakers with SFCL. For the same operating condition other generator’s response is presented in figure 33.

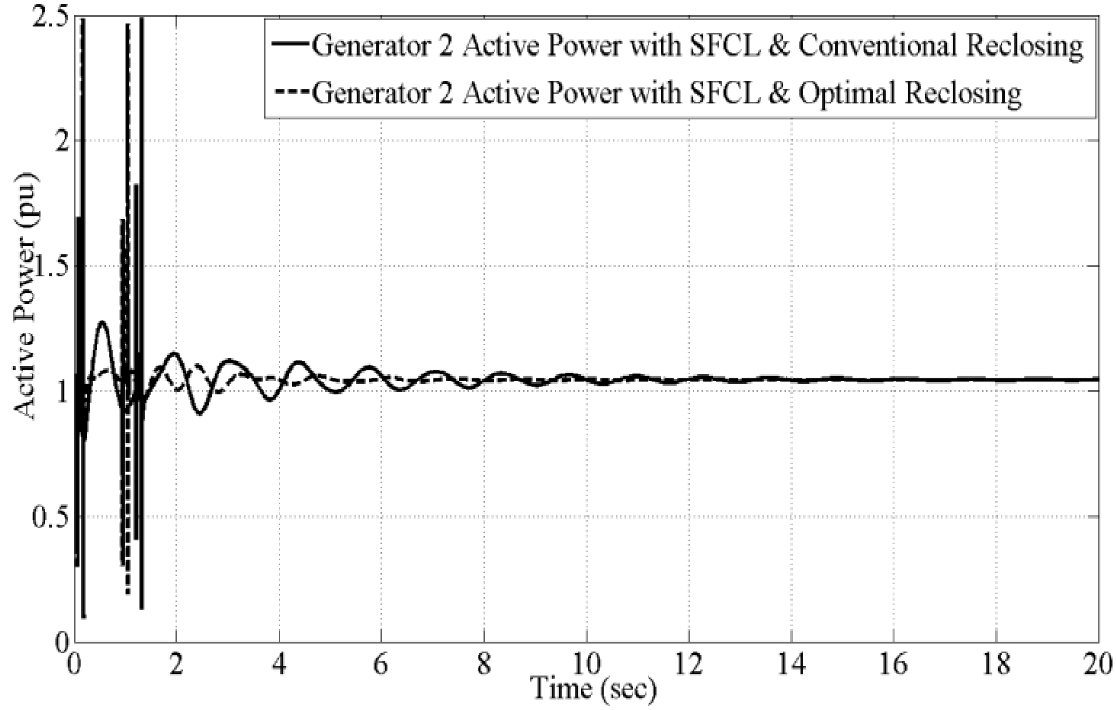


Figure 33: Generator 2 active power response with SFCL for 3LG fault at F2.

For generator 2 the active power responses with the presence of SFCL for both conventional reclosing and optimal reclosing with circuit breakers are almost identical. But from the response it is quite clear that for fault position 2 the effect of optimal reclosing with SFCL is better than that of conventional reclosing with SFCL. So, active power oscillation of generator 2 becomes stable more quickly and it indicates the effect of SFCL in system stabilization. In case of 1LG at the same fault position, the active power response of generator 1 is presented in figure 34.

