

A comprehensive overview, behavioral model and simulation of a Fault Current Limiter

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Abstract

Distribution systems across most parts of the globe are highly radial in nature. As loads are gradually increased on a particular distribution system, a higher operating current state leading to increased fault current levels is attained. Hence, the relay co-ordination is disturbed and equipments such as feeders and circuit breakers need to be replaced with higher rating so that they can handle the new currents often leading to expensive retrofit costs.

The use of fault current limiter (FCL) is proposed to mitigate the effects of high current levels on a distribution system. A comprehensive and up-to-date literature review of FCL technologies is presented. Detailed efforts of an in-house developed behavioral superconducting FCL model are delineated, including FCL control algorithm and its implementation in PSCAD[®]/EMTDC environment. Results from simulation studies are investigated and compared to an actual FCL commissioned by Z-energy to highlight the effectiveness of a generic model without having to access proprietary details. Extending those concepts, a solid-state and hybrid type of limiter is also modeled and its results discussed. Finally, an impact assessment is conducted on the distribution protection scheme, due to the FCL being inserted and subsequently operated in the distribution system.

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Chapter 1. INTRODUCTION

Most, if not all of the devices that we use on a daily basis, utilize electrical power in some way or another. As such, our lifestyles depend upon a reliable supply of electricity that is available whenever we need it. Because our electrical supply is fairly reliable, it is assumed that the lights will come on at the flip of a switch, that the refrigerator will keep food from spoiling, and that the air conditioner will keep homes and offices comfortable.

The electricity that we use is typically supplied via a network of transmission lines that carry the bulk of the power, and distribution lines that reach out to customer loads; like a house or industry. The majority of the distribution systems in the United States operate in a radial topology in which there is a single source of power that feeds the loads connected downstream [1]. The topology is very simple to understand and their protection schemes are well understood and work to protect loads and sources under fault conditions. However, over a period of years, loads connected on a particular distribution system keeps increasing as new neighborhoods or small industries are added to the system. This creates a situation where the normal operating current increases, resulting in a proportional increase in the fault current levels. This may lead to frequent power outages and ultimately customer dissatisfaction if corrective actions are not taken. In order to operate within reliability and security constraints, an increase in current levels necessitates two sizable modifications to the distributed system:

- 1) Retrofitting installed circuit breakers and feeders with higher rated equipment that can handle the new fault current levels.
- 2) Re-configuration of protective devices with updated parameters.

In addition, with increased interest in distributed generation, sources like wind farms, solar panels, fuel cells etc are being connected to the distribution system. The addition of sources to

radial systems means that the current can now flow in either direction leading to massive and costly overhauls of the protection system.

A Fault Current Limiter (FCL) is a revolutionary power system device that addresses the problems due to increased fault current levels. As the name implies, a FCL is a device that mitigates prospective fault currents to a lower manageable level. Building on this basis, the thesis statement can be stated as follows:

“The appropriate approach to determine the feasibility of FCL technology is through the development of flexible and faithful computer-aided models and then applying them in a distribution system environment to analyze their performance, effects and practical realization.”

Following from the thesis statement, the work in this thesis makes two major contributions. First, a consolidated and up-to-date literature study of a wide variety of the FCL(s) that have been researched, prototyped and field tested. Second, the development of FCL models for the computer aided design software called PSCAD[®] that can be used for network studies and modified to accommodate other kinds of FCL(s) to distribution systems.

1.1. Review of distribution system protection strategies

Fault location, prediction, and protection are the most important aspects of fault management for the reduction of outage time. In the past, most of the research and development on power system faults in these areas has focused on transmission systems, and it is not until recently with deregulation and competition, that research on power system faults has begun to focus on the unique aspects of distribution systems [2] . Below is a brief overview of some of the techniques used or proposed for fault location, prediction and protection.

1.1.1. Fault location techniques

Early methods of fault location were performed via visual inspection of the line in question. For short and easily accessible lines, this method was reasonable effective and required no special equipment. A second method utilized the reflective properties of transmission line. Some of the newer methods of fault location techniques introduced by Takagi et al. in the late 1970's comprised of single-ended methods. This approach makes use of Intelligent Electronic Devices (IEDs) to calculate the location of a single line-to-ground fault. Another new technology is synchronized sampling of data and phasor measurements. The device used for this application is called a phasor measurement unit or PMU, which was invented at Virginia Tech. Two PMU(s) are positioned on both ends of a very long transmission line. These devices are locked on to a GPS satellite for very high accuracy time keeping. Local measurements made by these PMU(s) are time tagged and the data generated by each of them is sent to a data acquisition system over a communication channel where the measurements taken by both relays are aligned in time and are used to pin point the exact location of the fault on the transmission line. The protection scheme is arranged as per Figure 1.1.

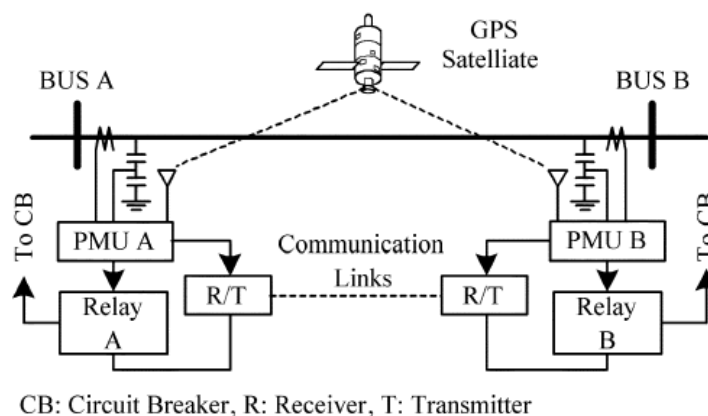


Figure 1.1 PMU fault location method [3]

1.1.2. Fault prediction techniques

The intent of fault prediction is to determine a failure in a system component early enough to allow for maintenance or replacement of the suspected component. Fault prediction can be divided into early detection techniques, data mining, and hidden failures.

A large portion of the research into early detection techniques concentrates on thermal analysis and other non-invasive techniques for the early detection of damaged components such as transformers, fault arresters, and insulators [2]. Microprocessor based control, automation and instrumentation has allowed us to capture voltage and current measurements, to name a few, before, during and after the fault. This combined with high speed communications and storage media, makes the availability of large fault databases on which statistical data mining approach is used to analyze and address the cause of distribution faults [2]. Hidden failures in protection systems have been identified as key contributors in the cascading of power system wide-area disturbances [4]. Although, primarily developed for transmission systems, these concepts may also be applicable to preventing the spread of distribution systems faults.

1.1.3. Fault protection techniques

Fault protection of distribution faults is a mature subject and has been well understood. Some of the advanced techniques of fault protection are distributed automation, detecting high impedance faults and fault current limiters [2]. The most common automated functions in distribution systems include the following: Volt/Var Control, Fault Location Isolation and Service Restoration (FLIR), Optimal Feeder Reconfiguration, Automated Meter Reading, and Relay Protection Re-coordination [2]. High impedance faults is defined by IEEE PSRC working group as those that “do not produce enough fault current to be detected by conventional over-current relays or fuses” [5]. This is a relatively recent subject of interest where very few facilities

exist to test for high impedance faults. Fault current limiters, as already mentioned before are finding increased use in distribution system protection.

1.2. Activities by system operators to improve protection – A survey

A short survey was carried out as a part of the research project of fault current limiters. Questions related to the current strategies for distribution protection, adaptive protection using automation and high end computing were asked to distribution system engineers. Also, communication topologies, advanced data management and processing, and types of sensors used were also queried as a part of the survey. About a dozen companies, most of them utilities, responded to the survey [Appendix E]. Below is a snapshot of the responses:

In order to carry out fault protection, most of the companies are using advanced decentralized systems that monitors a particular section and reports to a central database. Each system acts as a child of the overall system (parent) which has built-in intelligence to take necessary corrective action without human interaction. A company reports that they have recently installed Feeder Automation System Technology (FAST), which is an intelligent switching mechanism that will restore power in the event of an outage. Others are developing in-house protection scheme such as Remedial Action Scheme (RAS) for back up power supplies and Overload Scheme (OLS) for grid protection. Also, specific hardware and software technologies are being deployed that measure the performance of transformers, circuit breakers, and other components for efficient utilization of assets and predict failure. Reliability statistical analysis data about customer outages is being used to feed into an indigenously developed application that can take corrective action.

With the advent of reliable fiber-optic technology, many companies have started to retrofit their existing system with fiber. These cables are installed along with the power

conductors and in power duct banks to transmit real-time temperature for dynamic ratings and increased asset utilization. Fiber optic voltage and current sensors are also being used, which have a better precision and are also portable to a certain extent. Utilities have also installed numerous smart meters at strategic locations to better predict an outage size and location based on historical trends stored within these meters. These smart meters can also communicate fault location faster than the traditional “call-in” method. Besides the above mentioned, utilities have also discussed their plans on testing fault current limiter technology in the near future.

1.3. Motivation and objective

The current trend in distribution systems is pointing towards more sophisticated and intelligent ways of protection without jeopardizing system stability and maintaining continuous power supply to customers. The current “New Energy for America” plan calls for 10% of electricity to come from renewable sources by 2010 and 25% by 2025 [6]. This power will mostly be fed in the form of distributed generation. As stated before, distributed generation injects additional current to the system under fault, which cannot be handled by existing protection schemes.

The motivation arises with the fact that “as the deregulation environment takes hold and utilities seek more efficient and cost-effective methods to couple grids, improve power quality, and delay expensive upgrades,” [7] fault current limiters will find increased application in distribution systems. Currently, researchers have been experimenting with various FCL technologies strictly via computer simulation that is very specific in nature. Power companies have also started investing in this technology as they see immense potential in current limiting technologies.

The objective of this thesis is to create a flexible FCL model for PSCAD[®] based on the most promising technologies that can be used for fault and system analysis. PSCAD[®] is graphical user interface based power system software that allows for detailed modeling of transmission, distribution systems, machines etc and is widely used in the industry. It is the author's hope that this work will be beneficial to power engineers when considering installing a fault current limiter in their particular system.

1.4. Outline of thesis

The subsequent content is structured as follows:

Chapter 2, Fault current limiters – An Overview, reviews the role of an FCL and the need for it. A comprehensive table summarizes some of the different categories and the most promising types of FCL, explaining the method of operation along with references. A brief summary of the current status of the FCL technology and potential concerns have also been addressed.

Chapter 3, FCL model, presents a practical approach to a computer aided model using industry standard PSCAD[®] software. Special emphasis is given to modeling a superconducting FCL, outlining the operation principle, fault detection and activation algorithms. Solid-state and hybrid limiters are also modeled and some of the techniques involved with them.

Chapter 4, Simulation results, presents the findings of the FCL models under a test distribution system. Comparisons of an in-house developed superconducting fault current limiter (SFCL) are made against the results obtained by the SFCL from Z-energy. Short case studies are conducted on the test distribution system to check for FCL performance and assess its overall impact on the protection scheme. Results of solid-state limiter and hybrid limiters are also studied.

Chapter 5, Conclusions and Future Work, summarizes the work done, along with some of the major contributions that this thesis makes in the field of fault current limiters. A brief recommendation of prospective future direction is also delineated.

Chapter 2. FAULT CURRENT LIMITERS – AN OVERVIEW

Damage from short circuit currents is a constant threat to any electric power system, since it threatens the integrity of its generators, bus-bars, transformers, switchgears, and transmission and distribution lines [8]. Building on this statement, the FCL is described below.

2.1. Role of fault current limiter

As mentioned earlier, the role of the FCL is to limit prospective fault current levels to a more manageable level without a significant impact on the distribution system. Consider a simple power system model, as shown in Figure 2.1, consisting of a source with voltage V_s , internal impedance Z_s , load Z_{Load} , and fault impedance Z_{fault} .

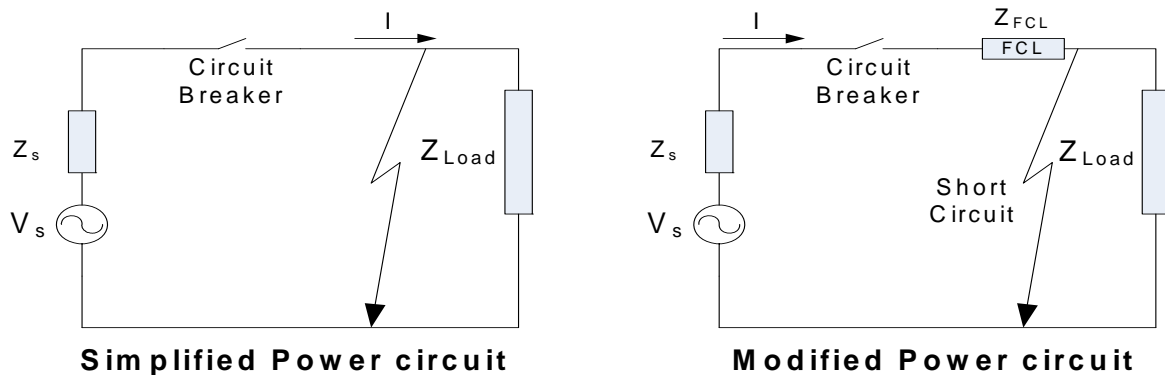


Figure 2.1 Simple power circuit with and without FCL [9]

In steady state,

$$I_{line} = \frac{V_s}{Z_s + Z_{LOAD}} \quad (2.1)$$

When a fault occurs in a system,

$$I_{fault} = \frac{V_s}{Z_s + Z_{fault}}, \quad \text{Where, } Z_{fault} \ll Z_{load} \quad (2.2)$$

Since the supply impedance Z_s is much smaller than the load impedance, Equation (2.2) shows that the short circuiting of the load will substantially increase the current flow. However, if a FCL is placed in series, as shown in the modified circuit, Equation (2.3) will hold true;

$$I_{fault} = \frac{V_s}{Z_s + Z_{FCL} + Z_{fault}} \quad (2.3)$$

Equation (2.3) tells that, with an insertion of a FCL, the fault current will now be a function of not only the source Z_s and fault impedance Z_{fault} , but also the impedance of the FCL. Hence, for a given source voltage and increasing Z_{FCL} will decrease the fault current I_{fault} .

2.2. Ideal fault current limiter characteristics

Before discussing any further, it is important that some of the ideal characteristics be laid out for an FCL. An ideal FCL should meet the following operational requirements [1, 7, 10, 11]:-

- 1) Virtually inexistent during steady state. This implies almost zero voltage drop across the FCL itself
- 2) Detection of the fault current within the first cycle (less than 16.667ms for 60Hz and 20ms for 50Hz) and reduction to a desirable percentage in the next few cycles.
- 3) Capable of repeated operations for multiple faults in a short period of time
- 4) Automatic recovery of the FCL to pre-fault state without human intervention
- 5) No impact on voltage and angle stability
- 6) Ability to work up to the distribution voltage level class
- 7) No impact on the normal operation of relays and circuit breakers
- 8) Finally, small-size device that is relatively portable, lightweight and maintenance free

In reality, one would like to have an FCL that would satisfy all of the foregoing characteristics. However, certain trade-offs and compromises have been made in nearly all categories and types.

2.3. Types of fault current limiters

This section presents a brief review of the various kinds of FCL that has been implemented or proposed. FCL(s) can generally be categorized into three broad types:

- 1) Passive limiters
- 2) Solid state type limiters, and
- 3) Hybrid limiters

In the past, many approaches to the FCL design have been conducted ranging from the very simple to complex designs. A brief description of each category of limiter is given below. Appendix A of this thesis has a consolidated and more detailed list of the different FCL types.

2.3.1. Passive limiters

Fault limiters that do not require an external trigger for activation are called passive limiters. The current limiting task is achieved by the physics involved in the FCL itself. The simplest of all kinds of fault current limiter is the inductor. The current limiting strategy is achieved by inserting impedance $Z = j\omega L$. Since current cannot change instantaneously in an inductor, current is therefore limited at the moment of a fault. Figure 2.2 shows an inductor in series with the load and source.

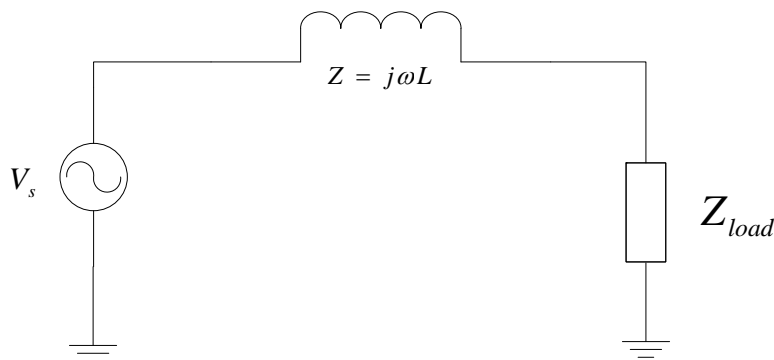


Figure 2.2 Series inductor application as a fault current limiter

There are a few pros and cons in using an inductor for FCL application:

- 1) Technique has been well known, installed, field tested and commissioned for many years
- 2) Relatively low cost and maintenance, but
- 3) Bulky to handle and replace
- 4) Produces a voltage drop in steady state and causes lagging power factors

Another kind of passive limiter that is gaining attention is the super conducting fault current limiter (SFCL). Superconductor materials lose their electrical resistance below certain critical values of temperature, magnetic field, and current density [8]. SFCL(s) work on the principle that under steady state, it allows for the load current to flow through it without appreciable voltage drop across it. During a fault, an increase in the current leads to a temperature rise and a sharp increase in the impedance of the superconducting material. SFCL(s) are discussed in greater detail in Chapter 3 and 4. Below are a few advantages and disadvantages of using an SFCL:

- 1) Virtually no voltage drop in steady state
- 2) Quick response times and effective current limiting, but
- 3) Cooling technologies still at infancy, leading to frequent break downs
- 4) Commercial deployment is still to be witnessed
- 5) Superconducting coils can saturate and lead to harmonics

2.3.2. Solid-state limiters

Recent developments in power switching technology have made solid state limiters suitable for voltage and power levels necessary for distribution system applications. Solid state limiters use a combination of inductors, capacitors and thyristors or gate turn off thyristors (GTO) to achieve fault limiting functionality.

An example of a solid state limiter is shown in Figure 2.3. This model was proposed by Karady in 1992 [10]. In this type of limiter, a capacitor is placed in parallel with an inductor and a pair of thyristors.

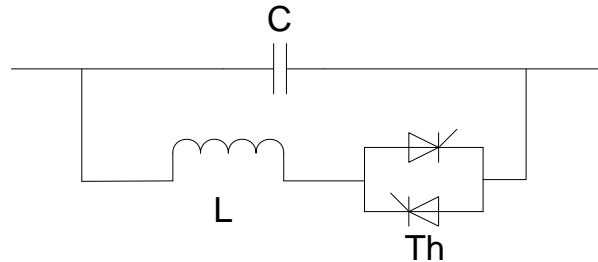


Figure 2.3 Resonant type solid state limiter [10]

In steady state, the thyristors are turned off and all current flows through the capacitor. The placement of the capacitor is also useful by nature because it provides series compensation for the inductive transmission line. Hence, equation (2.4) holds true:

$$Z_{FCL(NORMAL)} = \frac{-j}{\omega C} \quad (2.4)$$

However, when a fault occurs the thyristors are switched on, which forces most of the current to flow through the inductor branch. The net FCL impedance seen by the circuit is as follows.

$$Z_{FCL(FLT)} = \frac{j\omega L}{1 - \omega^2 LC} \quad (2.5)$$

Below are a few advantages and limitations of solid state limiters in general:-

- 1) Provide significant fault current limiting impedance
- 2) Low steady state impedance as capacitors and inductors can be tuned for a particular frequency to show virtually no impedance and voltage drops. but
- 3) Harmonics introduced due to switching devices
- 4) Voltage drop introduced during faults

2.3.3. Hybrid limiters

As the name implies, hybrid limiters use a combination of mechanical switches, solid state FCL(s), superconducting and other technologies to create current mitigation. It is a well know fact that circuit breakers and mechanical based switches suffer from delays in the few cycles range. Power electronic switches are fast in response and can open during a zero voltage crossing hence commutating the voltage across its contacts in a cycle [1].

In 2001, Shi et al proposed a novel Triggered Vacuum Switch (TVS) based FCL. Figure 2.4 shows the circuit arrangement of one such device.

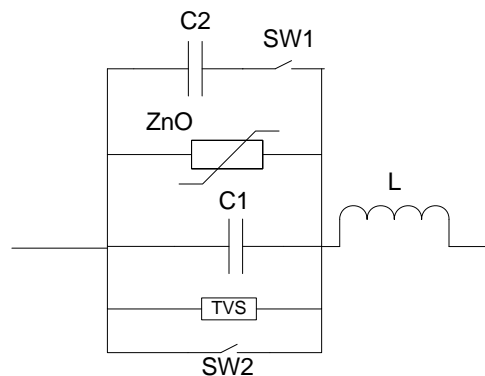


Figure 2.4 Triggered vacuum switch based hybrid limiter [12]

In their work, they state that the reactance of the capacitor C1 and reactor L is about zero at nominal power frequencies. In steady state, the TVS and SW2 are in the off state. SW2 is a quick permanent magnetism vacuum contactor with a 3-10ms closure delay, which prevents TVS from long-time arc erosion. When a fault occurs, a trigger signal is sent to both TVS and the contactor turning on the bypass capacitor C1. This creates a situation where the reactor L will limit the fault current immediately. The ZnO arrester is used for over voltage protection and capacitor C2 and switch SW1 are set-up as a conventional series compensation [12].

2.4. Current status of FCL technology and potential concerns

In recent years, FCL technology based on superconductivity and solid state has attracted greater attention. This is because with the advent of High Temperature Superconductor wires (HTS), the cooling costs have reduced significantly. In addition, with advancement in high power switching technology, solid state limiters have become viable devices. These along with superconductors are the most promising kinds of FCL(s) of the future. Currently the United States Department of Energy is funding four major prototype R&D FCL efforts. In [13], Ndeye et al. discuss in detail the status of these projects as of 2009. Three out of the four limiters are based on superconducting principle and one using solid state. Figure 2.5 shows the current and voltage ratings for these projects along with the corporations involved.

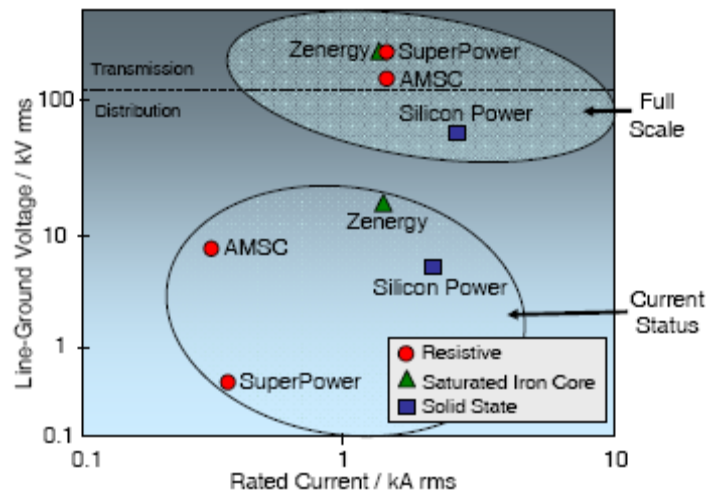


Figure 2.5 Current and Voltage ratings for DOE sponsored projects [13]

As mentioned previously, FCL technology is still at its infancy and is yet to see widespread commercial deployment. One of the main reasons for this delayed interest is that the purchasing cost to current limiting ratio, at the time of this writing, is very high. Also, majority of the FCL(s) do not deliver a significant amount of current reduction. However, a “Utility Needs survey for Fault Current Limiter” was carried out by the Electric Power Research Institute,

EPRI in 2008. In his presentation [14], Eckroad reports that potential market for FCL technology is about two FCLs per utility per year. This is based on the assumption that FCL is the most cost effective way to manage fault currents. He also mentions that roughly 50% of the potential customers would accept two to five times the cost of a novel FCL over a circuit breaker. However, the cost of ownership and fail safe design are the fundamental features that all customers would like to see in an FCL so that their investments are justified [14]. Also, “one of the delays to the faster adoption of FCLs is that there are currently no standardized testing protocols in place to test them,”[13]. There are very few test facilities across the globe that provides a one-stop place to test out the FCLs. For instance, liquid nitrogen for cooling is required in testing some superconducting types of FCLs. It is very hard to find facilities that provide advance cooling apparatus along with high voltage and power. International partnerships and scholars are helping pave the way to a more streamlined testing standards, procedures and facilities.

2.5. Summary

In this chapter, the role of the FCL and some of the ideal characteristics of an FCL model were discussed. Also a brief overview of the various kinds of FCL(s) was given along with their respective advantages and disadvantages. A much more detailed literature review can be found in Appendix A. A summary of the current status of FCL(s) and potential concerns with testing out this technology has also been addressed.

Based on the trends reviewed for FCL, it is a ripe time to model various FCL(s). Chapter 3 will show in detail the process of modeling a superconducting, solid-state and hybrid limiter in PSCAD[®]/EMTDC software along with the results of the simulation and test cases in Chapter 4.

Chapter 3. FAULT CURRENT LIMITER MODEL

Computer-aided modeling and simulation of any physical device or phenomena is perhaps one of the most fundamental practices in power system studies. In this chapter, a PSCAD[®] model for a superconducting, solid state and hybrid type of fault current limiter is proposed and its implementation process is presented. The proposed FCL is a behavioral model whose sole aim is to simulate the operation of a real device without the need of proprietary parameters and functional descriptions from the manufacturers. In summary, the developed PSCAD[®] model requires only a handful of input parameters for which the user has complete control.

3.1. PSCAD[®] v4.2.1 simulation software

To study the effects of a FCL model, simulation software is chosen as a preferred investigative means rather than a physical system testing which is more time consuming and expensive. The use of simulation software allows for a quick and easy way to model FCL(s) and to test their effect in a distribution system. PSCAD[®] version 4.2.1 is industry leading, powerful and flexible power systems software. It uses the world renowned EMTDC solution engine that enables for simulating the time domain instantaneous responses (electromagnetic transients) of electrical systems. PSCAD allows the user to graphically assemble the circuit, run the simulation, and analyze the results. PSCAD comes complete with a library of pre-programmed and tested models, ranging from simple passive elements and control functions, to more complex models, such as electric machines, FACTS devices, transmission lines and cables that can be dragged-and-dropped to create systems and obtain accurate responses [15]. Furthermore, PSCAD also allows the user to create custom blocks by combining basic elements along with control

functions. This is especially useful for our study as it will enable us to model the FCL more realistically and to package it in a single block of code with a set number of user input and output functions. Following are a few case studies that are typically conducted on PSCAD[®] [15]:-

- Contingency studies of AC networks consisting of machines, exciters, governors etc
- Relay coordination
- Transformer saturation effects
- Evaluation of filter design and harmonic analysis
- Control system design and coordination of FACTS and HVDC
- Optimal design of controller parameters
- Investigation of new circuit and control concepts

Figure 3.1 shows the user interface of PSCAD[®].

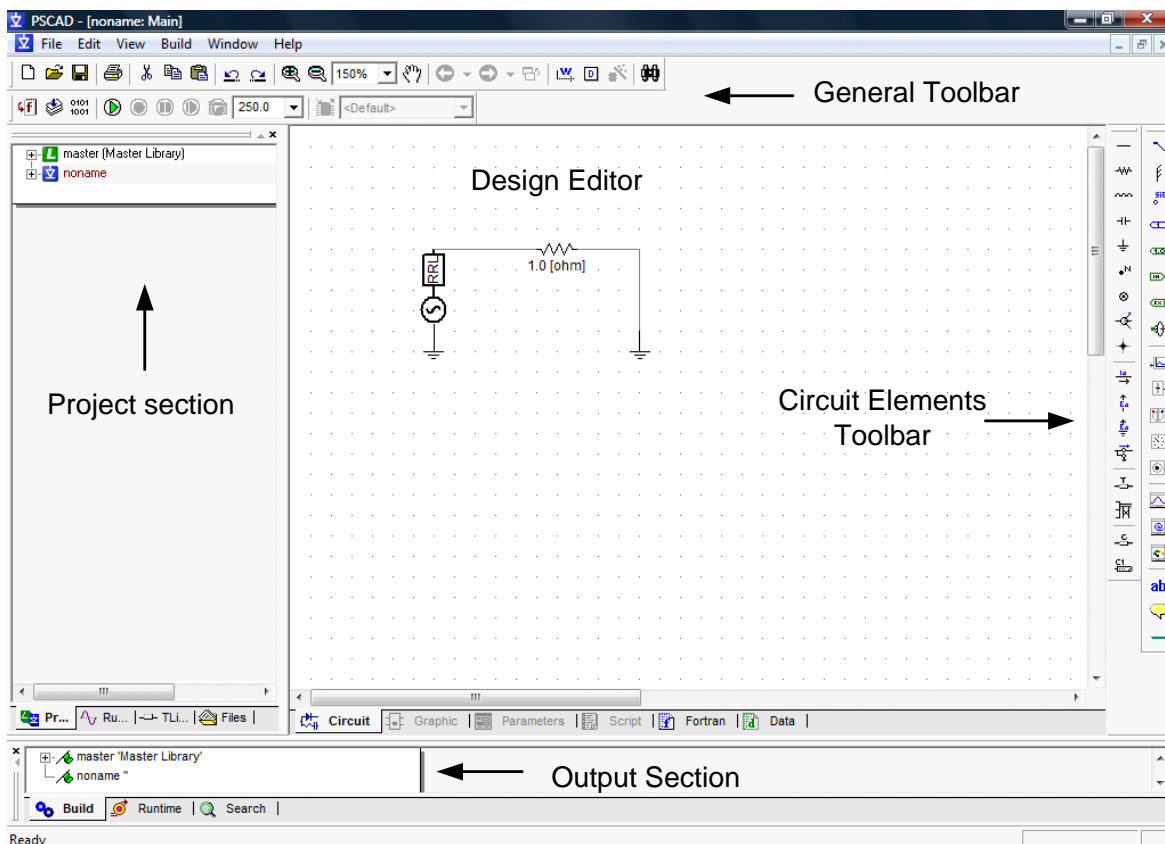


Figure 3.1 PSCAD[®] v4.2.1 graphical user interface (GUI) [15]

The workspace can be divided into three sections. The “Project section” lists all the loaded cases and libraries. The “Output section” shows the status of each project and any errors or warnings that the project might have. The “Design editor” section consists of the actual circuit diagram that is under investigation. The “Circuit element toolbar” provides an easy drag-and-drop feature to insert circuit elements, although a larger selection is available via the master library. The “General Toolbar” consists of standard Windows® features like cut, copy, paste, zoom etc. All of these features provide for a very user oriented interface that is easy and fun to work with.

3.2. Superconducting FCL model (FCL-1)

As mentioned previously, SFCL is one of the most promising type of limiter and has the greatest potential. A detailed time domain model of the SFCL is proposed and implemented, here after referred as FCL-1. Details such as major FCL components, operation principles and sequence of events, fault detection techniques, and timing diagrams are presented.

3.2.1. Major circuital components

The first model created is a saturated core high temperature superconducting (HTS) type fault current limiter. High temperature superconductors are cooled to a much higher temperature than conventional superconductors hence saving significant space and costs in cooling apparatus. This is the same model as conceptualized by Z-energy, but using different components and developed in-house. In principle, the saturated core FCL utilizes larger differences in the permeability of magnetic material. Fundamentally, high permeability materials allow for a low impedance during normal operation and a very high impedance during fault current levels [16]. However, from a modeling standpoint, FCL-1 can be modeled as a combination of inductor wound with superconducting HTS wire, thyristor and variable resistor. This arrangement is shown below in Figure 3.2.

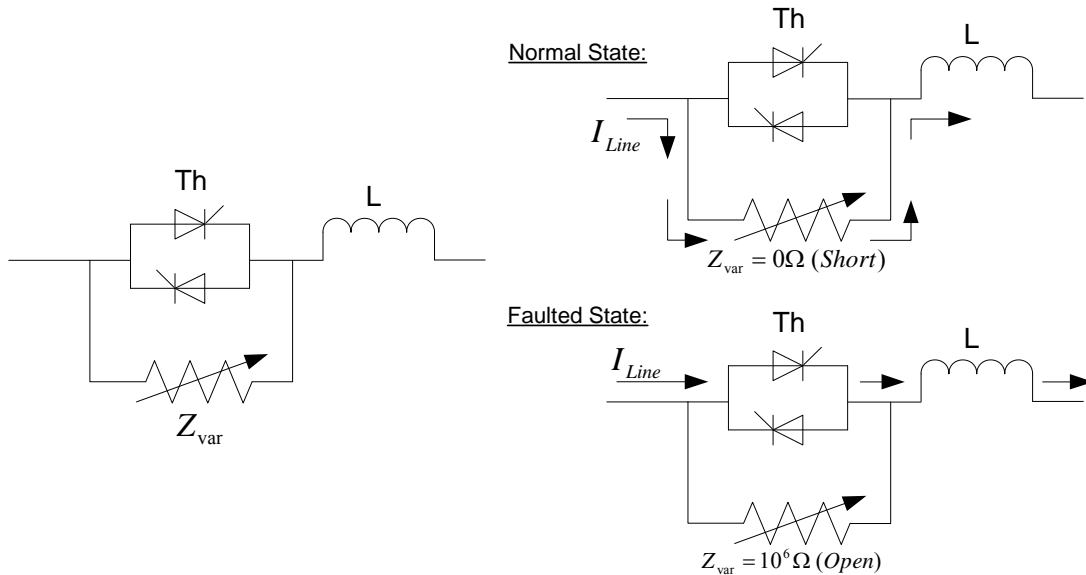


Figure 3.2 Superconducting fault current limiter (FCL-1) circuit diagram

The significance of each of the components is as follows:-

- 1) The inductor is wound with a HTS superconducting wire that is cooled by a separate cooling apparatus. Upon a high fault current, the impedance of the wire increases sharply with time and temperature hence providing the current limiting feature. Also, since current cannot change instantaneously in an inductor, it provides an effective way of mitigating high currents within the first cycle.
- 2) The thyristor is inserted to closely model the harmonic component in the FCL operation. This is crucial to model as other power system components might have adverse effect due to harmonics.
- 3) Linear variable impedance is employed to model the opening of a mechanical switch and the arc voltage produced by it.

3.2.2. Operation principle and sequence of events

The basic idea of any super conducting fault current limiter (SFCL), is as follows,

- 1) At $t < T_{fault}$, the impedance of the SFCL is close to 0Ω

- 2) At $t > T_{fault}$, the impedance of the SFCL rises sharply within a few milliseconds.

Consider the FCL-1 circuit diagram in Figure 3.3 reproduced from Figure 3.2. The sequence of events is as follows:-

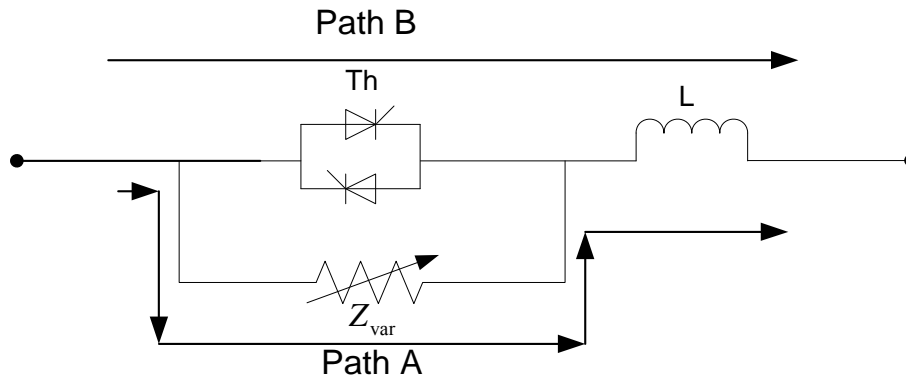


Figure 3.3 FCL-1 sequence of events

- 1) For time $t < T_{fault}$, the thyristors (TH) are switched off and the variable impedance Z_{var} is close to 0Ω . All the line current flows through the resistor and the inductor as per “Path A”. Since the inductor is wound with a HTS wire, there is no significant line impedance and the voltage drop is very negligible, ($<1\%$)
- 2) At time $t = T_{fault}$, a bolted three phase-to-ground fault is inserted right at the terminals of the FCL on the load side.
- 3) At time $t = T_{fault} + 100ms$, the thyristors are fired and Z_{var} is sharply increased to simulate the opening of a switch and the arc voltage produced by it.
- 4) At time $t = T_{fault} + 150ms$, all the current is now commutated through the thyristor and the inductor. The current is mitigated and flows as per “Path B”.
- 5) For time $t \geq T_{fault} + fault\ duration$, the fault is kept inserted in the system
- 6) At time $t = T_{faultclear}$, the fault is removed and the impedance of resistor is ramped down to 0Ω and the thyristors are switched off, commutating the current through “Path A”.

7) At time $t \gg T_{faultclear}$, the FCL comes back to the steady operating state

From a simulation standpoint, the important aspect to develop is the automatic fault detection algorithm and correct reaction by the SFCL to mitigate the effects of dangerous fault currents. By automatic detection, we mean that there is no external trigger or relay to the SFCL to start its operation. The triggering of SFCL is purely a function of the line quantities and its appropriate manipulation to predict a fault situation. This was briefly discussed in section 2.3.1.

In the following section, the actual implementation of the modeling efforts is presented. First, let us decompose the FCL model into three components A, B, and C respectively as shown in Figure 3.4

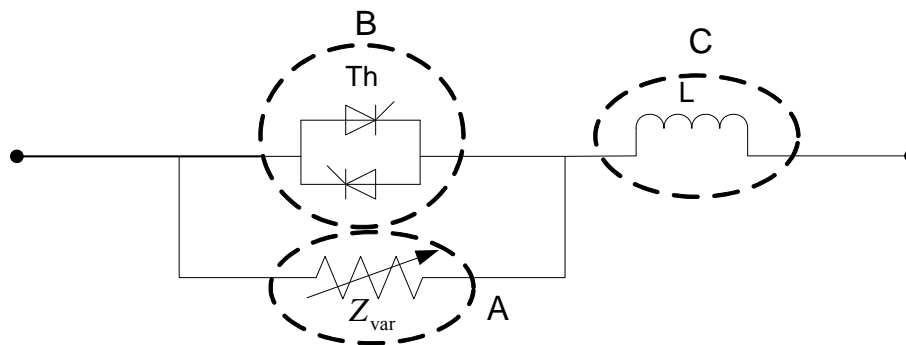
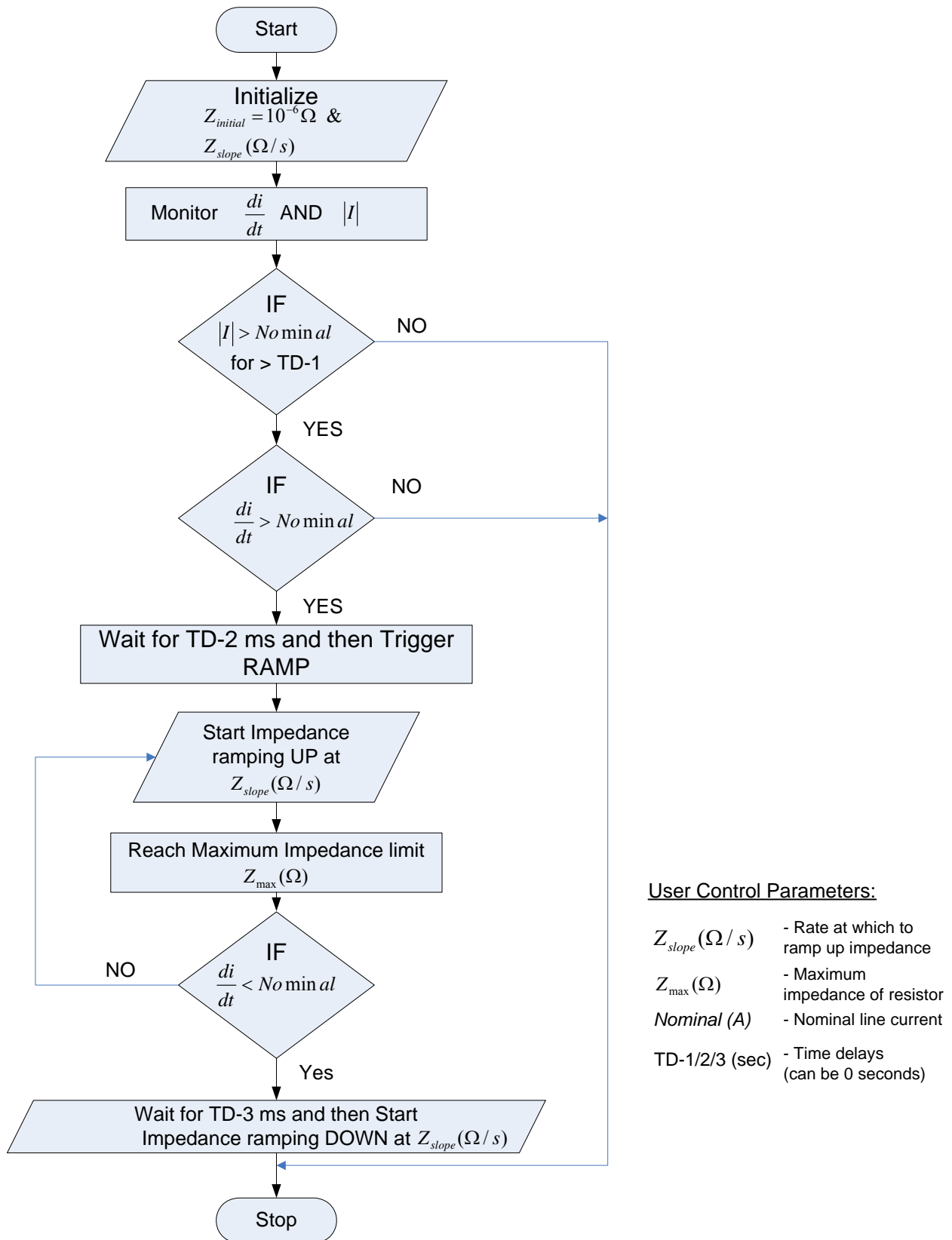


Figure 3.4 FCL-1 component decomposition, per phase

3.2.3. Modeling Component A, Variable impedance (Z_{var})

Component A in Figure 3.4 consists of a variable impedance that is at 0Ω (short circuit) at steady state. When a fault occurs, the impedance is quickly increased simulating the opening of a switch at the rate of $100 - 200\Omega/s$ (user settable). Accurate modeling of this component is critical as ramp reference to this component will be given ONLY after it is announced that a fault does exist in the system and subsequently an action is to be taken.