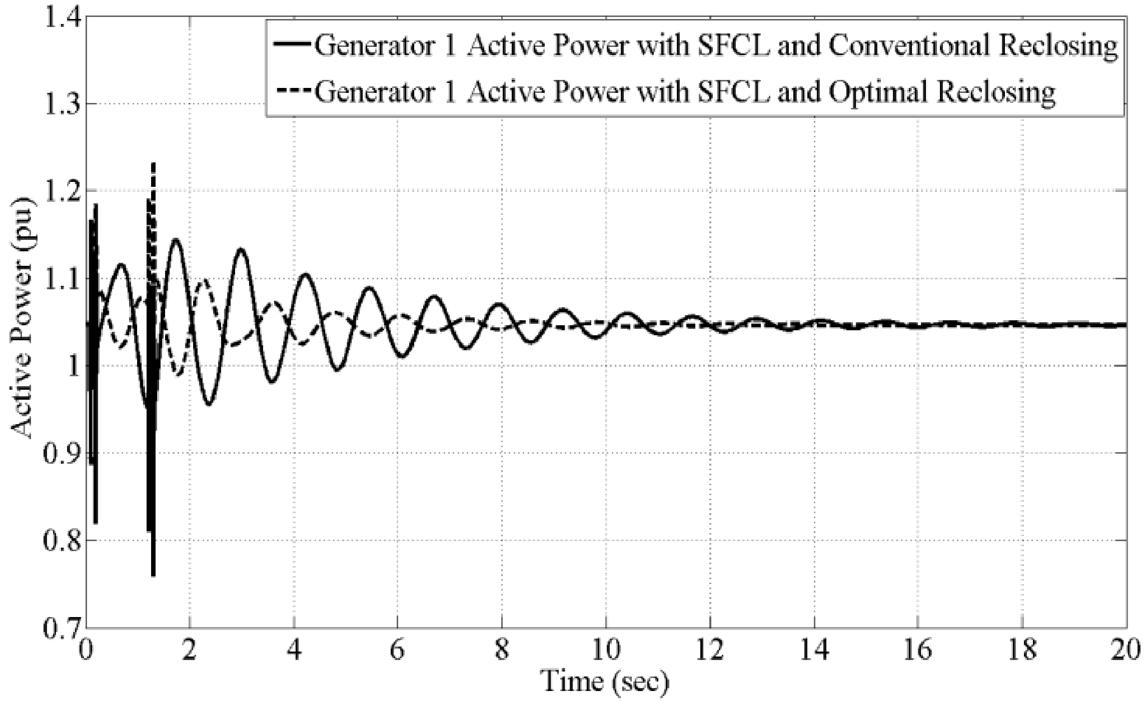


Figure 34: Generator 1 active power response with SFCL for 1LG fault at F2.

As SFCL is an active power compensating auxiliary device which limits the damaging effect of high fault current, in the event of fault when a SFCL comes into action it is important to follow the generators terminal current response. The responses of the rms terminal current of the generators are presented from figure 35 to figure 37.

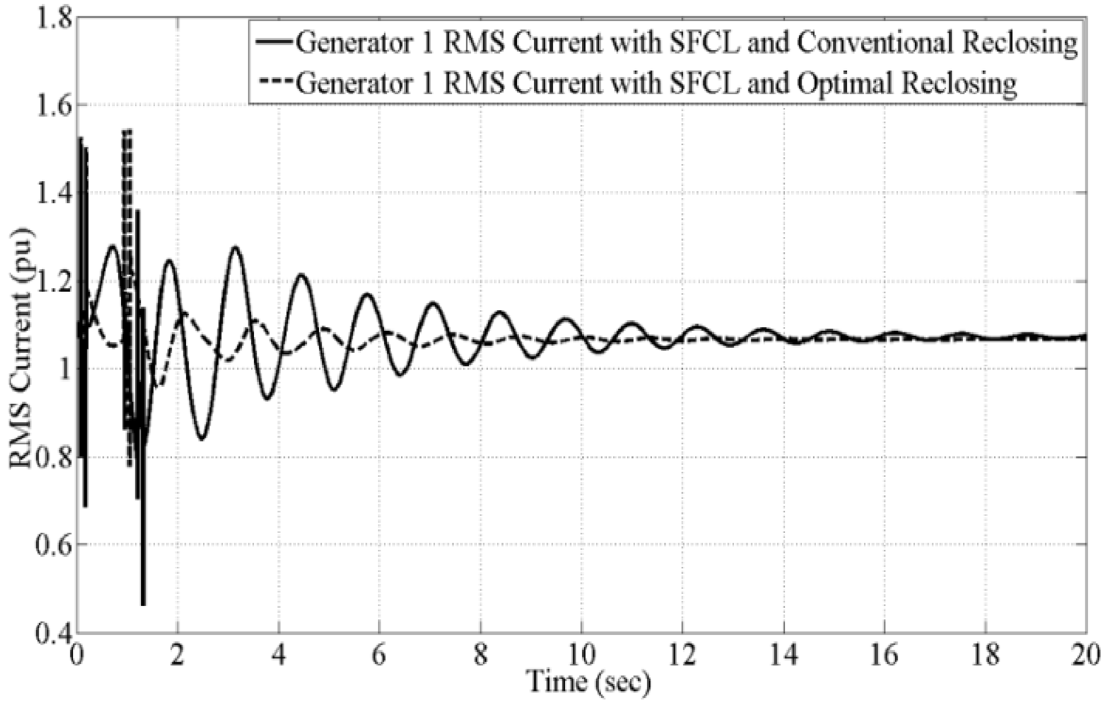


Figure 35: Generator 1 rms current response with SFCL for 3LG fault at F2.

For 3LG at fault point 2 with the presence of SFCL for both conventional reclosing and optimal reclosing of circuit breakers, the terminal current response of generator 1 is shown in figure 35. The responses indicate the effectiveness of combined operation of optimal reclosing of circuit breakers and SFCL in enhancing the transient stability of the power system. It is clear from the response that the combined operation of optimal reclosing of circuit breakers and SFCL makes terminal current to be stable more early after the occurrence of fault. For the same operating condition, the terminal current response of generator 2 is presented in figure 36.