The sequence of operation of this variable resistor is shown in Figure 3.5. A description is also given following the flowchart.



User Control Parameters:

- $Z_{slope} (\Omega / s)$ - Rate at which to ramp up impedance
- $Z_{max} (\Omega)$ - Maximum impedance of resistor
- $Nominal (A)$ - Nominal line current
- TD-1/2/3 (sec) - Time delays (can be 0 seconds)

Figure 3.5 Sequence of activation for variable impedance Z_{var}

Before starting the simulation, the resistor is initialized with an initial impedance value $Z_{initial} (\Omega)$ and a ramp rate $Z_{slope} (\Omega)$. The simulation is then started where the current magnitude and the rate of change of current is monitored during the entire simulation time. After achieving some steady state operating point a three phase-to-ground fault is inserted into the system external to the FCL. As soon as the fault is inserted, the magnitude of the line current jumps up instantaneously and achieves a new steady state value as long as the fault is present. However, in order to make sure that there is indeed a fault in the distribution system and that the impedance is not falsely triggered, the rate of change of current is also monitored. A fault will change the rate instantaneously. After setting the necessary flags, the impedance is ramped up at a rate $Z_{slope} (\Omega)$. As long as the fault is present, the impedance will keep increasing till a maximum value $Z_{max} (\Omega)$. After the fault is cleared the impedance will be ramped down to the initial impedance. This cycle takes place whenever there is a fault.

Typically in industrial automation and control, a time delay (TD) is added before any action is taken. This is especially true if the action to be taken is dependent on inputs from sensors, limit switches, proximity switches, etc. By doing so, momentary switching which would otherwise trigger an action is eliminated. Similar concepts can also be applied to a power protection. Many times, faults come and go at an instant. This might happen because of a tree touching the line due to windy weather or a squirrel trying to jump between lines or even momentary in-rush currents due to a heavy load coming online. Hence, the goal would be to trigger the FCL only after making sure that there is indeed a fault. This is possible by inserting a delay timer. Appropriate delay times can be 2 to 3 cycles or more. A similar delay timer can be used when switching off the FCL. This is done by making sure that the fault has been cleared before the FCL impedance is ramped down.

3.2.4. Modeling Component B, Phase controlled switch, (TH)

The power electronic switch acts as a means of inserting harmonics into the FCL.

Harmonics can be introduced into the line due to any of the following reasons:-

- 1) The core present in the FCL gets saturated
- 2) Switching components used as a part of FCL operation scheme
- 3) Other non linearity in the FCL device itself.

The Z-energy model, that we are going to compare in chapter 4, has significant harmonics when it is triggered. In particular, after doing a real-time Fast-Fourier Transform (FFT) it is identified that there is a strong third harmonic component which is roughly about 2 to 5% of the nominal current. A third harmonic sine wave is shown in Figure 3.6.

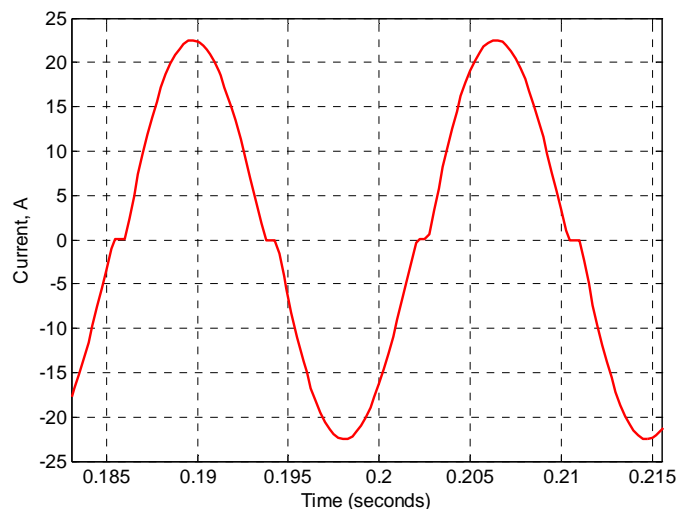


Figure 3.6 Third harmonic sinusoidal waveform

A phase controlled AC thyristor switch is used in the model to act as a source of harmonic injections as shown in Figure 3.7. Phase control implies that the switch is ON for every half cycle of the input sine wave. Hence, during the positive cycle, switch 1 will be on and during the negative cycle, switch 2 will conduct. Thyristors require a zero current before they will turn OFF. Hence, there exists a minimum firing angle below which the thyristors will never turn off. This is the circuit critical angle and is equal to the angle of the circuit phase angle [17].

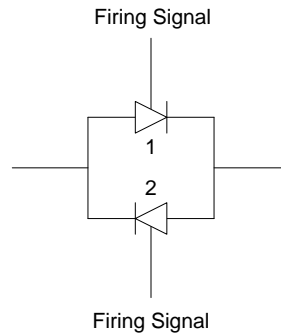


Figure 3.7 Thyristor switch arrangement for harmonic injection

Under steady state, the switch is turned off and all the current flows through the variable impedance. When a fault occurs, the switches are turned ON and fired. Also the impedance of the variable resistor is high enough, commutating all the current via the switch which can then introduce the desired harmonic component.

3.2.5. Modeling Component C, Inductor, (L)

As the name suggests, a standard inductor is chosen which commands the amount of current limitation that is needed. The larger the inductance value, the greater the current limitation.

3.2.6. Fault detection techniques

As noted in section 3.2.2, automatic fault detection is perhaps the single most important ingredient in modeling a SFCL. There are essentially two ways to detect faults:

- 1) The easiest method to check for a fault situation is to monitor the magnitude of line current at all times (I_{rms}).
- 2) The other alternative is to check for the rate of change of current (di/dt).

Although, either one of the above approaches can be used, however each of them has certain limitations which are as follows:

- 1) If only the magnitude is used as a detection technique, the FCL might be falsely triggered by inrush currents due to heavy loads being connected to the system which are not faults.
- 2) If only the rate of change of current is used, we might not necessarily have a fault condition.

Hence, a fast acting generic algorithm based on rate of rise of current (di/dt) and fault current magnitude (I_{rms}) has been developed. The complete PSCAD[®] logic can be found in Appendix B.

3.2.7. FCL activation timing

Timing the operation of FCL triggering is of paramount importance when modeling any device. The time of activation of a FCL can be a function of its physical properties or user settable parameters via a relay or built-in timers. Figure 3.8 shows the FCL activation timing diagram.

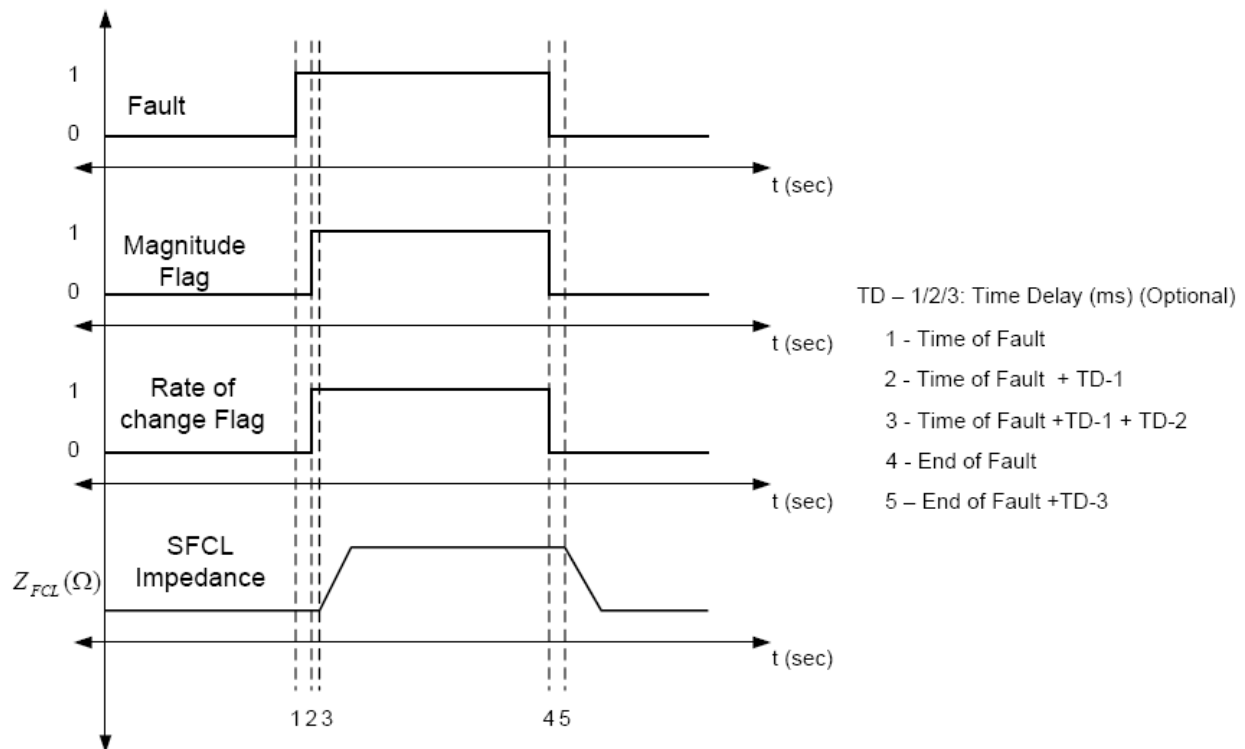


Figure 3.8 FCL-1 activation timing diagram

From Figure 3.8, a fault is inserted at time 1. Immediately, the magnitude of the line current increases and the “Magnitude flag” is raised. Also, the “Rate of change flag” is asserted since the rate at which line current changes is non-zero. After waiting for a few milliseconds (optional), the impedance of the FCL is ramped up so that the current limiting can proceed. This procedure is applicable to most of the kinds of FCL.

3.2.8. Implementation methodology

In this section, the implementation methodology is presented in order to achieve the functionality as per flowchart shown in Figure 3.5 for the variable impedance. The following is a general method of detecting faults and subsequently triggering the SFCL. This methodology is generic, implying that these concepts can also be extended to other categories and types of FCL.

A. Magnitude, I_{rms}

There are two ways to monitor a magnitude in PSCAD[®]:

- 1) Take the root mean square (RMS) of the line current.
- 2) Take the phasor value of the current and extract the magnitude.

B. Rate of change, di/dt

From classical AC circuits, it is a well known fact that in steady state, the area covered by a pure sinusoid over one cycle (~16.667ms) should equate to zero or very close to zero. However, if the area under the curve is NOT equal to zero, it can be concluded that the current waveforms are no longer a symmetrical sine wave and there might be an impending fault situation. Figure 3.9 illustrates this behavior graphically.

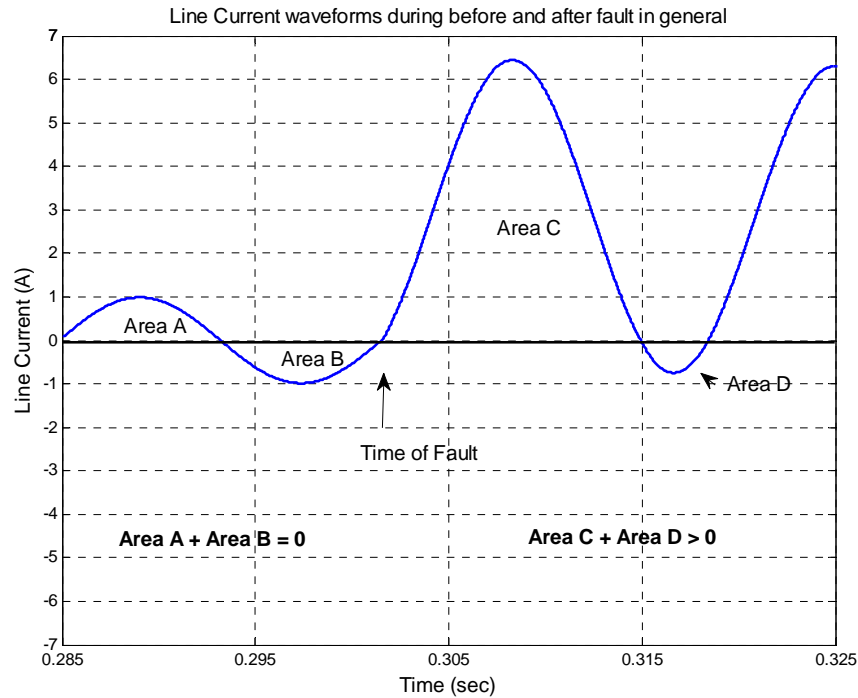


Figure 3.9 Line Current waveform before and during a fault

A detection algorithm, using this traditional transient monitor technique has been implemented by using an integration function to calculate the area under the curve over one cycle.

C. FCL impedance ramping, Z_{slope}

Programming the impedance ramping in the PSCAD[®] environment is perhaps the most challenging task. In general the equation for a ramp is given as follows:

$$\underbrace{\text{Ramp}} = \underbrace{\text{Starting Point}} + \underbrace{(\text{Set Point} - \text{Starting Point})}_{\text{Ramp Rate: } Z_{slope}} \times \underbrace{\text{Time elapsed}}_{\text{Elapsed time since FCL triggering}} \tag{3.1}$$

From 3.1, we see that the impedance of the FCL increases linearly with time. The ramp rate is user configurable which is a function of the FCL physical properties and design. At this point it must also be noted that the impedance is clamped to a final value, after which it will not increase any further.

3.2.9. General user control parameters

From a simulation standpoint, it is often a welcome feature when the prospective user has control over some of the model parameters. This is to facilitate in changing some values easily and to quickly record the response with the updated parameter. Table 3.1 is a list of some values that are appropriate for the FCL.

Table 3.1 Description of user control parameters for FCL-1

Parameter	Description
$Z_{slope} (\Omega)$	<ul style="list-style-type: none"> - This parameter controls the rate at which to increase the impedance. - Typically this depends on the physical device and can also be sometimes obtained by the current limiting curves provided by manufacturers
$Z_{max} (\Omega)$	<ul style="list-style-type: none"> - This parameter specifies the maximum amount of impedance to apply to the FCL. - The direct method to obtain would be from the manufacturer.
$Z_{initial} (\Omega)$	<ul style="list-style-type: none"> - Initial impedance of the resistor. - Ideally should be 0, but set to $1 \mu\Omega$ to prevent issues with 0 value in simulation
Nominal Current (kA)	<ul style="list-style-type: none"> - This parameter specifies the nominal steady state current for the system under full load. - This value is obtained from the system itself. - Adding sufficient amount of cushion to this value along with making educated tradeoffs between system security and reliability, a current triggering FCL value can be decided.
Time delays (ms)	<ul style="list-style-type: none"> - This parameter inserts a delay into the FCL. - Some categories of FCL are activated by an external device which waits for a few cycles to confirm a fault situation, after which the FCL impedance is seen in the circuit.
Inductance (H)	<ul style="list-style-type: none"> - This parameter controls the key inductance value for current limiting. - Value is dependent on the FCL manufacturer
Thyristor Firing Angle, (degrees)	<ul style="list-style-type: none"> - This parameter controls the firing angle of the thyristors. - The firing angle has to be higher than the circuit angle to see its harmonics effect.

3.3. Solid-State FCL model (FCL-2)

A second kind of fault current limiter (FCL-2) originally developed by Wanmin Fei et al [18] is chosen for modeling in PSCAD[®]. This model is based on IGCT power electronic switches. Figure 3.10 shows the topology of the single phase FCL as proposed in [18]:-

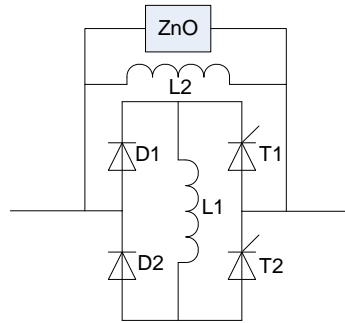


Figure 3.10 IGCT-based half-controlled bridge FCL [18]

3.3.1. Major circuital components

The model consists of the following components [18]:-

- 1) DC reactor, L1
- 2) Two diodes
- 3) Two self turn-off IGCT
- 4) Current limiting by-pass reactor, L2
- 5) Zinc oxide surge arrester to prevent over-voltage across the FCL

By optimizing the size of the inductors and with the introduction of switches that can handle high power, this type of FCL can be made relatively compact in size. The authors in [18] provide a good overview of the technical details involved in the model.

3.3.2. Operation principle and sequence of events

Solid-state types of limiters harness the capabilities of power electronic switches fast operation. Hence they are able to commutate current in the order of a few milliseconds while withstanding high breakdown voltage. Consider Figure 3.11 that is reproduced from Figure 3.10:-

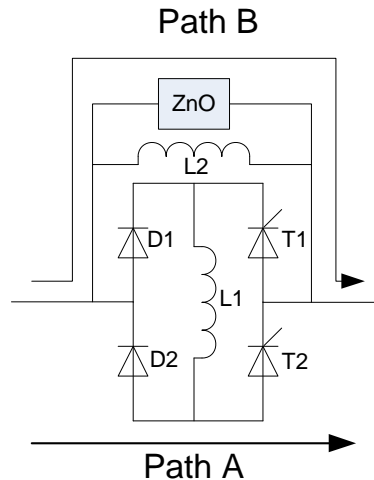


Figure 3.11 FCL-2 sequence of events [18]

The basic operation principle is as follows:-

- 1) For time $t < T_{fault}$, the IGCT T1 and T2 and the diodes D1 and D2 remain in full conduction. All current flows through the diode-IGCT bridge (Path A) with one pair of diode and IGCT switched on during the positive cycle and the other pair during the negative cycle. The current through L1 is constant and the voltage drop across L1 is zero.
- 2) At time $t = T_{fault}$, a bolted three phase-to-ground fault is inserted right at the terminals of FCL on the load side.
- 3) At time $t = T_{fault} + 10ms$, T1 and T2 are gated OFF.
- 4) At time $t = T_{fault} + 50ms$, all the current is now commutated through the bypass reactor L2 and the current now flows through “Path B”. Also, some of the remaining current free-wheels through the diodes D1, D2 and inductor L1, until it falls to 0.
- 5) For time $t \geq T_{fault} + fault\ duration$, the fault is kept inserted in the system
- 6) At time $t = T_{faultclear}$, the fault is removed and IGCT T1 and T2 are gated ON to resume steady state current flow as per “Path A”.

3.3.3. FCL control strategy

From the above sequence of events, it is evident that the main control input required for FCL-2 is the correct time at which to gate the IGCT T1 and T2 OFF so that the current can be commutated through the bypass inductor L2. To achieve this, it is fundamental to first correctly detect the fault so that the gating signal can be sent to the two switches. Section 3.2.6, Fault detection techniques, discussed the methods of detecting a fault and subsequently section 3.2.8 (A, B) discussed the implementation methodology. Building on this rock-solid detection method; its application is extended to control this FCL and as it is shown in Chapter 4, the FCL performs satisfactorily. Appendix C shows a detailed implementation of the FCL model in PSCAD[®].

3.4. Hybrid FCL model (FCL-3)

A third and a final kind of fault current limiter (FCL-3) originally developed by H. Arai et al [19] is chosen for modeling in PSCAD[®]. This model is based on the resonance characteristics exhibited when an inductor and capacitor are in series with each other. Since the FCL uses solid state as well as superconducting technology, this can be categorized as a hybrid type of limiter.

3.4.1. Major circuital components

The LC resonance based hybrid limiter has just two components, namely an inductor and a capacitor. However, the interesting aspect of this FCL lies in the fact that the inductor is a superconducting coil wound with Bi-2223/Ag High Temperature Superconducting tape [19]. It was mentioned earlier that an inductor wound with HTS wire allows for a very low voltage drop during steady state while the capacitor acts as a series compensator for the inductive transmission line. Also, the value of the capacitor and inductor are chosen in such a manner that at nominal

system frequency the impedance of the FCL itself is 0Ω . Figure 3.12 shows this FCL arrangement.

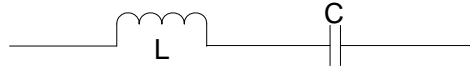


Figure 3.12 LC resonance based hybrid FCL (FCL-3)

3.4.2. Operation principle

The method of operation of this FCL device is very simple. Consider a test system as shown in Figure 3.13 consisting of a source voltage in series with an FCL and a resistive load.

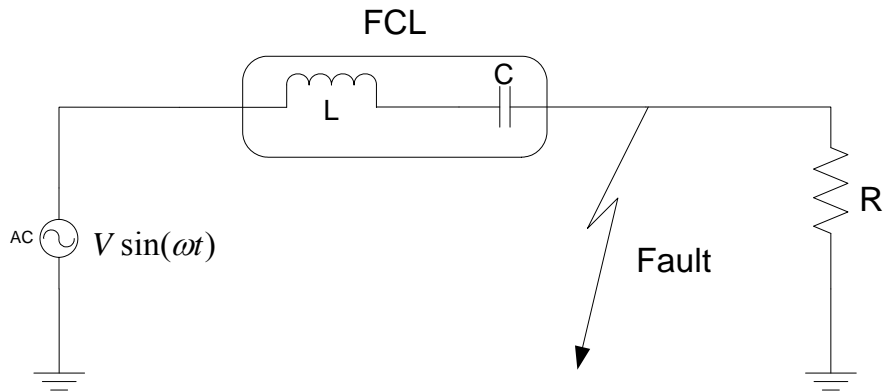


Figure 3.13 Circuit for hybrid limiter (FCL-3) explanation [19]

Let us assume initially that there is no fault. After switching on the source voltage, a steady state operating current is achieved and the inductor and the capacitor are tuned so that they do not require any further current and merely act as a pass through for the load current.

First, as an exercise let us derive the net impedance of this FCL. From fundamental AC circuits we know that:-

$$Z_{FCL} = Z_L + Z_C$$

$$\therefore Z_{FCL} = j\omega L + \frac{1}{j\omega C} \quad (3.2)$$

Re arranging the terms in (3.2), we get,

$$Z_{FCL(STEADY)} = \frac{(\omega^2 LC - 1)}{\omega C} j \quad (3.3)$$

Also, for $Z_{FCL(STEADY)} = 0$, we have,

$$\omega = \frac{1}{\sqrt{LC}} \quad (3.4)$$

Hence, for a particular system frequency, we can choose appropriate values for L and C so that the net impedance of the FCL is zero and hence they will be tuned.

When a short circuit is introduced, the current in the circuit can be obtained as follows [19]:-

$$L \frac{di}{dt} + \frac{1}{C} \int i dt = V \sin(\omega t) \quad (3.5)$$

Solving the above equation and assuming that a fault occurs at time $t = 0$, we have;

$$i(t) = \frac{V}{R} \sin(\omega t) + \frac{V}{2L} \times t \times \sin(\omega t) \quad (3.6)$$

From (3.6) we see that when the fault occurs, the current is a function of two parts. First is the steady state current which was flowing before the fault and still continues to flow after it for some time. Second, the current is also dependent on the duration of the fault and increases constantly. An important implication of this behavior is that by using the an LC resonant circuit, the rate of change of current is gradually increased allowing time for the relays and breakers to take action, rather than the more conventional FCL(s) that do not limit the rate of change of current [19].

3.4.3. Sequence of events

The sequence of events for FCL-3 is as follows:-

- 1) For time $t < T_{fault}$, the source voltage supplies regular current to the load through FCL-3.

Since L and C are tuned to the source voltage frequency, there is negligible impedance from the FCL itself
- 2) At time $t = T_{fault}$, a bolted three phase-to-ground fault is inserted right at the terminals of FCL-3 on the load side.
- 3) At time $t > T_{fault}$, the FCL is de-tuned from resonance and the current is limited by the inductor
- 4) For time $t \geq T_{fault} + fault\ duration$, the fault is kept inserted in the system
- 5) At time $t = T_{faultclear}$, the fault is removed and the FCL goes back to the resonance state.

Chapter 4 will show in detail the results obtained by simulating this FCL.

Chapter 4. SIMULATION RESULTS

This chapter presents the results obtained from the FCL modeling efforts in chapter 3. A brief overview about the test bed and case studies are described.

4.1. Test bed system and case study overview

In order to simulate the FCL and check its performance, a realistic test distribution system is needed. The test bed used for simulation studies for the FCL model consists of an actual system. A PSCAD[®] file of the distribution system from Southern California Edison (SCE) was secured. The model consists of all busses, nodes, loads and generation. However, due to the limitation of 200 single phase nodes on the PSCAD[®] 4.2.1 Educational version (available at Virginia Tech), the circuit loads were combined (leading to fewer nodes) in the most logical manner to reduce the number of nodes but with the net effect very close to the original system.

Consider the model distribution system connected to an infinite bus. Figure 4.1 shows the distribution system topology used for all simulation studies.

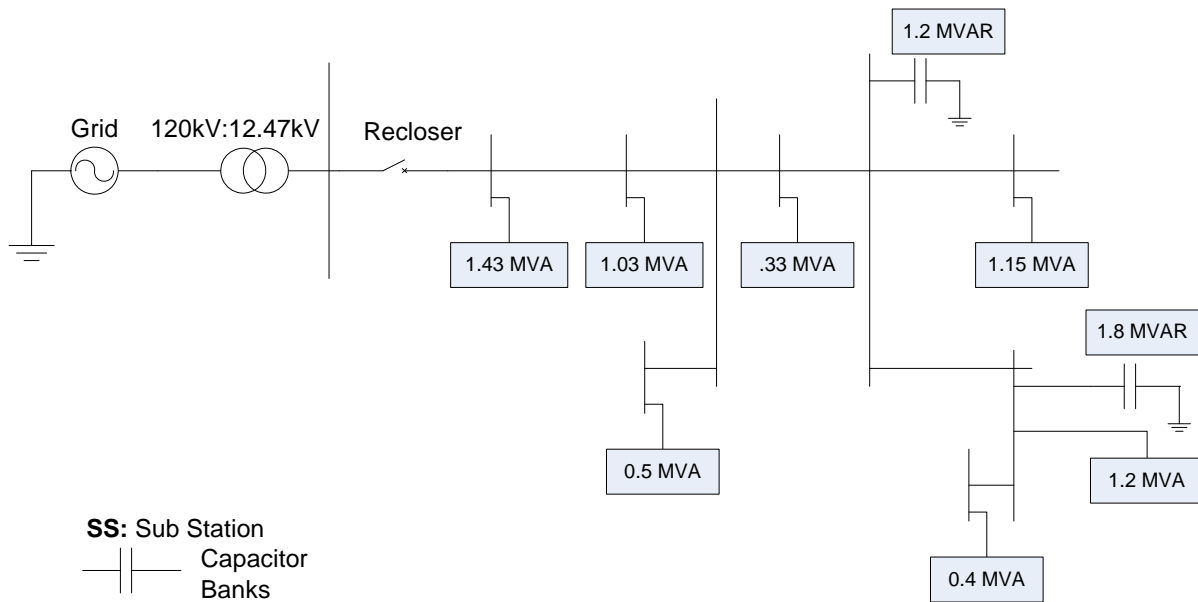


Figure 4.1 Test bed radial distribution system used for FCL simulation

Some of the key parameters of this system at an aggregate level are summarized in Table 4.1

Table 4.1 Summary of test system steady-state parameters

Parameter	Value
Operating Voltage	$\approx 12.5kV_{LL}$
Nominal Line Current	$\approx 260A_{rms}$
Net Load	5.82 MVA (incl. transmission losses, 0.74MW)
System Frequency	60 Hz
Number of Busses	45 (not all shown)
Substation Transformer	120 kV / 12.5 kV
Line Types	Underground and Overhead

A total of five case studies involving the three modeled FCL(s) are conducted. Out of the five, the first three involve superconducting FCL (FCL-1). The three FCL-1 cases are as follows:

- 1) The distribution system with and without an FCL-1 to check for current and voltage waveforms, effect on real and reactive power and time required by the FCL to reduce the fault current to a pre-determined level.
- 2) A comparative study between the developed HTS FCL-1 model and FCL commissioned by Z-energy. Emphasis has been given on achieving a very close behavior by FCL-1 to the one by Z-Energy.
- 3) The overall impact assessment of the FCL-1 device in the operation of sectionalizers and relay co-ordination.

The last two case studies investigate the operation and behavior of the solid state FCL (FCL-2) and the hybrid limiter (FCL-3). Along with these cases, Table 4.2 summarizes the simulation settings that were used in PSCAD[®]:-

Table 4.2 Simulation Parameter settings

Parameter	Value
Total simulation time	1 second
Time of fault insertion	0.3 seconds
Duration of fault	0.5 seconds (30 cycles)
Type of fault	ABC \rightarrow G
Scan time	0.1 ms

A bolted three phase-to-ground fault is used in all simulations as this will produce the highest amount of fault current. This is the worst case scenario for the given distribution system. This also helps in sizing the FCL parameters accordingly, since the device will be certain to work for any other type of fault (like phase-to-ground and phase-to-phase fault) with a lesser fault current value than a three phase to ground fault. Also, dedicated logic was developed in order to facilitate the insertion of the fault at the zero crossing (from negative to positive) of the voltage. This ensures that the current will be at its peak and worst the case scenario can be analyzed.

Before getting into the details of the results, let us establish some of the threshold magnitudes of fault currents that are observed in this particular distribution system. Table 4.3 shows the peak and the steady state faulted current values for faults placed at increasing distances from the main substation recloser.

Table 4.3 Line current values for fault at different distances from recloser

Fault Distance (meters)	Line Current (kA_{rms})	
	Peak current at time of fault	Steady state while faulted
0	30.4	19.8
3200	12.9	10.8
5900	8.60	7.50
7500	7.02	6.25

As expected, that as the distance of the fault is increased from the re-closer; the magnitude of the fault current level reduces. The objective of the FCL is to mitigate the fault current in the event of a fault being inserted right at the terminals on the load side and generation connected at the source side of the FCL (Note: the distribution system is radial in nature). This will result in the maximum amount of fault current levels. From Table 4.3, it is clear that the FCL must be able to withstand a steady state faulted current level of at least 19.8 kA and a surge current of 30.4 kA for the first few cycles. Building on this basis, the results of the study are presented below.

4.2. System study 1: General Results with and without FCL-1

4.2.1. Problem background

This section presents the results of the FCL operation in a distribution system. The goal of this study is to show the effectiveness of an FCL in limiting the current and its subsequent effects on bus voltage, and power.

4.2.2. Approach and test bed

Consider the circuit shown in Figure 4.2 which is derived from Figure 4.1 with all loads combined. The FCL to be tested is placed in series with the load and immediately after the main substation automatic re-closer. A bolted three phase to ground fault is inserted right at the terminals of the FCL for 30 cycles ($\sim 500\text{ms}$) with a fault impedance of $10\text{ m}\Omega$.

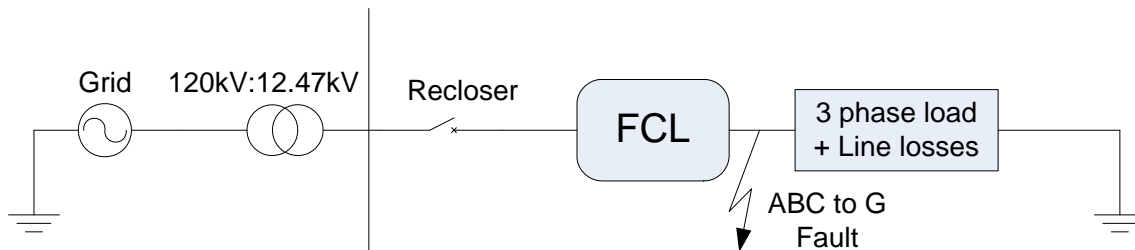


Figure 4.2 A typical radial distribution system used for FCL simulation

4.2.3. Results and discussion

From Table 4.3, we know that the peak current for a fault of this type has been found to be roughly 30.4 kA_{rms} while the steady state fault current is 19.8 kA_{rms} . However after inserting a FCL, we expect the current to be limited. Figure 4.3 and 4.4 show the current waveform and RMS waveform with and without FCL. We note that by inserting the FCL with a 0.23mH inductor for a 12.5kV and 5.8MVA system the current can be limited by at least 19% to 16kA_{rms} . By varying the inductance of the FCL, a better current limitation can be achieved. From simulation studies, there exists a linear relationship between the value of FCL impedance and how much current is limited.

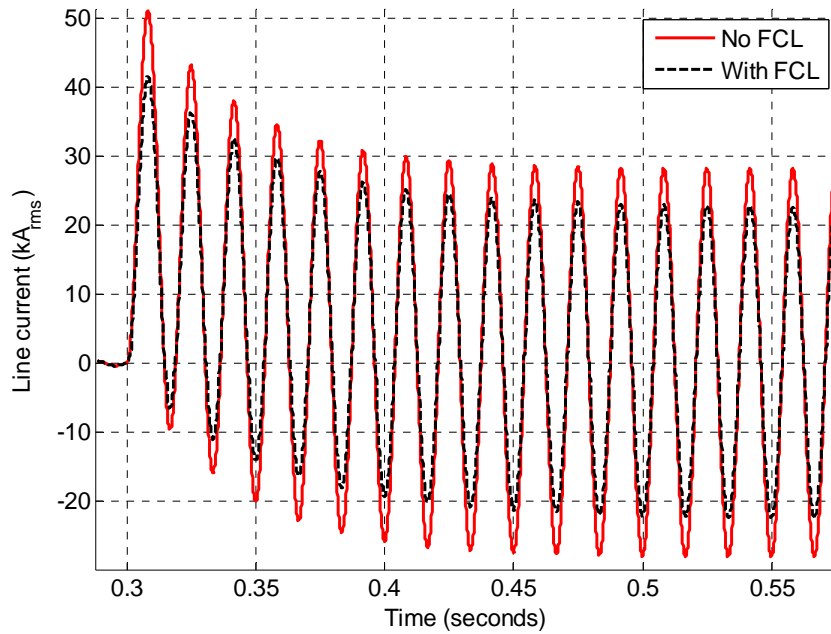


Figure 4.3 Phase A current waveform with and without FCL

Another important point to note in Figure 4.3 and 4.4 is the upward shifting of the signal from zero, known as DC offset. This is caused due to the inductance of the line, load and in the FCL. Also, we observe that the time constant is about 9 cycles after which a steady state faulted current is achieved.

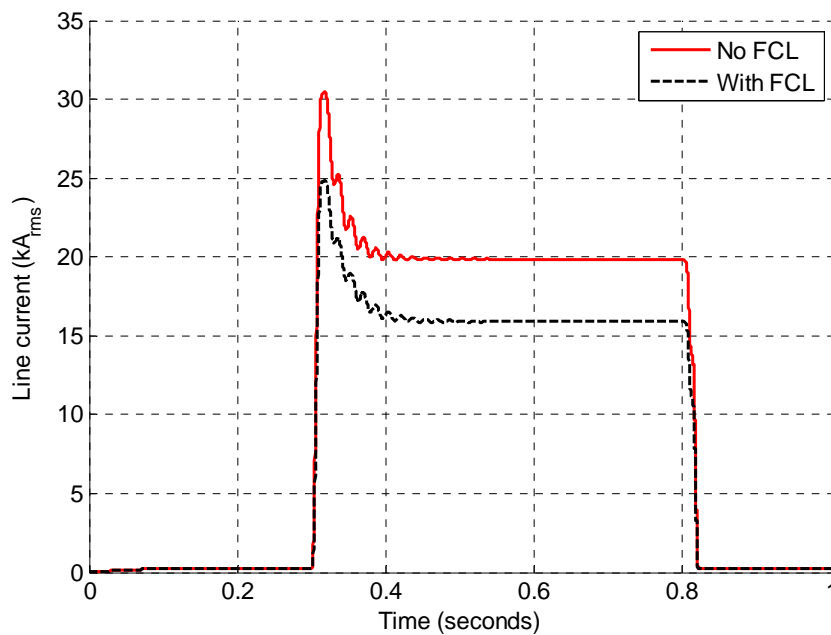


Figure 4.4 Phase A current RMS for with/without FCL

Figure 4.5 shows the effect of FCL on the main substation voltage drop. Clearly, a better voltage profile is maintained while the FCL is in operation as opposed to having no FCL. Simulation results also show a roughly 8% improvement over a non-FCL circuit (for a 19% FCL).

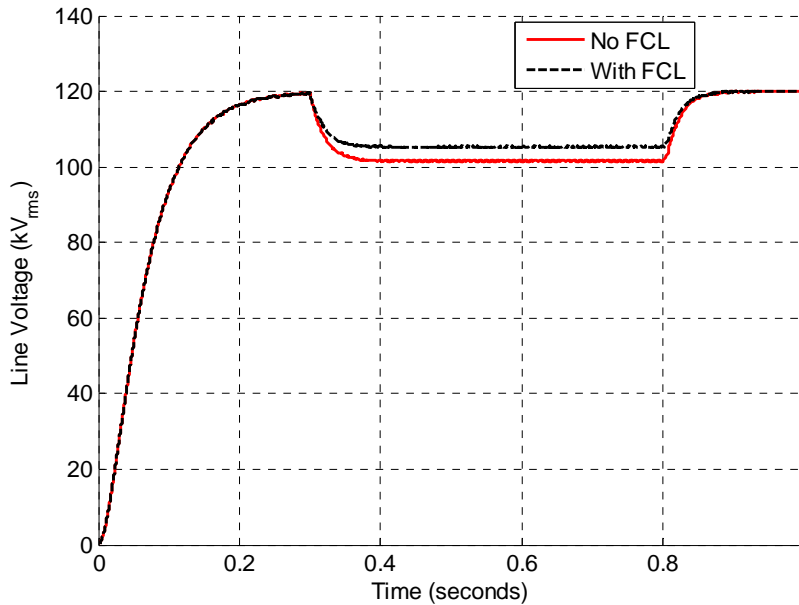


Figure 4.5 Substation voltage with/without FCL

Figure 4.6 shows that a significant amount of power is absorbed by the FCL itself. This power absorption generates heat that is controlled by a dedicated fail-proof cooling apparatus.