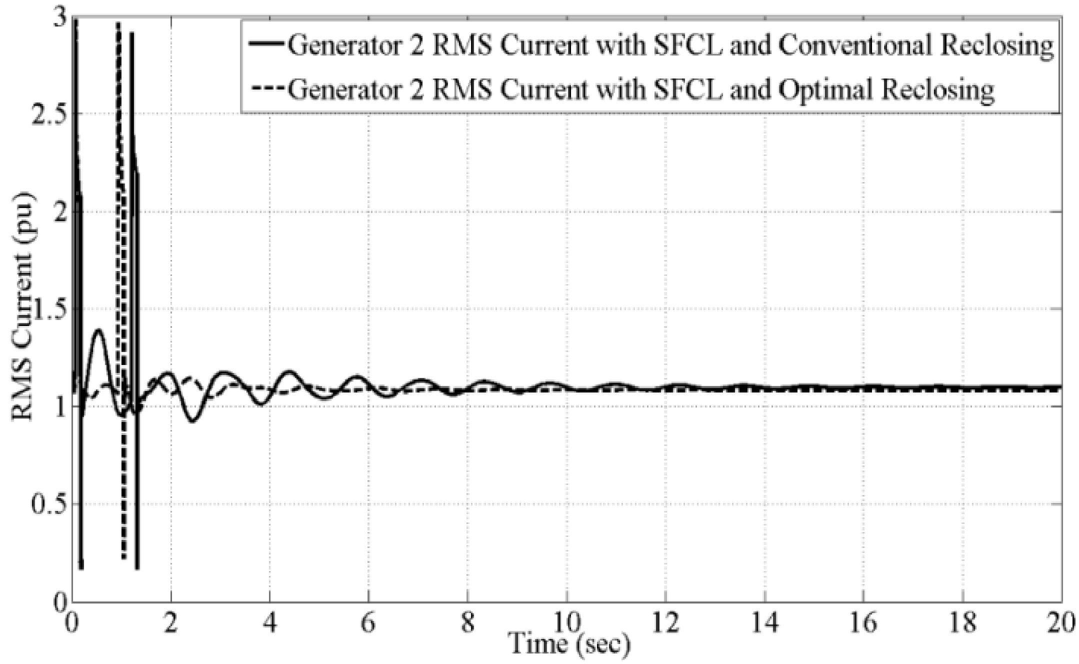


Figure 36: Generator 2 rms current response with SFCL for 3LG fault at F2.

The terminal current responses of generator 2 for conventional reclosing with SFCL and optimal reclosing with SFCL are very much identical to each other, but there is certain difference between them. It is clear that optimal reclosing with SFCL takes little time to stabilize the terminal current oscillation after the occurrence of fault. In case of 1LG the terminal current response of generator 1 is presented in figure 37.

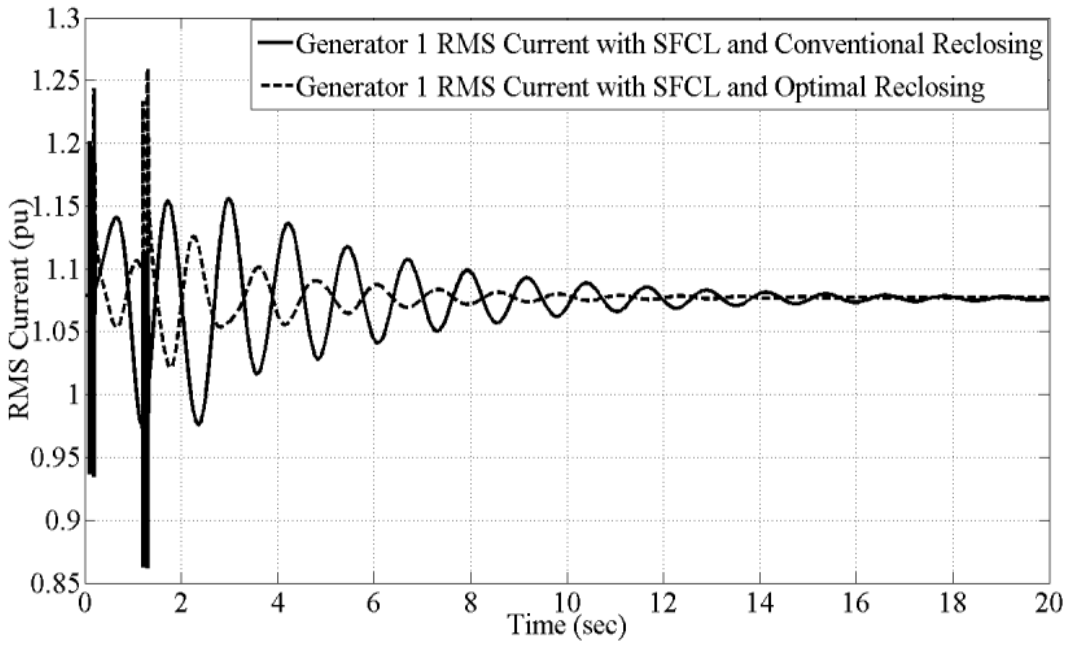


Figure 37: Generator 1 rms current response with SFCL for 1LG fault at F2.