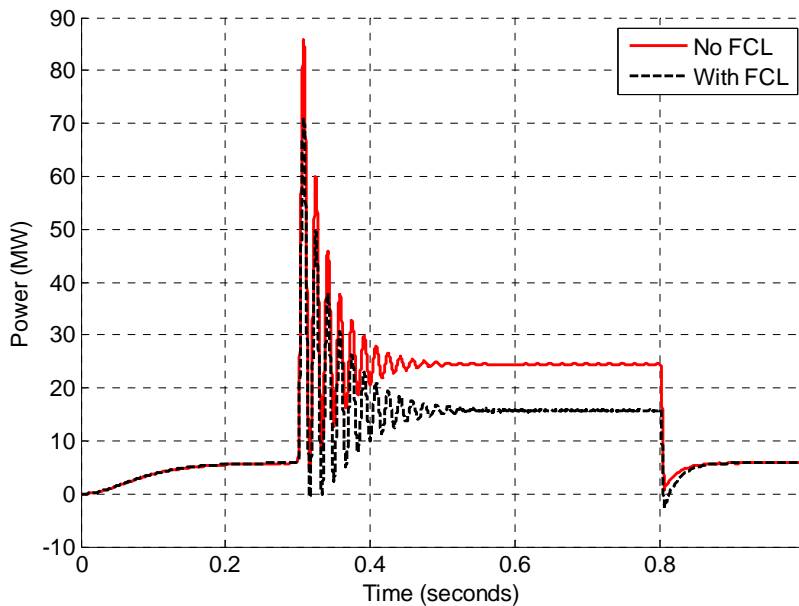


Figure 4.6 Real power with/without FCL

4.3. System study 2: Comparative testing of FCL-1 with Z-Energy model

4.3.1. Problem background

The simulation results of FCL-1 as modeled in Chapter 3, section 3.2, have been described in detail. Results such as fault current limiting capabilities, bus voltage drop, fault current, etc are presented. Also, results from FCL-1 are compared with the Z-energy model. The fundamental reason for comparing the modeled curves with the one obtained from Z-energy is to emphasize the fact that without access to confidential data of the device itself, a generic and flexible model can be a faithful representation of the physical device.

4.3.2. Approach and test bed

To perform a comparative study between FCL-1 and Z-energy model, a PSCAD[®] file was obtained from SCE which consisted of the Z-energy model. The model was purely fictional, that behaved very similarly to the actual one. Various simulations are carried out to check for the performance of FCL-1 against the Z-Energy model.

4.3.3. Results and discussion

As a part of the project, it was required to model an FCL that behaved very closely to the Z-energy model. As it will be shown by the following curves, significant amount of work was required to get the models to match satisfactorily.

Figures 4.7 and 4.8 show the line current and RMS waveform through FCL-1 and Z-energy FCL for phase A. There are a few things to note in these figures:-

- 1) Both models exhibit a DC offset and a time constant characteristic. The time constant is a function of the inductance and resistance of the FCL. Also note in Figure 4.8 that the peak line current at the time of fault is also same at $25kA_{rms}$.

- 2) The time constant on the FCL-1 model is about three cycles shorter than the Z-energy model. This can be improved by changing the rate at which the variable impedance Z_{var} is simulated and also the value of the inductor.
- 3) Finally, both the FCLs limit the same amount of current ($\sim 19\%$)

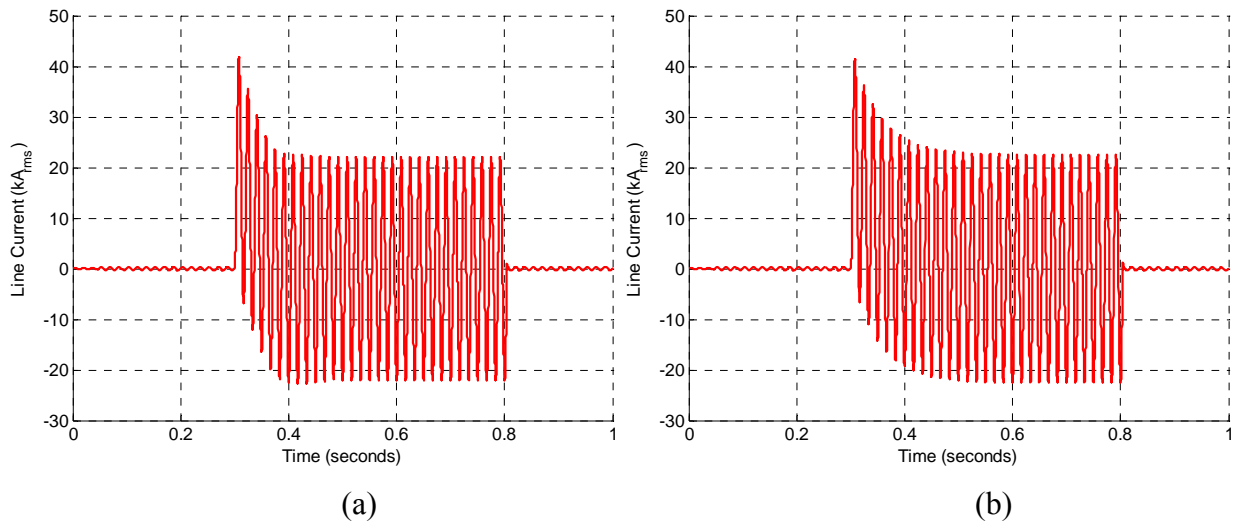


Figure 4.7 Line current waveform through (a) FCL-1, (b) Z-energy

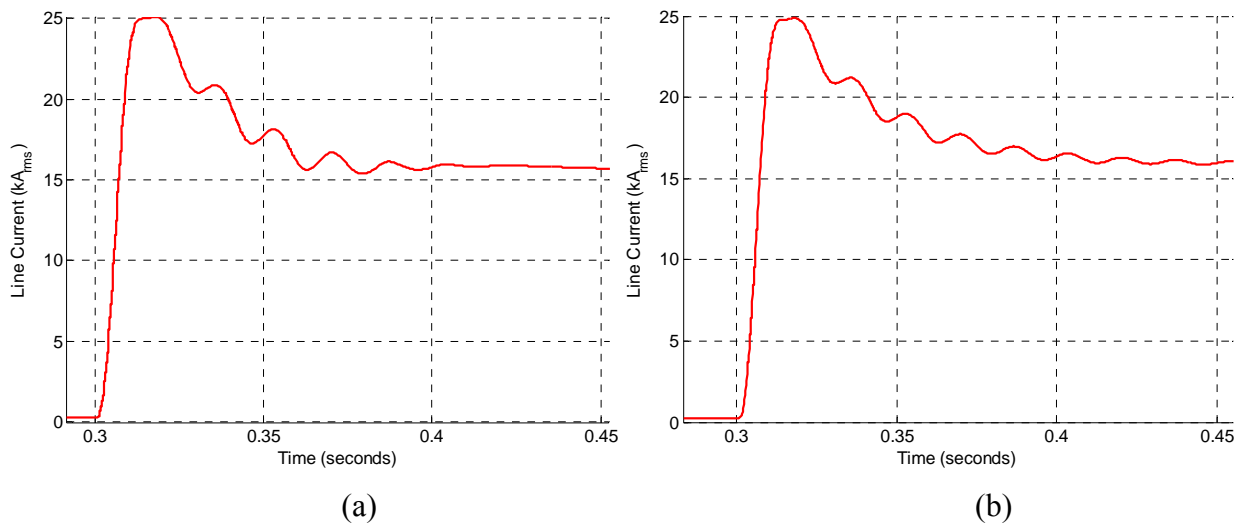


Figure 4.8 Line current RMS through (a) FCL-1, (b) Z-energy

Figure 4.9 is the zoomed version of Figure 4.7. As we outlined earlier, the Z-energy model showed evidence of a strong third harmonic component (Figure 4.9 (b)). This is also been incorporated in the FCL-1 model which is evident from Figure 4.9(a)

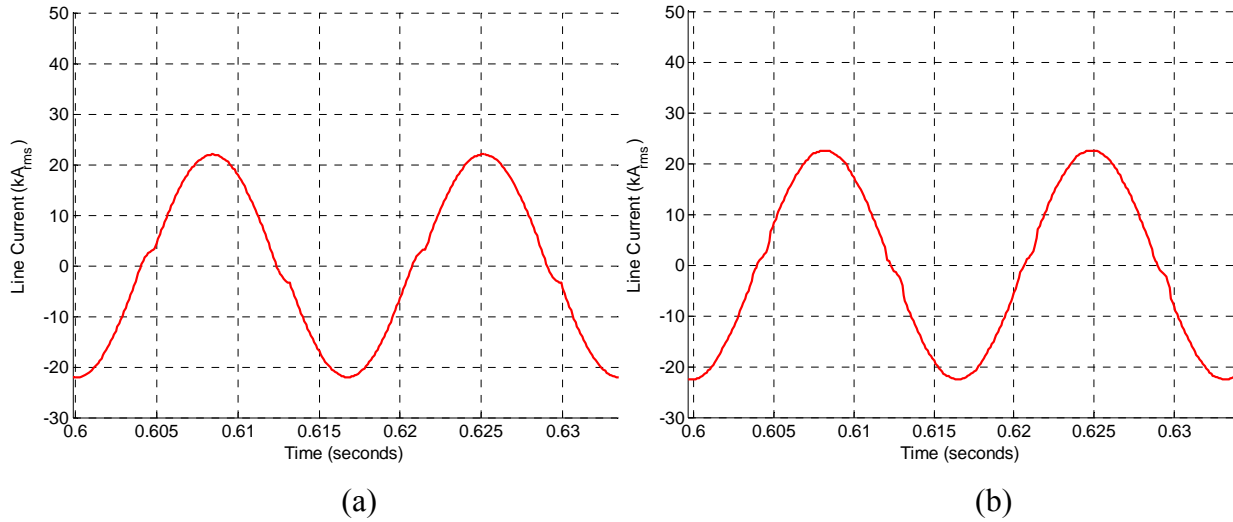


Figure 4.9 Line current waveform through (a) FCL-1, (b) Z-energy (Zoomed)

Finally, the effects on voltage drop across the FCL are investigated. From Figure 4.10(a) it can be seen that the voltage drop (in %) of FCL-1 is close to 0% in steady state. However, when a fault occurs, the voltage drops is close to 93.7%. This is because the fault is placed right at the terminals of the FCL on the load side. Same is also true for Z-Energy model and the results are shown below:-

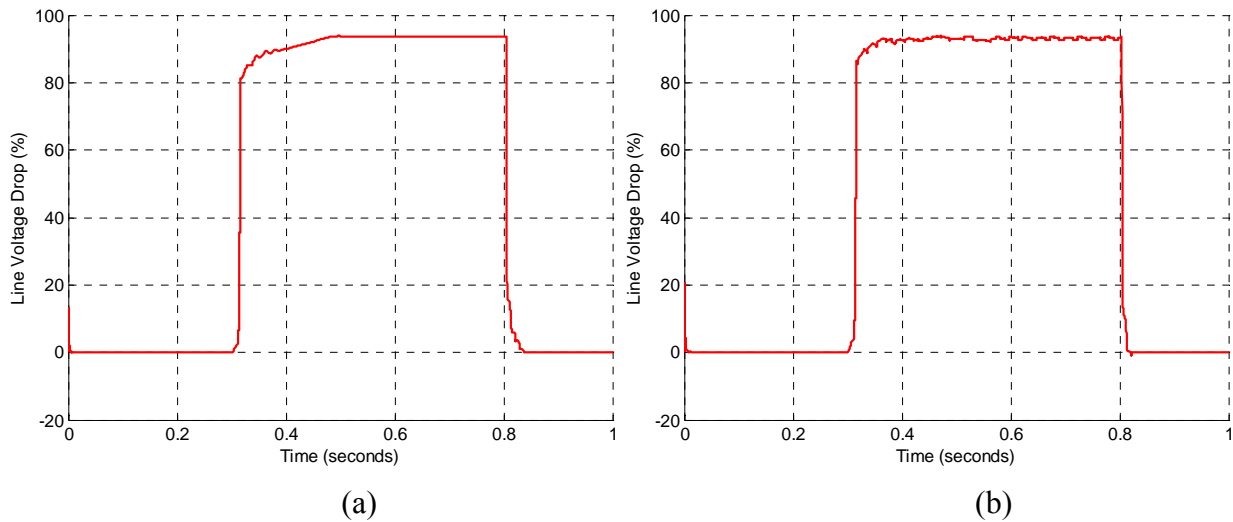


Figure 4.10 Percent voltage drop pre-, during and post- fault for (a) FCL-1, (b) Z-energy

After investigating the above results, it can be concluded that the developed FCL-1 model behaves very closely to the Z-energy model in terms of current limiting, harmonic content, settling times and FCL voltage drop.

Having established that FCL-1 can limit current effectively and also behave as per Z-Energy model lets us now reproduce Table 4.3 to investigate the effect on current limiting as the distance of the fault increases from FCL-1. Table 4.4 shows this study followed by a graphical representation of the data:-

Table 4.4 Line current with/without FCL-1 for fault at increasing distances from recloser

Fault Distance (meters)	Line current w/o FCL-1 (kA_{rms})		Line current with FCL-1 (kA_{rms})	
	Peak	Steady	Peak	Steady
0	30.4	19.8	25	16
3200	12.9	10.8	11.7	9.65
5900	8.60	7.50	7.8	6.8
7500	7.02	6.25	6.6	5.8

Figure 4.11 shows the data in Table 4.4 graphically:-

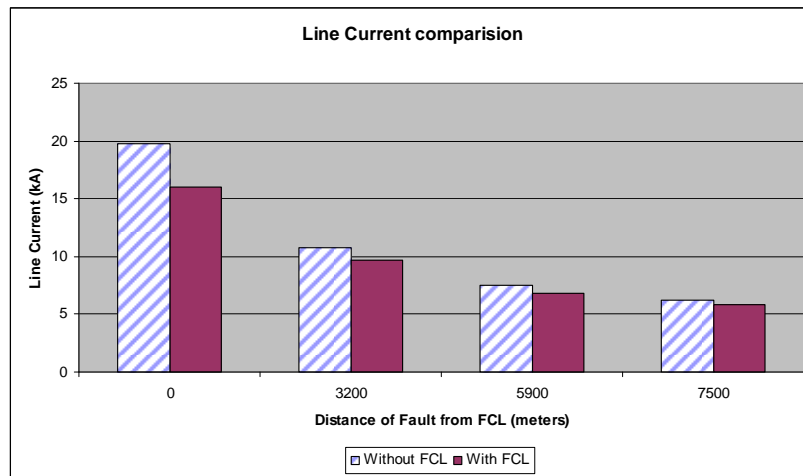


Figure 4.11 Line current with/without FCL-1 as fault distance increases

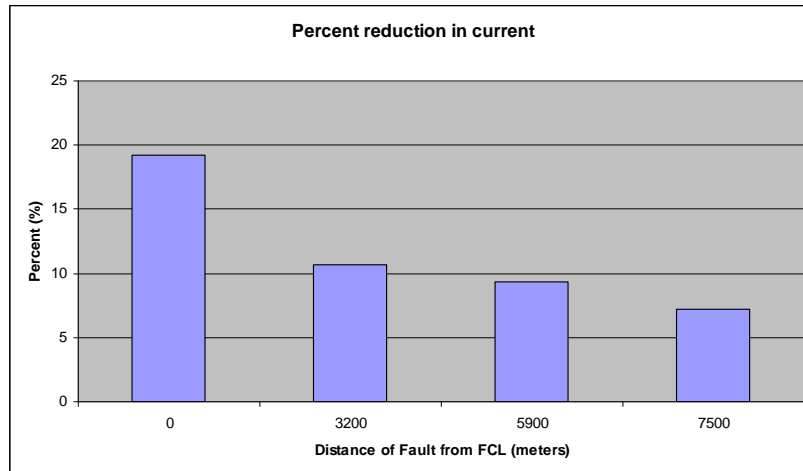


Figure 4.12 Percent reduction in current with FCL-1 as fault distance increases

From Figure 4.11 and 4.12 we see that the fault current is limited by a maximum of 19% for the given FCL impedance. As the fault distance is increased, the current limitation effectiveness is reduced. Possible solutions would be to add another FCL further downstream if more current mitigation is required.

4.4. System study 3: Impact of FCL-1 operation on protection scheme

4.4.1. Problem background

An impact assessment of the FCL on the protection scheme of the distribution system is presented. The goal of this study is to estimate the critical value of the FCL insertion impedance Z_{FCL} at which the protection scheme will fail to operate as desired. In essence, should the technology mature to an extent that the FCL is capable of limiting the fault current below the pick-up settings of the relay, then the protection scheme will not see the fault even when it is present. This will lead to a decrease in the reliability of the protection system unless all relays and other devices are upgraded to the new fault current values.

4.4.2. Approach and test bed

Typically distribution systems use an automatic recloser at the source end and sectionalizers downstream to protect individual loads and interconnections. As an overview, sectionalizers are automatic switches that are controlled by a built-in logic system. The sectionalizer determines that a fault exists downstream in the circuit by recognizing that the current flowing through it has exceeded a preset threshold value. The sectionalizer also determines that a fault is not temporary in nature by counting the number of times the upstream source side re-closer operates [20]. After a set number of counts occur within a stipulated timeframe, the sectionalizer will open and lock-out, hence isolating the fault ahead of it. It is important to note that the sectionalizer will open only after the recloser opens. This is due to the fact that the sectionalizer by itself cannot interrupt the fault current.

Consider the distribution system in Figure 4.13. Four sectionalizers are strategically placed in the circuit so that minimum disruption of power to loads occurs in case of a fault anywhere in the system. The boxes show the approximate area that a particular sectionalizer will protect in the event of a fault.

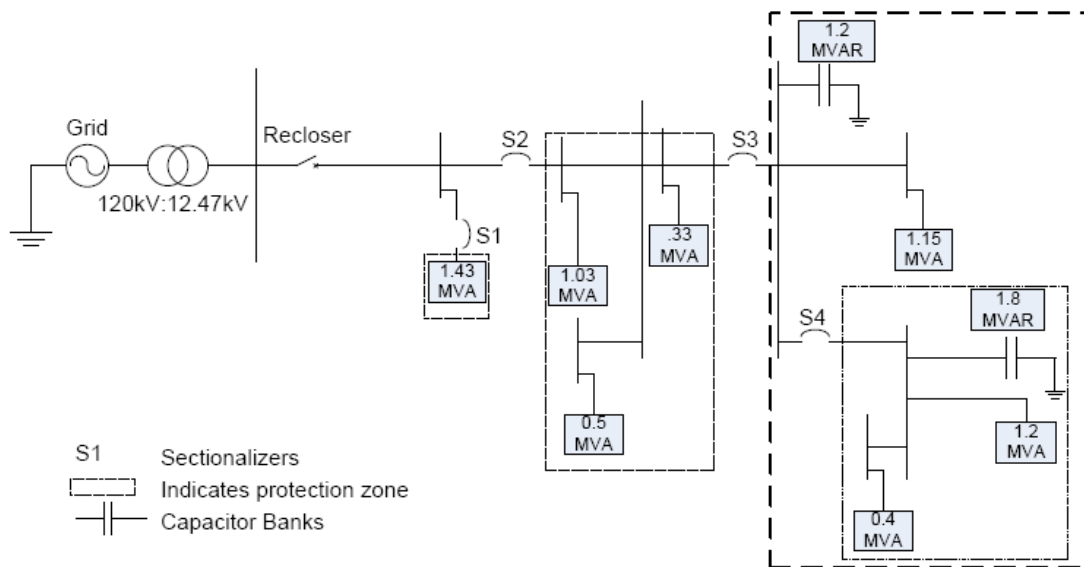


Figure 4.13 A typical radial distribution system used for sectionalizer study

The main recloser is programmed for a 2-2 sequence. This implies that the recloser will operate for 2 fast trips and 2 slow trips [21]. Sectionalizer S4 is configured for 2 counts. As an example, consider a fault beyond S4. The sequence of events for protection will be as follows [20]:-

- 1) The current through S4 is greater than the threshold current. The re-closer opens on the fast curve protecting other loads. S4 counts 1 and is now armed.
- 2) Next, the recloser closes. If the fault is still present, the recloser will open once again. Sectionalizer S4 counts 2. After a few milliseconds of the recloser opening, S4 opens. The fault is now isolated.
- 3) The recloser closes once again and power is restored to all the loads except any loads connected beyond S4.

Figure 4.14 shows the recloser and sectionalizer timing diagram.

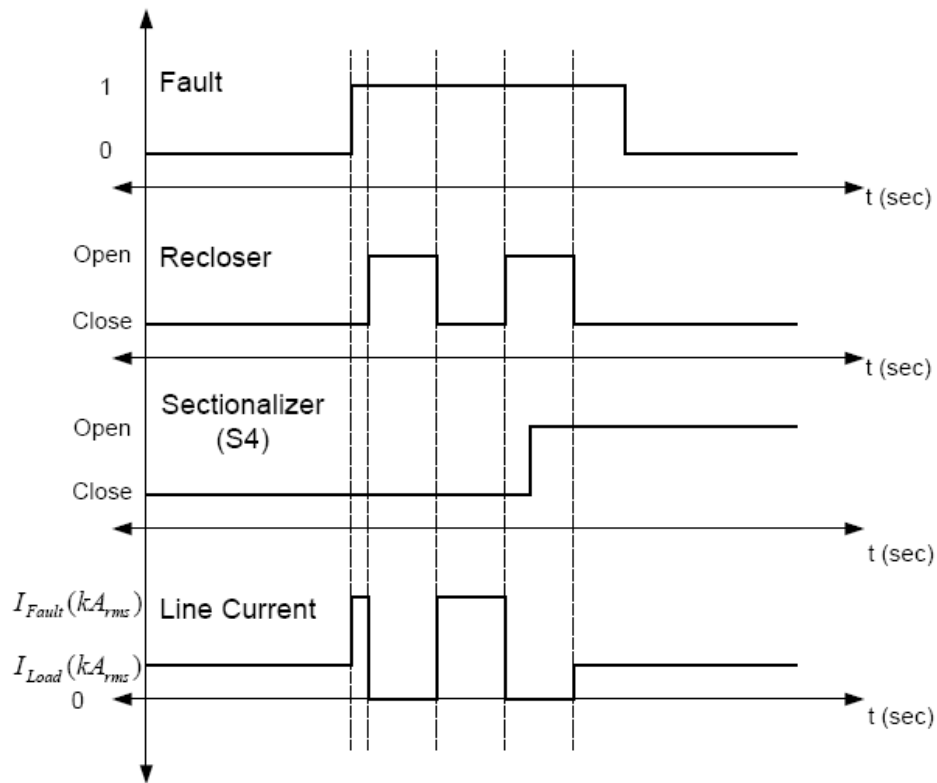


Figure 4.14 Recloser-Sectionalizer timing for fault beyond S4

After having established the sequence of events, the next step for this study is to select pick-up current settings for the recloser and all the sectionalizers as shown in Table 4.5

Table 4.5 Sectionalizer/recloser settings

Sectionalizer	Count	Nominal current (A_{rms})	Pick-up current (A_{rms})
Recloser	N/A	260	800
S1	2	17.2	30
S2	4	190	300
S3	3	140	225
S4	2	80	130

From Table 4.5, based on classical method, the pick-up currents setting for the recloser has been chosen as 3 times maximum load current and 160% of the steady state current for sectionalizers. This setting will insure that a false operation is avoided, hence being secure, while assuring only correct operation for dependability [20, 22]. Four faults, F1, F2, F3 and F4 are sequentially inserted into the system as shown in Figure 4.15.

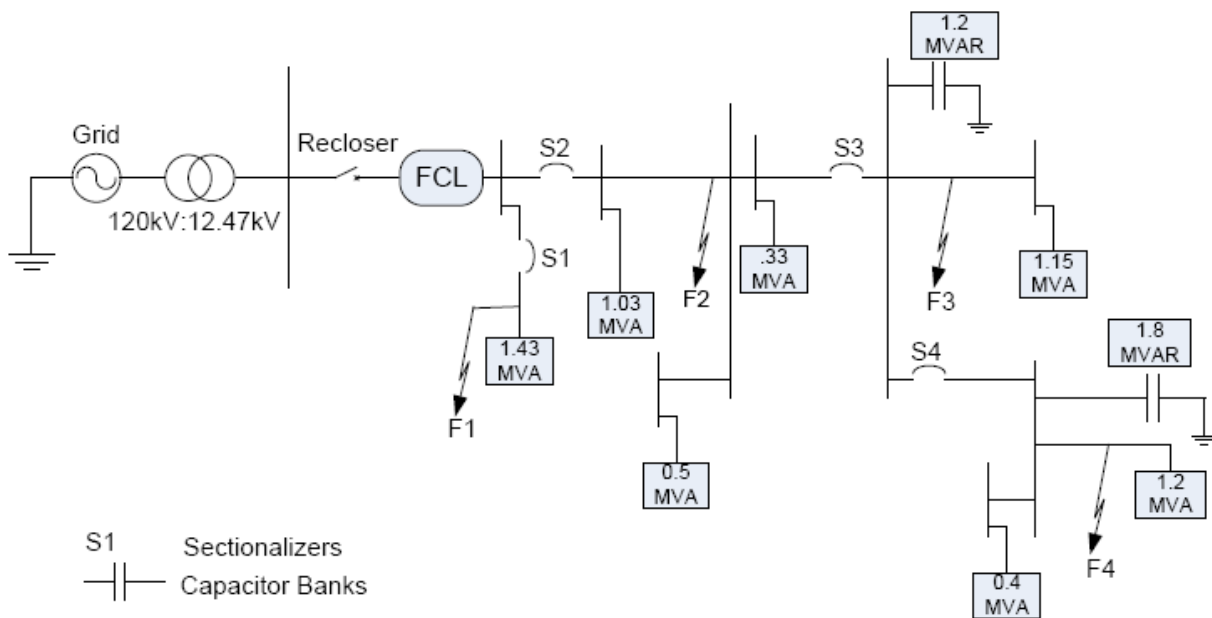


Figure 4.15 Radial distribution system fault testing used for FCL simulation

Table 4.6 is a matrix showing which all devices will see a fault current when a fault is placed at the four different places in the system (Y=Yes, N=No).

Table 4.6 Sectionalizer/recloser operation

Device/Location	F1	F2	F3	F4
Recloser	Y	Y	Y	Y
S1	Y	N	N	N
S2	N	Y	Y	Y
S3	N	N	Y	Y
S4	N	N	N	Y

From Table 4.6 we infer that the recloser will see the fault current for all the faults. Also, note that for fault F3, sectionalizer S2 and S3 will see the fault current. However, since S3 is configured to lock out at 3 counts, S2 will not operate (4 counts), before which we expect the fault to be cleared by S3. S2 acts as a back up protection in the event S3 fails to operate. The same also holds true for fault at F4.

4.4.3. Results and potential impacts

After running the simulations by placing the fault at the four locations above, it is found that, on average, a minimum of 85% percent current limitation is required before the main substation re-closer will not “see” a fault even though it is present. However, in some cases the current limitation required is close to 95%. This is certainly due to the FCL insertion impedance which mitigates this current. The issues arising due to this can be summarized as follows:-

- 1) Inability of the re-closer to see the fault even though it is present.
- 2) Periods of long high level fault currents will damage the FCL itself because each FCL is rated for a particular amount of current for specific times.
- 3) Increased stresses on equipment connected upstream which might be handling more than 100% of their ratings for long periods of time.

Hence, there are two important implications arising from this study:-

- 1) Since the developed FCL-1 behaves very closely to the Z-energy FCL, there is sufficient trust in its faithful representation of the actual device.

- 2) Building on the above basis and, with the development of a flexible model, the impedance of the FCL Z_{FCL} can be changed on-the-fly to see the effects on the protection scheme and timing.

Currently, only one FCL by American Super Conductor Corporation (AMSC) is capable of limiting more than **85%** fault current. This is still a prototype model and under test. Three phase prototype tests have shown that a 28kA fault current can be reduced to 3kA for a 13.3kV voltage level. This is almost a 90% reduction in current [13]. Hence, if this limiter was to be deployed in the distribution system under consideration, there will be significant impacts on relay coordination and subsequently protection.

4.5. System study 4: Simulation of Solid-State limiter (FCL-2)

4.5.1. Problem background

A second kind of fault current limiter which is based on solid state technology is investigated. The goal of this study is to outline the effectiveness of current limiting by a solid-state kind of limiter as modeled in Chapter 3 and also to highlight the effectiveness of a flexible modeling approach by rearranging and/or adding extra components to the FCL.

4.5.2. Approach and test bed

Consider the circuit shown in Figure 4.16 derived from Figure 4.1 and parameters as per Table 4.1. FCL-2 is placed in series with the load and immediately after the main substation automatic re-closer. A bolted three phase to ground fault is inserted at the terminals of FCL-2 for 30 cycles (~500ms) with a fault impedance of $10\text{ m}\Omega$.

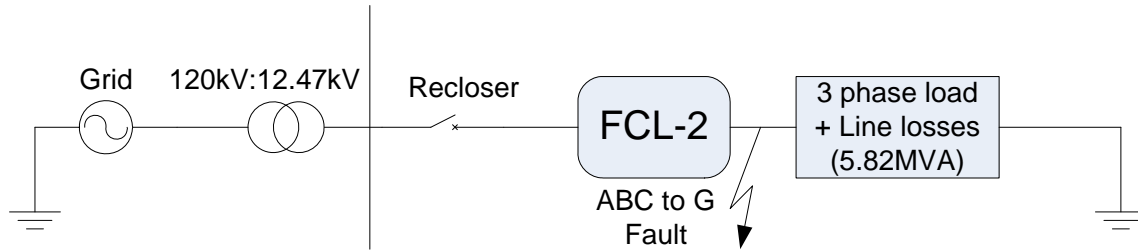


Figure 4.16 Test bed model for system study 4: Solid state model (FCL-2)

4.5.3. Results and discussion

The results obtained via simulation of FCL-2 were found to be very satisfactory. Figure 4.17 shows the effectiveness of current limiting for increasing levels of inductance.

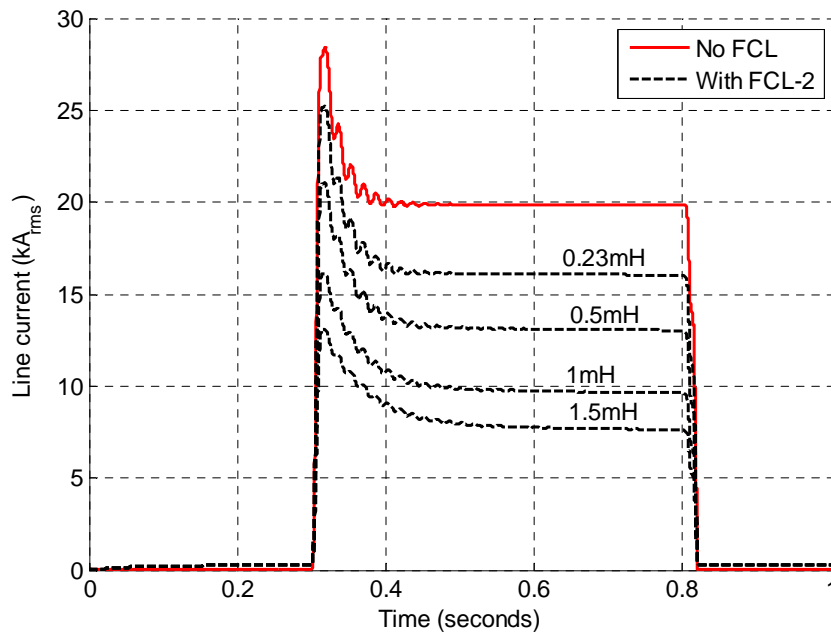


Figure 4.17 Line current through FCL-2 for increasing impedances

From Figure 4.17 we observe, as expected, that as the impedance of the FCL is increased, more current is limited. Also, the use of power electronic switches helps in commutating the current almost instantaneously to the by-pass reactor which can then limit the current. Another very interesting aspect to note is that as the impedance is increased, the FCL takes a longer time to settle to a steady state fault current value. This is because the time constant of the FCL, that is directly proportional to the inductance present in it.

Since, FCL-2 also uses an inductor to limit the current; the behavior is very similar to the superconducting FCL-1 model that was shown before. Figure 4.18 shows the zoomed-in wave form for phase A. Note that, there are no harmonics introduced in the current waveform for FCL-2 (a) as the inductor is sized appropriately so that it is not driven into saturation unlike FCL-1 (b).

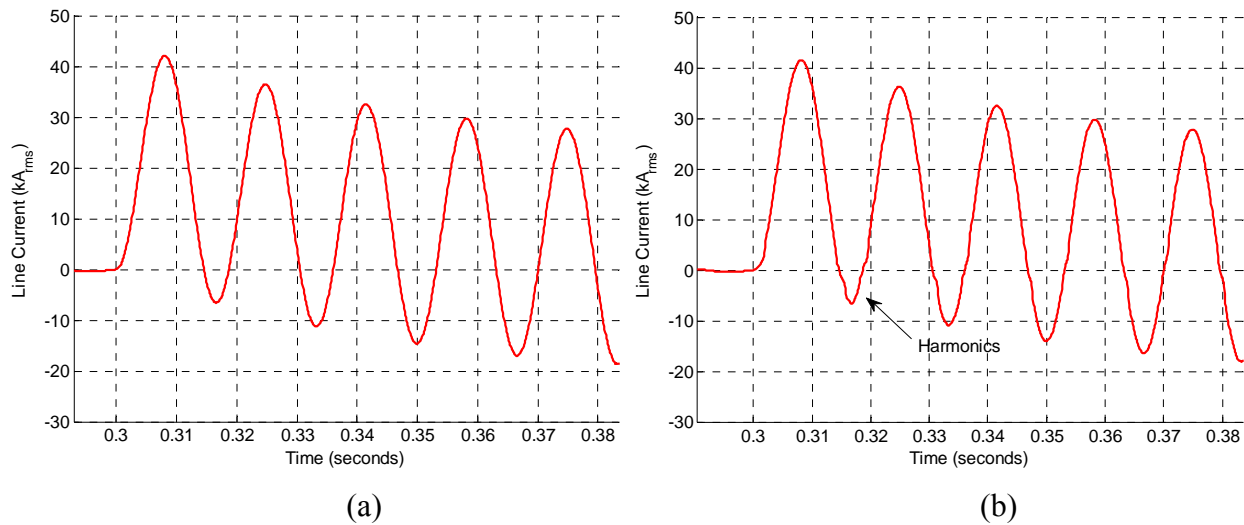


Figure 4.18 Line current waveform for (a) FCL-2, (b) FCL-1

As an exercise, we also investigated the effect on voltage drop across FCL-1 and FCL-2 before, during and after fault for the same net impedance and simulation parameters. Figure 4.19 shows a super imposed curve of the voltage drop for the two FCL(s). As expected, the voltage drop pre and post-fault is almost zero. However, we immediately note that the voltage drop on FCL-2 is much lower than that of FCL-1. This is due to the fact that, in FCL-2 the voltage drop is only caused by the inductor whereas in FCL-1, addition of variable impedance and the firing switches in series with the inductor leads to an additional drop in voltage.

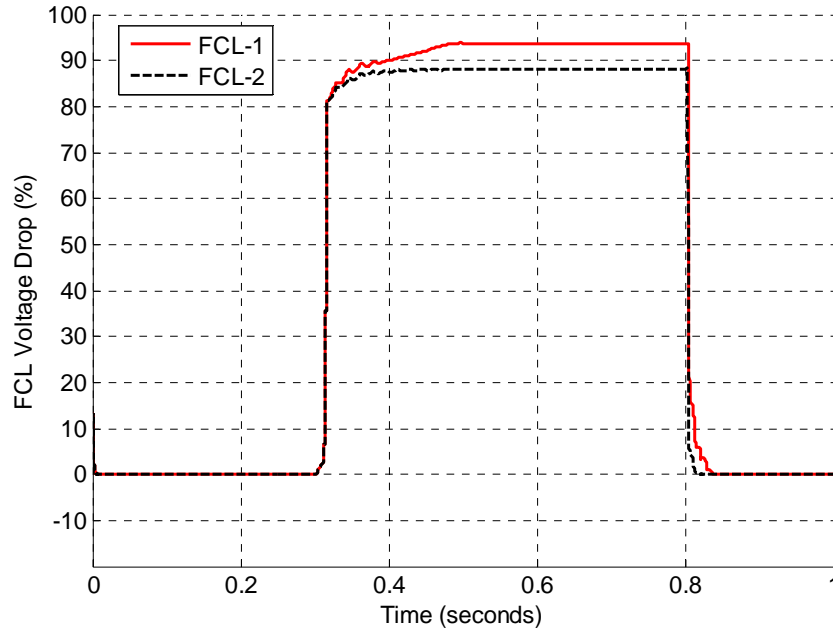


Figure 4.19 Voltage drop percentage comparison between FCL-1 and FCL-2

Hence, after investigating the above results, it can be concluded that solid-state based limiters can perform well in mitigating fault currents by employing power electronic switches along with passive elements like an inductor. As power electronic switches pack more power, current and voltage handling capabilities in a small package and with their reducing cost of manufacturing, solid-state limiters like the one just discussed will find increased use in distribution systems and will be a strong contender as viable FCL devices.

4.6. System study 5: Simulation of Hybrid limiter (FCL-3)

4.6.1. Problem background

A third and final kind of fault current limiter which is based on resonance technology is investigated. The goal of this study is, as before, to outline the effectiveness of current limiting by a hybrid limiter (FCL-3) as modeled in chapter 3 and also to highlight the effectiveness of a flexible modeling approach by rearranging and/or adding extra components to the FCL.

4.6.2. Approach and test bed

Consider the circuit shown in Figure 4.20, which is derived from Figure 4.1, and parameters as per Table 4.1. FCL-3 is placed in series with the load and immediately after the main substation automatic re-closer. A bolted three phase to ground fault is inserted at the terminals of FCL-3 for 30 cycles (~500ms) with a fault impedance of $10\text{ m}\Omega$.

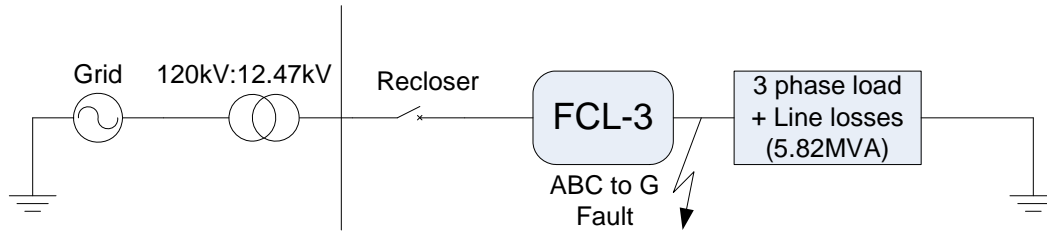


Figure 4.20 Test bed model for system study 5: LC resonant model (FCL-3)

4.6.3. Results and discussion

The results obtained via simulation of FCL-3 were found to be very satisfactory. Figure 4.21 shows the line current waveform through the FCL.

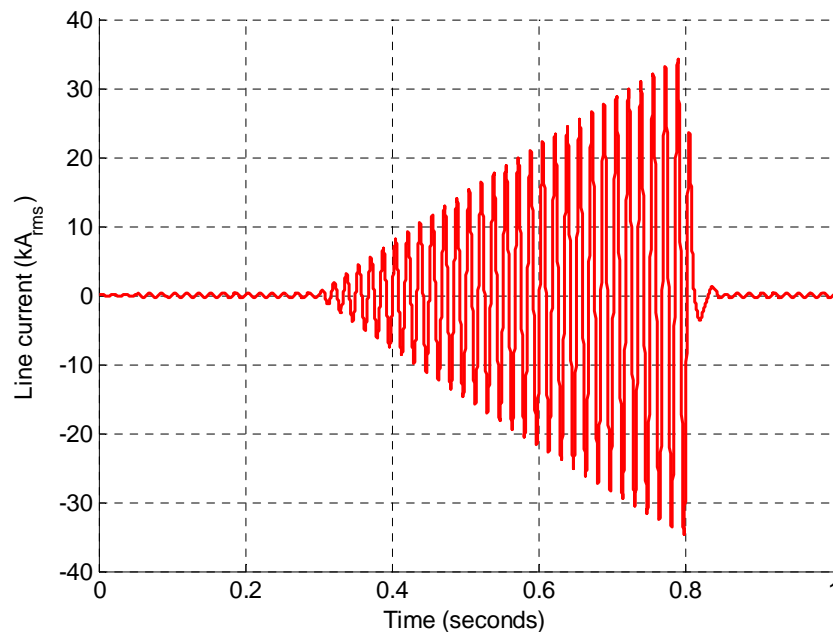


Figure 4.21 Line current waveform for FCL-3

Recall from Chapter 3, equation (3.6), the line current through FCL-3 is given by:-

$$i(t) = \frac{V}{R} \sin(\omega t) + \frac{V}{2L} \times t \times \sin(\omega t) \quad (4.1)$$

From (4.1), we note that the line current increases at a steady rate when the fault is inserted. From Figure 4.21, we see exactly the same phenomenon. Similarly, Figure 4.22(a) shows the RMS current curve. We immediately observe that the line current does not jump instantaneously but rather at a constant rate. Comparing the line current waveforms with FCL-1 or FCL-2, it is interesting to note that for the given set of parameters, the line current in FCL-1/2 jump instantaneously to 25kA while it takes about 30 cycles for FCL-3 to reach 25kA.