In the event of 1LG at fault position 2 the rms terminal current response of generator 1 is presented in figure 37. These responses are after the occurrence of fault and indicate the effectiveness of combined operation of optimal reclosing and SFCL.

As SVC is a reactive power compensating FACTS device used for transient stability enhancement in this work, it is important to observe the reactive power response of the SVCs for both the conventional reclosing and optimal reclosing operation.

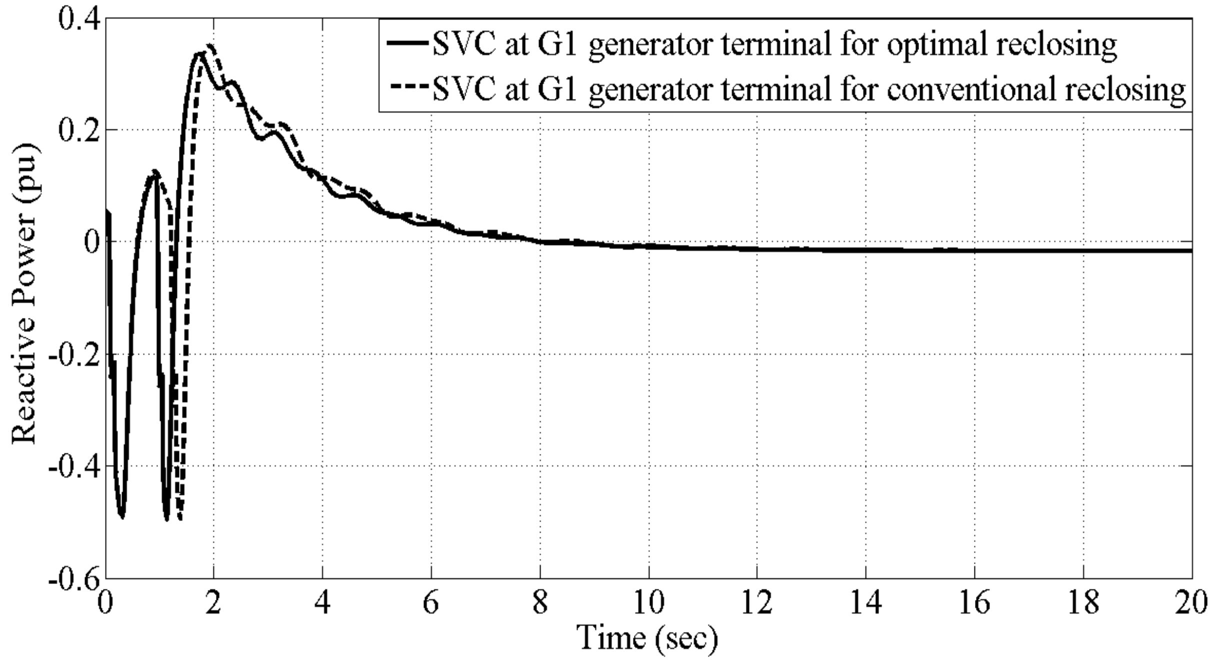


Figure 38: Reactive power response of SVC connected in generator 1 terminal for 3LG fault at F2.

Generator terminal voltage responses with the presence of SVCs are presented from figure 38 to figure 43. Moreover, as the fault at any point of the system can introduces voltage sag in the transmission lines, the terminal voltage responses of the generators is also of high interest. SVCs in the generator terminal tend to compensate the reactive power when a fault occurs and thus improve the voltage sag.