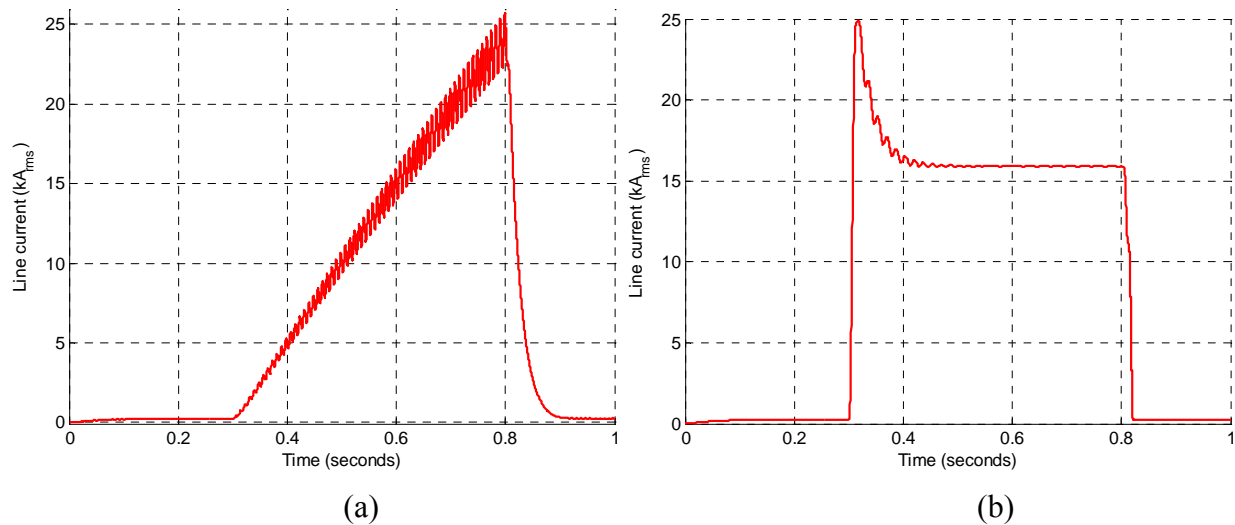


Figure 4.22 Line current through (a) FCL-3 and (b) FCL-1

Since the rate of change of current is an important factor in this FCL, it is apt to compare it with the rates obtained by FCL-1. Figure 4.23(a) shows the di/dt curve for hybrid FCL-3 and Figure 4.23(b) for FCL-1. We note that the rate of change of current on FCL-3 is much more gradual than that of FCL-1 which immediately spikes to 8kA/s and then settle down at a steady faulted state.

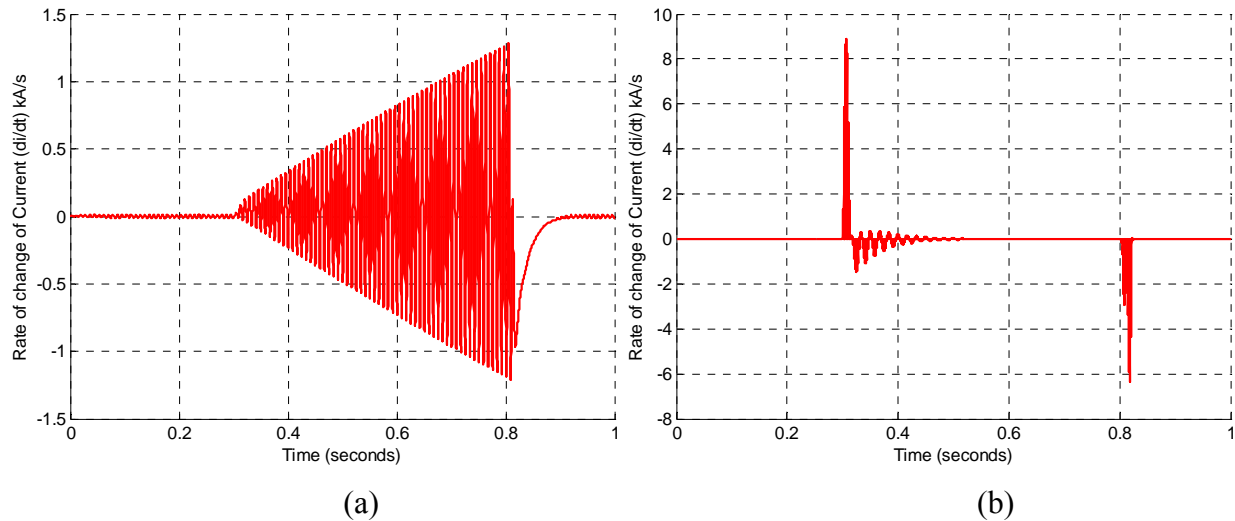


Figure 4.23 Rate of change of current for (a) FCL-3 and (b) FCL-1

Having investigated and compared FCL-3 with its counterparts, one critical question needs to be answered. What happens to FCL-3 in the event the fault is not cleared by the recloser, sectionalizer or breaker downstream? Since the curves show that the current will keep on increasing in the inductor until either the capacitor or the inductor blows out. This is one of the disadvantages of using a resonant kind of hybrid limiter.

4.6.4. Comparative results of FCL-3 with original model as in IEEE paper

As noted earlier, the LC resonance based hybrid limiter is a brainchild concept of H. Arai et al. In their paper [19], they have physically created an experimental FCL. However, since it is a lab scale prototype, the voltage and current levels are in the order of few hundred volts and amps. Nevertheless, the curves presented in their paper can still be used to validate the results obtained via our PSCAD[®] modeling of FCL-3. In order to compare on the same time scale, a 6 cycle fault is inserted into the distribution system. Figure 4.24(a) shows the line current through the modeled FCL-3 and Figure 4.24(b) shows the line current through the original FCL model for an R-L reactive load. It can be immediately noticed that the waveforms agree with each other exactly.

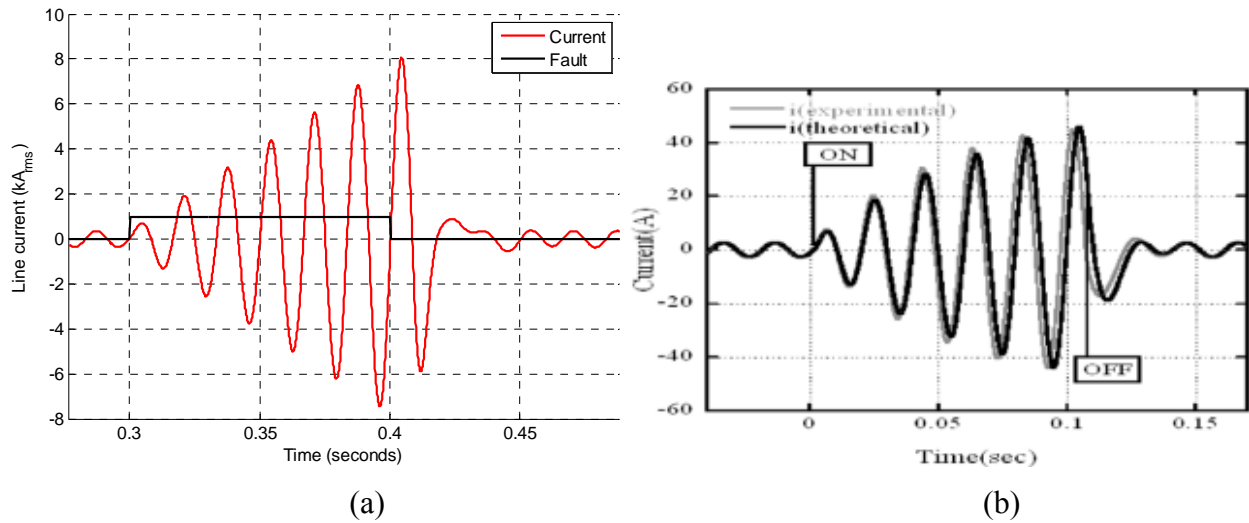


Figure 4.24 Line current through (a) FCL-3 and (b) original model [19]

Similarly, Figure 4.25(a) shows the voltage waveform across FCL-3 and Figure 4.25(b) shows for the original model. The waveforms are almost similar. From Figure 4.25(a) and (b) it can be seen that the FCL creates a very high pulse voltage when the fault is removed and eventually reaches steady state in about 5 cycles. It is important to note that this pulse can be almost 6 times the bus voltage. In order to mitigate those effects, a metal oxide surge arrester can be employed.

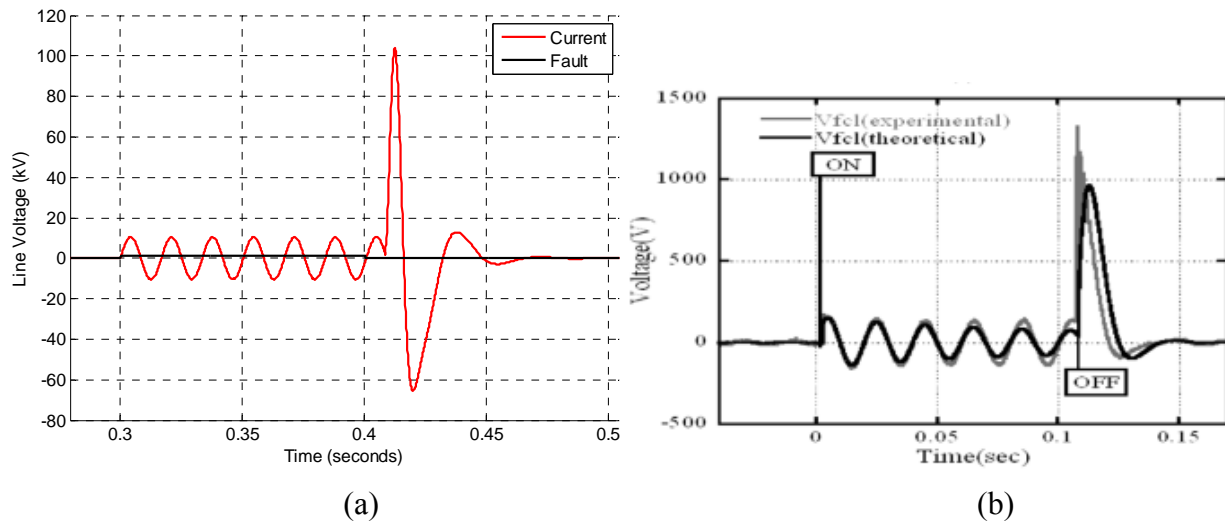


Figure 4.25 Voltage difference across FCL waveform (a) FCL-3 and (b) original model [19]

Chapter 5. CONCLUSIONS AND FUTURE WORK

This chapter provides an executive summary of the work presented in this thesis. Possible future work is also discussed briefly.

5.1. Summary and Conclusions of thesis

As it is evident now, FCL technology is still under development and at its infancy. Many research papers and journals have proposed various methods to limit currents either by simulation studies or by building lab scale prototypes. However, in most of the cases, there is very little information on how the FCL modeling is actually done. As more professionals get interested in this technology, it is important to create a general implementation methodology and algorithm for developing an FCL. Hence, the work in this thesis can be summarized as follows:-

- First, a comprehensive and up-to-date literature review of the major kinds of fault current limiters that have been simulated, lab tested and even installed in the field. Results from a utility survey regarding advanced protection, adoption of FCL, and upgrading activities, that was conducted as a part of the project is also reported. Current status of the FCL technology along with potential issues and concerns are discussed.
- Second, proposed some of the techniques to model a behavioral fault current limiter in the PSCAD[®] environment. This includes synthesizing of fault detection algorithms, FCL activation, operation and timing and their respective algorithmic implementations.
- In particular, three types of FCL(s) were modeled, i.e. superconducting, solid state and hybrid limiter.

- A total of five case studies using the developed FCL models were conducted:-
 - ▶ The first three case studies involved using the superconducting FCL (FCL-1). First, general results on a distribution system with and without an FCL were discussed. It was shown that the use of FCLs in general can help in mitigating currents while maintaining voltage stability and power. Also, the voltage drop across the FCL pre/post fault was negligible. Second, a comparative study was conducted between the modeled FCL-1 and the Z-energy model. It was shown that without having access to proprietary manufacturer parameters, a generic model can be created to behave in a similar fashion as that of real device. Finally, the impact assessment on the protection scheme was carried out when an FCL is inserted. It was reported that, when on average 85% current limitation is achieved, the main sub-station re-closer will not “see” the fault even though it is present.
 - ▶ The fourth study was conducted to study the operation and the behavior of a solid state kind of limiter model (FCL-2). From simulation studies it was shown that, by using power electronic switches, current can be commutated in a few microseconds to the bypass reactor that limits the current. Also, it was learnt that the use of a big enough inductor will not lead to un-necessary harmonics. As a comparison, it was observed that during fault, FCL-2 produced a lower voltage drop than FCL-1.
 - ▶ The final study was conducted to study the operation and the behavior of a LC resonant based hybrid limiter model (FCL-3). From simulation studies it was shown that, by using a superconducting coil and a capacitor in resonance can lead

to a very slow and constant rate of change of current di/dt during which the main recloser or the substation down stream can clear the fault. Comparing this limiter model to either FCL-1 or FCL-2, it was shown that upon fault insertion, the current does not jump to a peak value in case of FCL-3 where as in FCL-1 or 2, the current peaked for about one cycle and then started limiting the current. In addition, the curves obtained from FCL-3 modeling were compared to the actual literature paper under which this model appeared. It was shown that both the FCL-3 and the curves provided in the literature are the same.

Hence, it can now be concluded that the modeled FCL(s) worked as expected and produced satisfactory results. This also shows that by creating a flexible model, parameters can be changed at an instant and the effects of those changes can be monitored on a distribution system. This is particularly useful when engineers are planning to evaluate new FCL technology in a particular distribution system. This is the second major contribution of this thesis along with a comprehensive literature review.

5.2. Future Work

Future directions of this work include:-

- To run simulation studies with two or more FCL(s) in a larger distribution system, and monitor its effect on current mitigation, relay co-ordination and possible mis-operation.
- Also, with increased interest in distributed generation and smart micro-grid technology, it would be useful to evaluate the performance of the FCL in terms of current reduction and directional sensing. With increase installation of DG, current can now travel in both directions in a distribution system and the fault current contribution due to the

distributed generator is also significant. There can be potential impacts on the directional protection scheme and relay timing.

- As it was shown in the LC-resonant based hybrid limiter (FCL-3) that the current will keep on increasing until a breaker clears the fault. A good extension of this would be come up with an emergency control strategy that will effectively shut-off the FCL before any damage happens to the device itself. Since, the behavior of FCL-3 is different from FCL-1 or 2; it would be a good idea to assess its impact on the distribution protection scheme and relay coordination.
- Another future work would be to create more FCL(s) in PSCAD[®] and add it to the existing library of models that was created in this thesis. A simple drag-and-drop approach will make the use of FCL model in system studies seamless and less time consuming.

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Appendix: A Types of fault current limiters

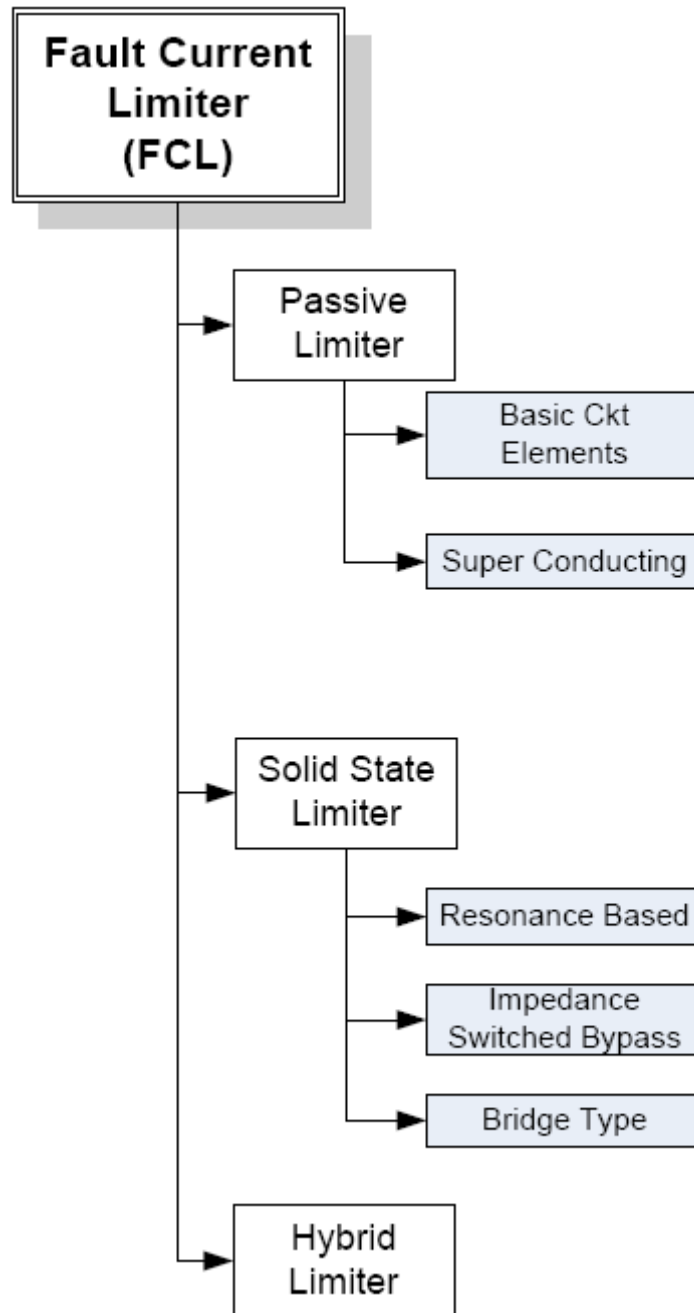


Figure A.1 Categories of Fault current limiter

Types of Fault Current limiters



Computer simulated



Field/Lab tested



Field installed & Running

Type of Limiter	Circuit Diagram	Paper appearance	Notes
<p>1. Passive</p> <p><u>Basic Circuit Elements</u></p>	$Z = j\omega L$	<p>Tang, G. and M. R. Iravani (2005). "Application of a Fault Current Limiter To Minimize Distributed Generation Impact on Coordinated Relay Protection." <u>International Conference on Power Systems Transients (IPST'05) in Montreal, Canada.</u></p>	<p>The nature of the device reduces current by 2-3 times.</p> <p>Well researched has disadvantages like lag pf, V drop. Adv are cheap, low maint.</p>
<p>2. Solid State</p> <p><u>Resonance Based</u></p>			
<p><u>Shunt Type</u></p>		<p>Tang, G. and M. R. Iravani (2005). "Application of a Fault Current Limiter To Minimize Distributed Generation Impact on Coordinated Relay Protection." <u>International Conference on Power Systems Transients (IPST'05) in Montreal, Canada.</u></p>	<p><u>Steady State:</u> Th = OFF, C provides series comp</p> <p><u>Fault State:</u> Th = ON, $Z_L > Z_C =$ Limit current</p> $Z_{FCL(NOR)} = \frac{-j}{\omega C}$ $Z_{FCL(FLT)} = \frac{j\omega L}{1 - \omega^2 LC}$
<p><u>Series Type</u></p>			<p><u>Steady State:</u> Th = OFF, L, C tuned for Z=0 and C provides series comp</p> <p><u>Fault State:</u> Th = ON, C=shorted, L => limit current</p> $Z_{FCL(NOR)} = j\omega L - \frac{j}{\omega C}$ $Z_{FCL(FLT)} = j\omega L$
<p><u>Shunt series</u></p>			<p><u>Steady State:</u> Th = OFF, L, C tuned for Z=0 and C provides series comp</p> <p><u>Fault State:</u> Th = ON, C=shorted, L => limit current</p> $Z_{FCL(NOR)} = j\omega L_1 - \frac{j}{\omega C}$ $Z_{FCL(FLT)} = \frac{j\omega L_2}{1 - \omega^2 L_2 C} + j\omega L_1$
<p><u>LC Res Link</u></p>			<p>Sarmiento, H. G. (2007). <u>A fault current limiter based on an LC resonant circuit: Design, scale model and prototype field tests.</u> Bulk Power System Dynamics and Control - VII.</p> <p>Revitalizing Operational Reliability, 2007 iREP Symposium.</p>
<p><u>Spark Gap</u></p>		<p>Zhang, X. and L. Ming (2008). "Using the Fault Current Limiter With Spark Gap to Reduce Short-Circuit Currents." <u>Power Delivery, IEEE Transactions on 23(1): 506-507.</u></p>	<p><u>Steady State:</u> V_c and $V_{spark} \ll V_{sys}$, No FCL effect</p> <p><u>Fault State:</u> V_c and V_{pri} are high and spark breakdown happens resulting in Eqv ckt shown</p> <p><u>Tested:</u> 46% current reduction</p>