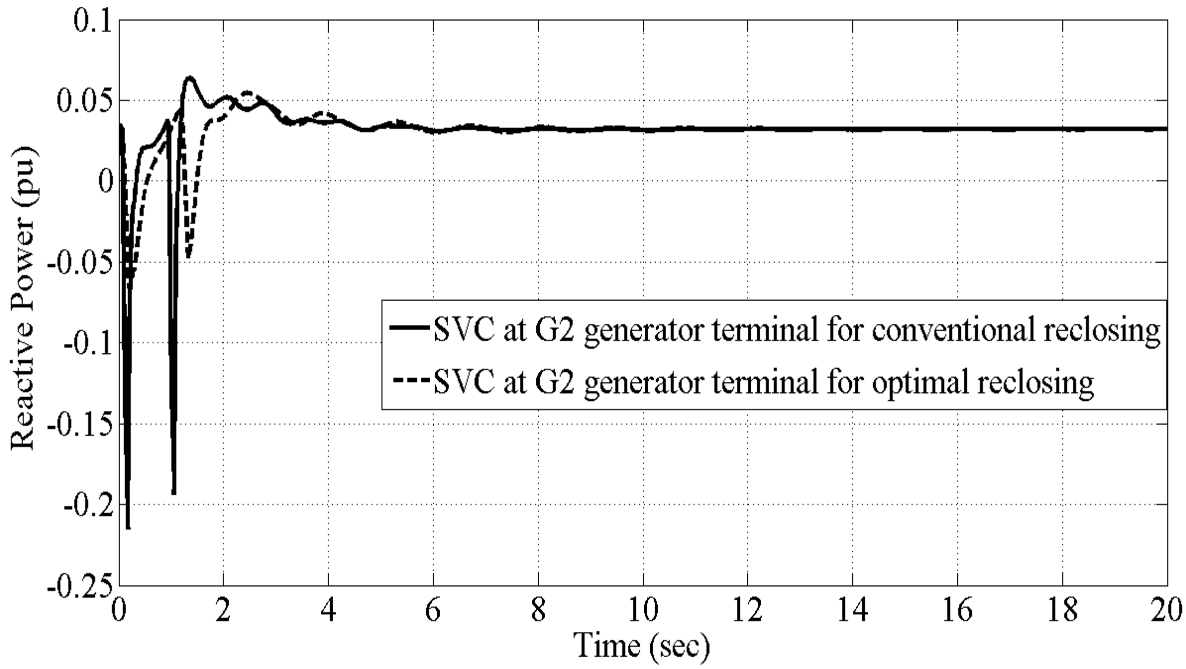


Figure 39: Reactive power response of SVC connected in generator 2 terminal for 3LG fault at F2.

In case of 3LG at fault position 2 the per unit reactive power responses of SVC at generator 1 terminal for both conventional reclosing of circuit breakers and optimal reclosing of circuit breakers is presented in figure 38. The reactive power responses are stabilized after fault and supplies steady reactive power towards the system for proper system stability.

In case of 3LG fault at fault position 2 the per unit reactive power responses of SVC at generator 2 terminal for both conventional reclosing of circuit breakers and optimal reclosing of circuit breakers is presented in figure 39.

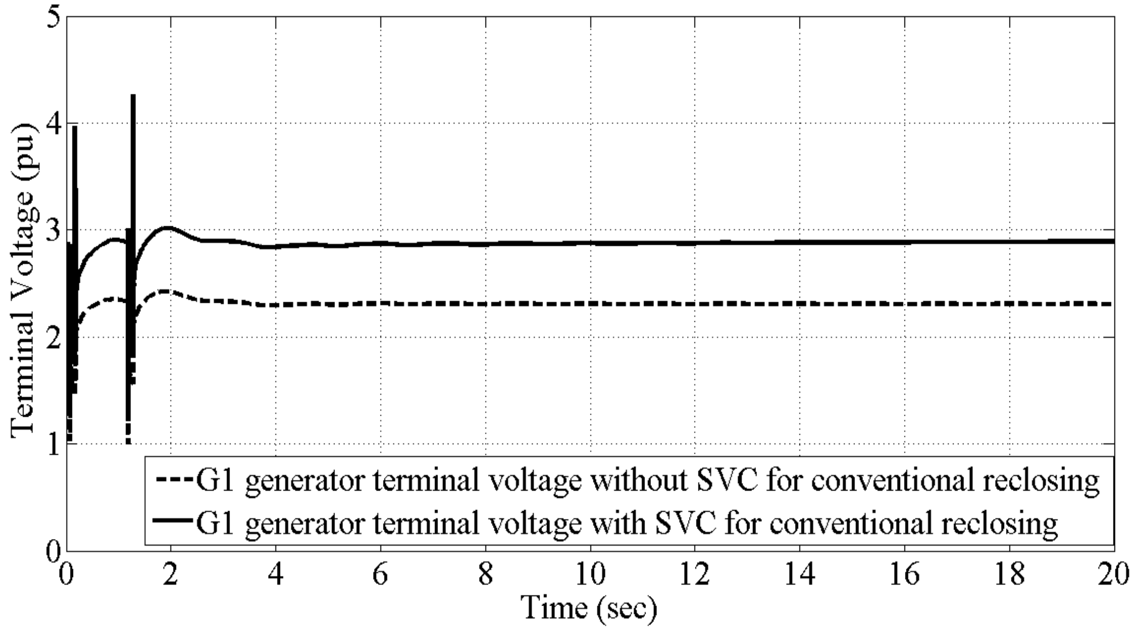


Figure 40: Generator 1 terminal voltage response for conventional reclosing with SVC for 3LG fault at F2.

In the event of fault the terminal voltage of the generator goes very low or voltage sag happens. To maintain the stability, the terminal voltage will have to come back into the previous stable position. SVC helps the generators restore the terminal voltage to the previous state after the fault. The responses of the generator terminal voltages for conventional and optimal reclosing are represented separately from figures 40 to 43.

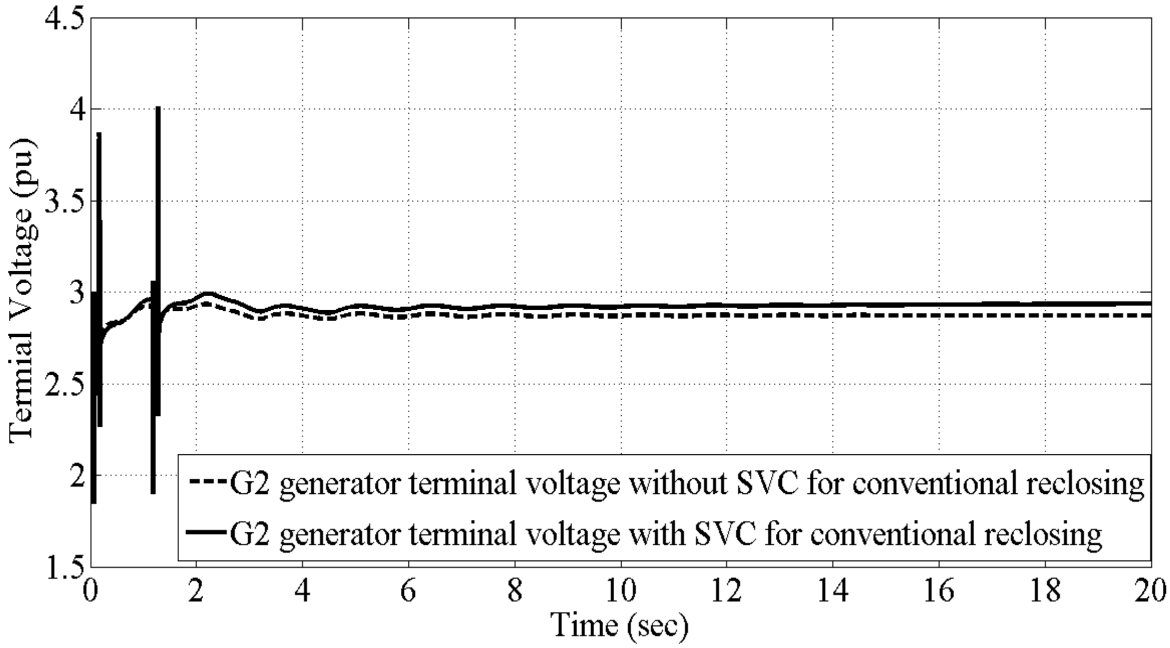


Figure 41: Generator 2 terminal voltage response for conventional reclosing with SVC for 3LG fault at F2.

In the event of 3LG at fault position 2 the terminal voltage of generator 1 for conventional reclosing with SVC and conventional reclosing without SVC is presented in figure 40. For both cases, the terminal voltage becomes low for a very short time. Due to the presence of the SVC, the terminal voltage comes back into the stable state as that was before the occurrence of any fault in the system. For the same operating condition, the terminal voltage of generator 2 is shown in figure 41.

In the event of 3LG at fault position 2 the terminal voltage of generator 2 for conventional reclosing with SVC and conventional reclosing without SVC is presented in figure 41. For both cases, the terminal voltage becomes low for a very short time. Due to the presence of the SVC, the terminal voltage comes back into the stable state as that was before the occurrence of any fault in the system. For the optimal reclosing of circuit breakers with and without SVC considering the same operating conditions are presented in figure 42. The responses of generator 1 and generator 2 are represented separately. For the same operating condition the terminal voltage of generator 2 is shown in Figure 43.

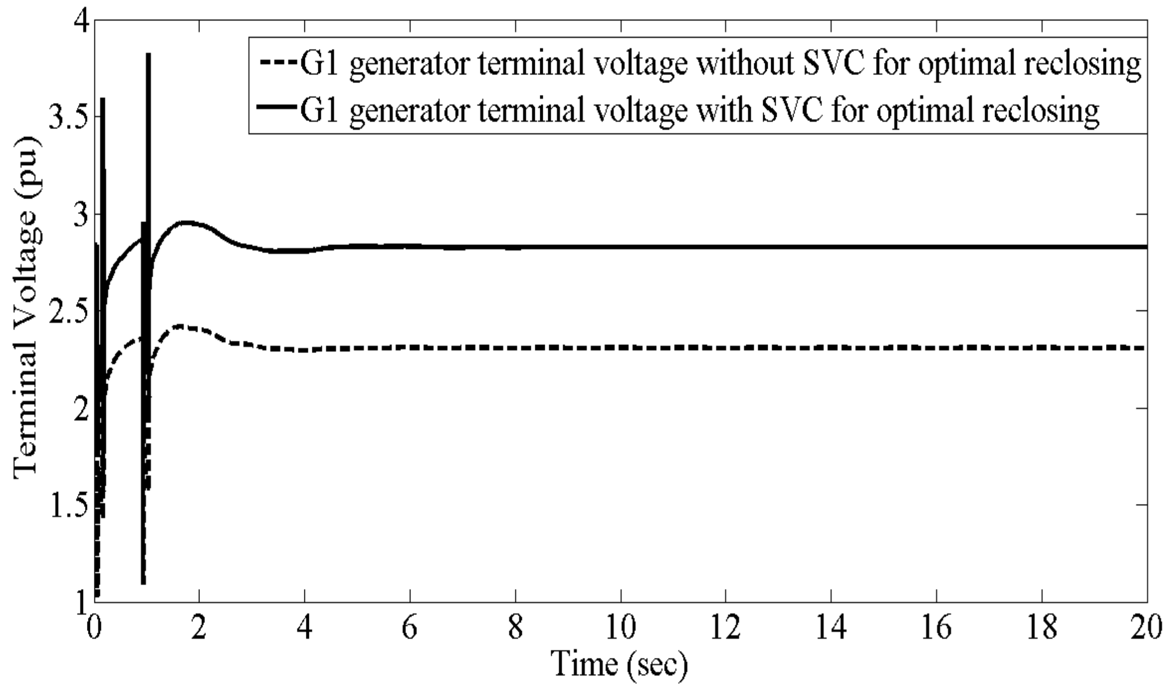


Figure 42: Generator 1 terminal voltage response for optimal reclosing with SVC for 3LG fault at F2.

In the event of 3LG at fault position 2 the terminal voltage of generator 1 for optimal reclosing with SVC and optimal reclosing without SVC is presented in figure 42. For both the cases, the terminal voltage becomes low for a very short time. Due to the presence of the SVC, the terminal voltage comes back into the stable state as that was before the occurrence of any fault in the system. For the same operating condition the terminal voltage of generator 2 is shown in figure 43.

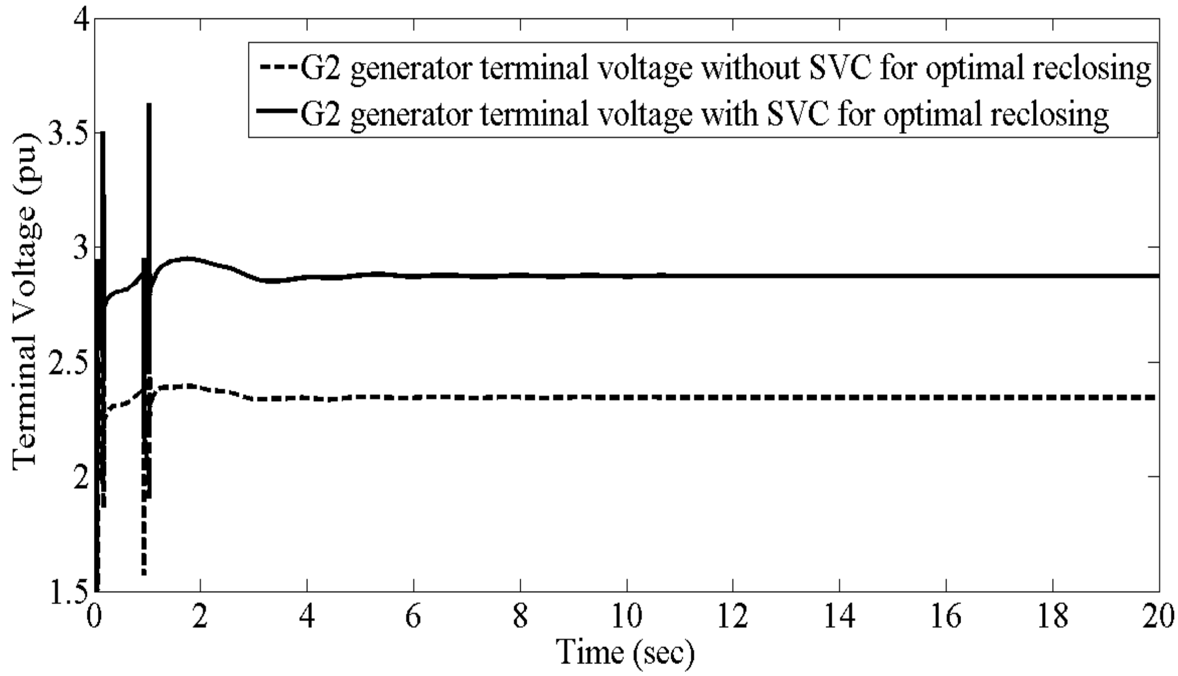


Figure 43: Generator 2 terminal voltage response for optimal reclosing with SVC for 3LG fault at F2.

In the event of 3LG position 2 the terminal voltage of generator 2 for optimal reclosing with SVC and optimal reclosing without SVC is presented in figure 43. For both the cases, the terminal voltage becomes low for a very short time. Due to the presence of the SVC, the terminal voltage comes back into the stable state as that was before the occurrence of any fault in the system. The terminal voltage response of the generators after the occurrence of fault and with SFCL and SVC were observed. Although all the responses are not presented here, but the terminal voltages were found to be stable in all situations.

H. Practical Implementation of the Proposed Method

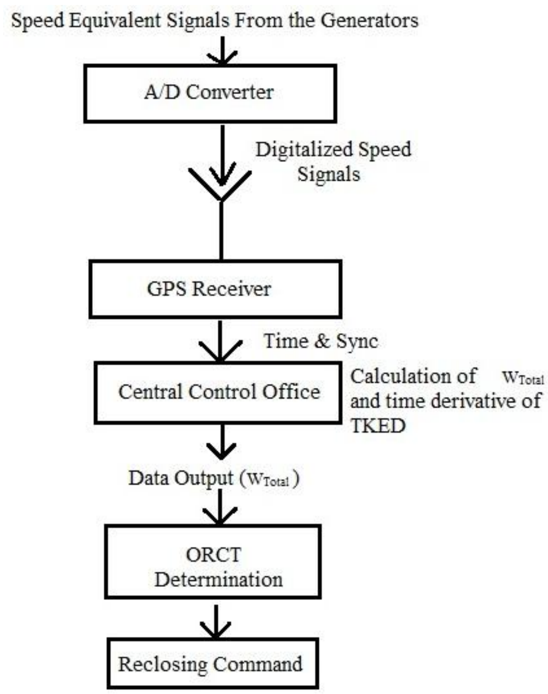


Figure 44: GPS functional block diagram.

The proposed method can be implemented in real time. The online measurement of the speed of different generators located at different locations and then calculation of the total kinetic energy using global positioning system (GPS) is described in **[**132**]**,**[**138**]-[**142**]**.

The functional block diagram of GPS is shown in figure 44, where the GPS receiver receives the digitalized speed signal collected from the generators. The central control office then can determine the ORCT easily.

SFCL operates depending on the fault current level. The superconducting element of SFCL senses the current level. So, its implementation in real system is very much possible and there is example of SFCL's real system operation.

SVC's in the system are connected to the bus terminals, and their susceptance and firing angle are dependent on voltage. The online voltage calculation required for SVC operation can also be performed in real time.

Chapter 4

CONCLUSIONS, CONTRIBUTIONS AND FUTURE WORK

I. Conclusions

In this thesis, the operation of optimal reclosing of circuit breakers and SFCL for improving the transient stability of power system is analyzed. Moreover, in order to see the effectiveness of SFCL in improving the transient stability, its performance is compared with the SVC. The results and conclusions can be described in the following points.

The performance of the combined operation of optimal reclosing and SFCL/SVC is compared with the combined operation of conventional reclosing and SFCL/SVC. Both balanced and unbalanced permanent faults at different locations in the system are considered. From the simulation plots and index values the following conclusions can be drawn.

a) The combination of optimal reclosing and SFCL/SVC as well as the combination of conventional reclosing and SFCL/SVC can improve the transient stability of the power system.

b) The performance of the combination of optimal reclosing and SFCL/SVC is better than that of the combination of conventional reclosing and SFCL/SVC.

c) SFCL is more effective than SVC as an auxiliary power system transient stability enhancing device.

Therefore, the proposed combination of optimal reclosing and SFCL can be considered as an effective means of transient stability enhancement in a multi-machine power system.

J. Contributions

There has a number of works available in the literature regarding the application of SFCL for power system transient stability. But there has no work on coordinated operation of SFCL and optimal reclosing of circuit breakers to enhance the transient stability, and that is the original contribution of this work. Moreover, in order to see the effectiveness of SFCL, SVC is used and compared.

K. Future Work

In the future, the proposed methodology will be investigated in a large system like IEEE 39 bus system. The comparison study of combined operation of optimal reclosing of circuit breakers and SFCL with combined operation of optimal reclosing of circuit breakers and SVC in larger system is a future work. As installation of SFCL in large system consequently increases the cost so it is important to find out the optimal number of SFCL units required for that large system. Moreover, the technical issue for reducing the high cost of superconducting device is another important research aspect. More sophisticated control of SFCL and the effect of combined operation of optimal reclosing of circuit breakers and other transient stability enhancement devices like STATCOM (static synchronous compensator) are also important research issues. In future study these issues will be considered.

One drawback of the proposed method is the time delay [133], [140]-[141]introduced by the online calculation of the total kinetic energy. This time delay can affect the transient stability. That is another future research issue. The proper and exact location and installation of the SFCL and SVC in the power system is also a matter of interest. The proper installation location of the SFCL and SVC can also influence the enhancement of the transient stability to some extent.

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