Types of Fault Current limiters



Computer simulated



Field/Lab tested



Field installed & Running


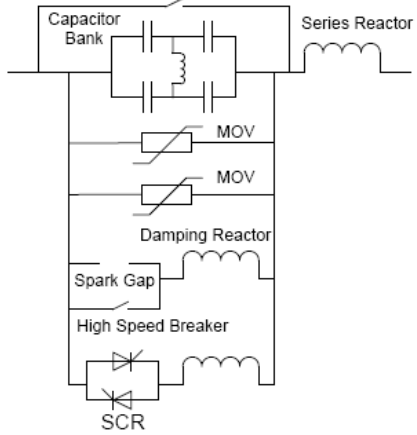


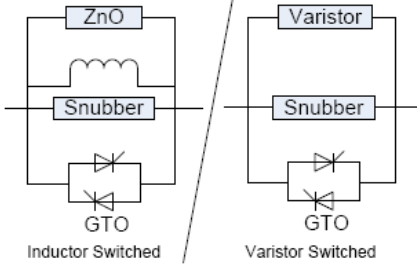
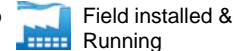
Type of Limiter	Circuit Diagram	Paper appearance	Notes
<p><i>Multi Bypass Series</i></p> 		<p>Wang, H., H. Xi, et al. (2006). Research of Main Circuit on the Series Resonance Fault Current Limiter. Power System Technology, 2006. PowerCon 2006. International Conference on.</p>	<p>Useful for EHV levels because of the sophistication of the device.</p>
<p><u>Impedance switched Bypass</u></p>  		<p>Tang, G. and M. R. Iravani (2005). "Application of a Fault Current Limiter To Minimize Distributed Generation Impact on Coordinated Relay Protection." International Conference on Power Systems Transients (IPST'05) in Montreal, Canada.</p>	<p><u>Steady State:</u> GTO work in alternate half cycle to provide a low impedance path. <u>Fault State:</u> gating signals to the GTO are stopped and L can be seen in the circuit</p>

Figure A.2 Passive and Solid State limiters





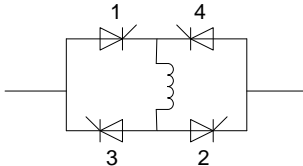

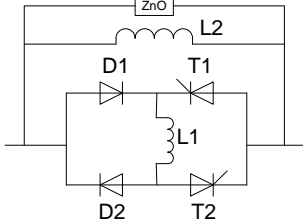

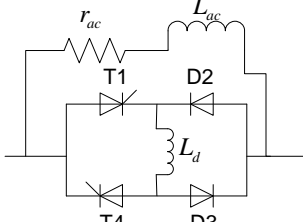

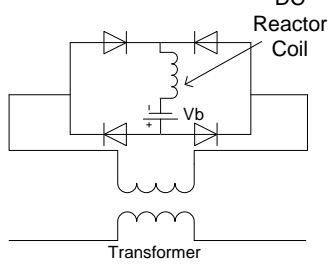

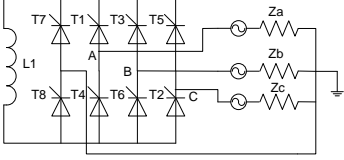
Type of Limiter	Circuit Diagram	References	Notes
<p><u>Bridge Type</u></p> <p><i>Regular</i></p>  		<p>Tang, G. and M. R. Iravani (2005). "Application of a Fault Current Limiter To Minimize Distributed Generation Impact on Coordinated Relay Protection." <u>International Conference on Power Systems Transients (IPST'05) in Montreal, Canada.</u></p>	<p><u>Steady State:</u> All Thyristors are gate on and bias current estb in L <u>Fault State:</u> since I cannot change inst in L, current is limited. At that same time T1 and T3 are switched off so that current can flow out of the inductor through T4 and T2 until fault cleared</p>
<p><i>IGCT</i></p> 	<p>T1, T2 = self turn off IGCT</p> 	<p>Wanmin, F. and Z. Yanli (2006). <u>A novel IGCT-based Half-controlled Bridge Type Fault Current Limiter.</u> Power Electronics and Motion Control Conference, 2006. IPEMC '06. CES/IEEE 5th International.</p>	<p><u>Steady State:</u> All diodes and IGCT are conducting and Bias current estb in L1 <u>Fault State:</u> Switch off T1 and T2, current will flow through D1 and D2 and excess through L2. ZnO is used for overvoltage protection</p>
<p><i>SFCL</i></p> 		<p>Hagh, M. T. and M. Abapour (2006). <u>A New Topology of Fault-current Limiter and its control strategy.</u> SICE-ICASE, 2006. International Joint Conference.</p>	<p><u>Steady State:</u> All diodes and thyristors are conducting and Bias current estb in Ld <u>Fault State:</u> Switch off T1 and T4, current will flow through D2 and D3 and excess through L_{ac} and $r_{ac} \cdot r_{ac} + L_{ac} = Z_{load}$</p>
<p><i>DC Reactor Using HTS</i></p> 		<p>Yamaguchi, M., S. Fukui, et al. (1999). "Performance of DC reactor type fault current limiter using high temperature superconducting coil." <u>Applied Superconductivity, IEEE Transactions on 9(2):</u> 940-943.</p>	<p><u>Steady State:</u> V_b provides the bias current to the reactor which flows through the two loops. All diodes are in conduction <u>Fault State:</u> Load current becomes greater than bias current and two diodes are reversed, switching the fault current to the reactor</p>
		<p>Wanmin, F., L. Zhenyu, et al. (2002). <u>Research of fault-current limiter for three-phase four-wire power system.</u> Power Electronics Specialists Conference, 2002. pesc 02. 2002 IEEE 33rd Annual.</p>	<p><u>Steady State:</u> All 8 thy are gated ON. Reactor current will reach peak load current in some cycles. V drop on L and thy are 0. <u>Fault State:</u> T1-T6 are switched OFF and T7, T8 are on so that the current can freewheel to 0.</p>

Figure A.3 Bridge type limiters



Computer simulated



Field/Lab tested



Field installed & Running


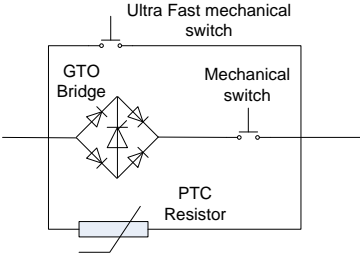

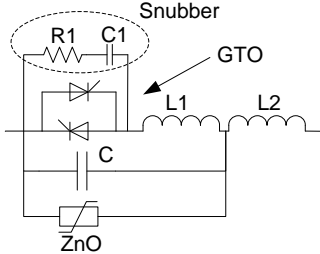


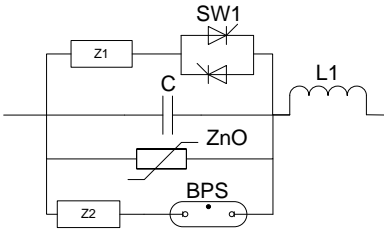


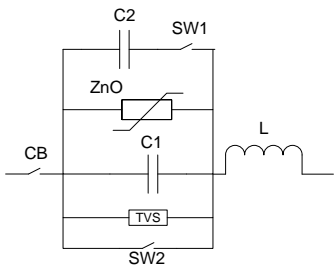
Type of Limiter	Circuit Diagram	References	Notes
<p>3. Hybrid Using Solid State switch/ Mechanical Switch</p> <p>GTO+ Mech SW</p> 		<p>Tang, G. and M. R. Iravani (2005). "Application of a Fault Current Limiter To Minimize Distributed Generation Impact on Coordinated Relay Protection." <u>International Conference on Power Systems Transients (IPST'05) in Montreal, Canada.</u></p>	<p><u>Steady State:</u> All mech. switches and GTO is ON. <u>Fault State:</u> UF mech. Switch opens with μs. After commutation and opening of the top path, GTO are OFF, forcing the current through the RTC resistor. <u>Tested:</u> 15Kv, 1kA steady state current</p>
<p>Series Compensation</p> 		<p>Xingyuan, L., Z. Min, et al. (2002). <u>A novel fault current limiter with series compensation.</u> Power System Technology, 2002. Proceedings. PowerCon 2002. International Conference on.</p>	<p><u>Steady State:</u> GTO is OFF, C carries the current and provides compensation <u>Fault State:</u> GTO turns ON, L1 starts conducting. If L1 and C have proper param., a high Z can be seen in series with L2.</p>
<p>Series Compensation</p>  		<p>Sugimoto, S., J. Kida, et al. (1996). "Principle and characteristics of a fault current limiter with series compensation." <u>Power Delivery. IEEE Transactions on 11(2): 842-847.</u></p>	<p><u>Steady State:</u> SW1 and BPS are OFF, C1 provides series compensation <u>Fault State:</u> SW1 quickly closes forcing the current through its branch and L1 does the current limiting. Z1 is used to limit inrush current. BPS and Z2 act as back up for SW1. ZnO is OV protection <u>Key aspects:</u> used for EHV systems</p>
<p>Triggered Vacuum</p>  		<p>Shi, J., J. Zou, et al. (2000). "Triggered-vacuum switch-based fault-current limiter." <u>Power Engineering Review, IEEE 20(6): 51-53.</u></p>	<p><u>Steady State:</u> TVS and SW2 are OFF. <u>Fault State:</u> TVS will turn ON and bypass C1 and L will limit current. ZnO is used for OV protection and C2 and SW1 act as series compensation <u>Key aspects:</u> TVS based devices available for EHV systems and the technology is reliable and fast to operate</p>

Figure A.4 Hybrid limiters

Appendix: B PSCAD[®] implementation of FCL – 1

This Appendix consists of the PSCAD[®] implementation of the superconducting FCL-1 model as delineated in Chapter 3, Section 3.2.

A. Overall FCL Model (Ref: Section 3.2)

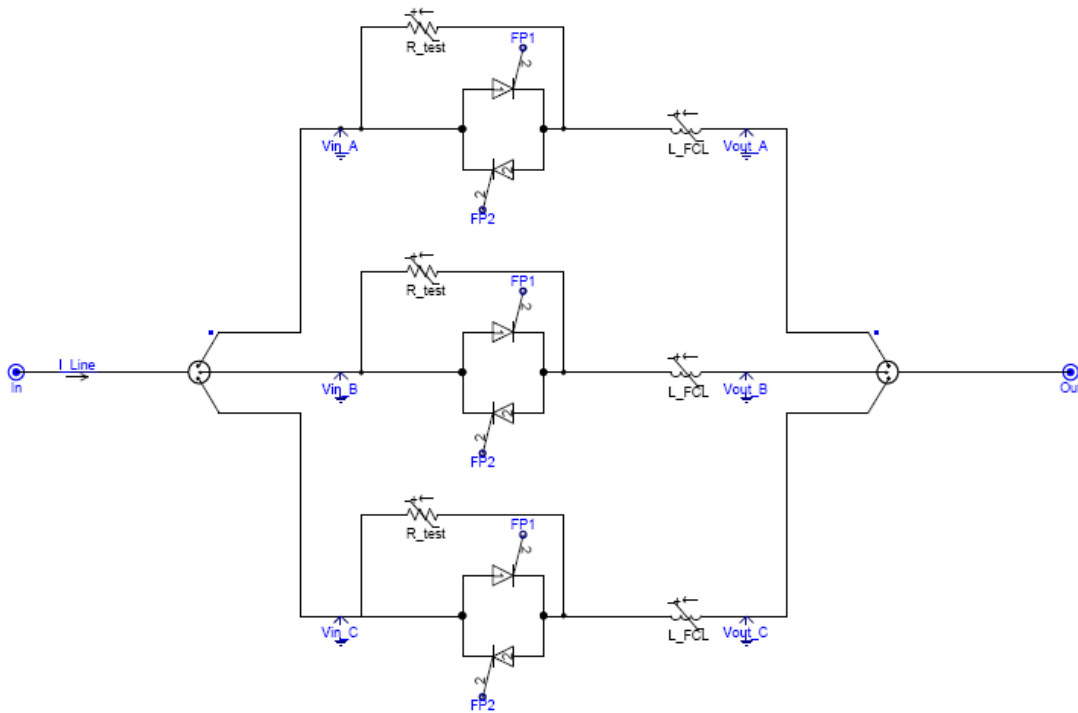


Figure B.1 PSCAD[®] FCL-1 Model (3-phase shown)

B. PSCAD implementation of component A (Ref: Section 3.2.3)

Shown below is just Phase A implementation. Phase B and C are same as A.

2. Monitor Magnitude



3. Monitor rate di/dt



4. Check for Current magnitude



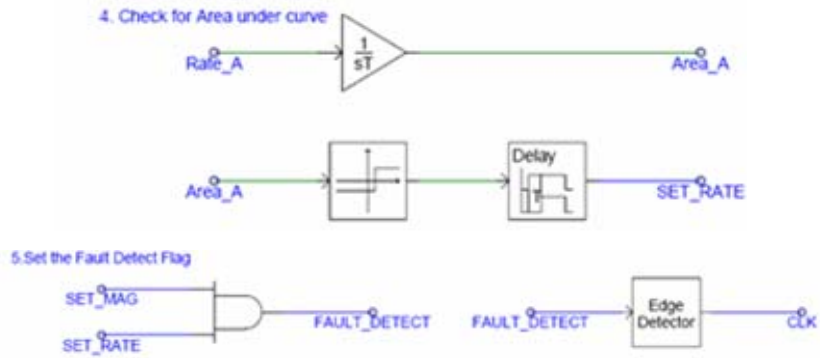


Figure B.2 Fault detection control

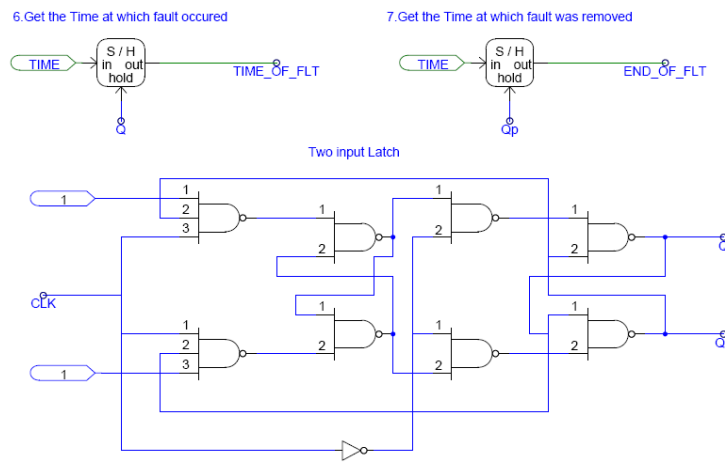


Figure B.3 Simulation time extraction for impedance ramping

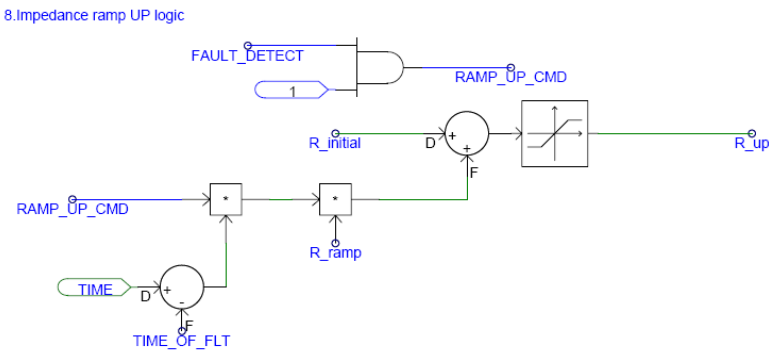


Figure B.4 Variable impedance (Component A) ramping UP control

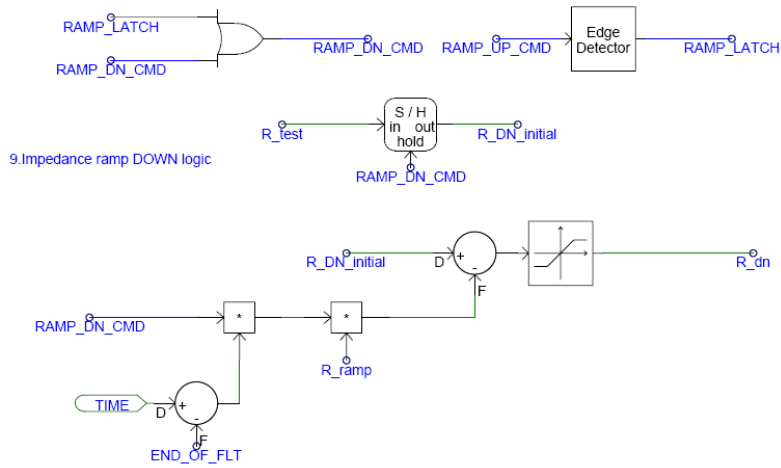


Figure B.5 Variable impedance (Component A) ramping DOWN control

10. Final impedance reference to the SFCL

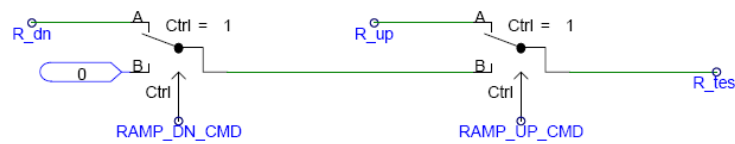


Figure B.6 Final reference to the variable impedance (Component A)

C. PSCAD implementation of component B (Ref: Section 3.2.4)

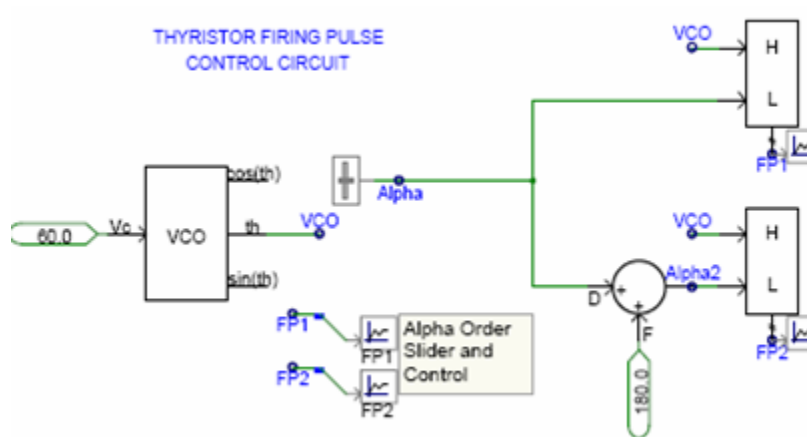


Figure B.7 Thyristor Firing Control (Courtesy: PSCAD®)

D. PSCAD implementation for fault insertion (applicable to all simulation studies)

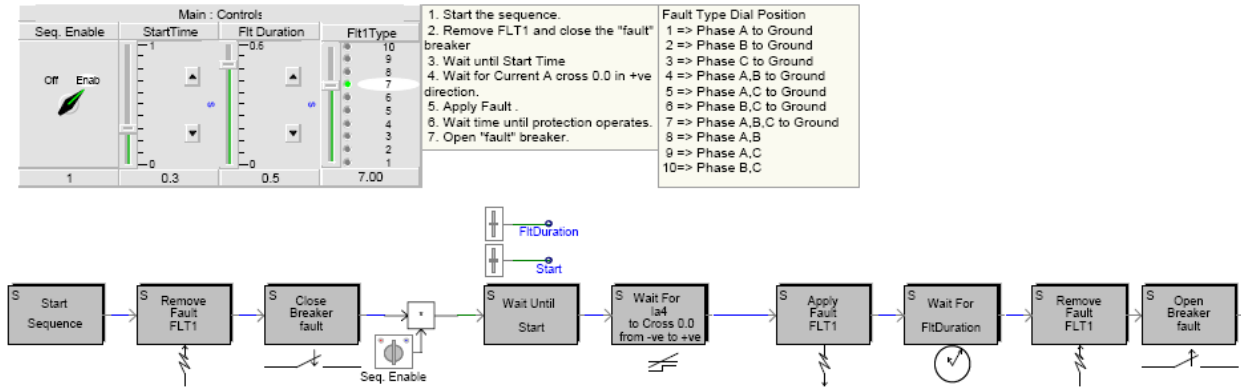


Figure B.8 Fault insertion control (Adapted from PSCAD® Master Library)

E. PSCAD implementation for Case study 3 (Ref: Section 4.4)

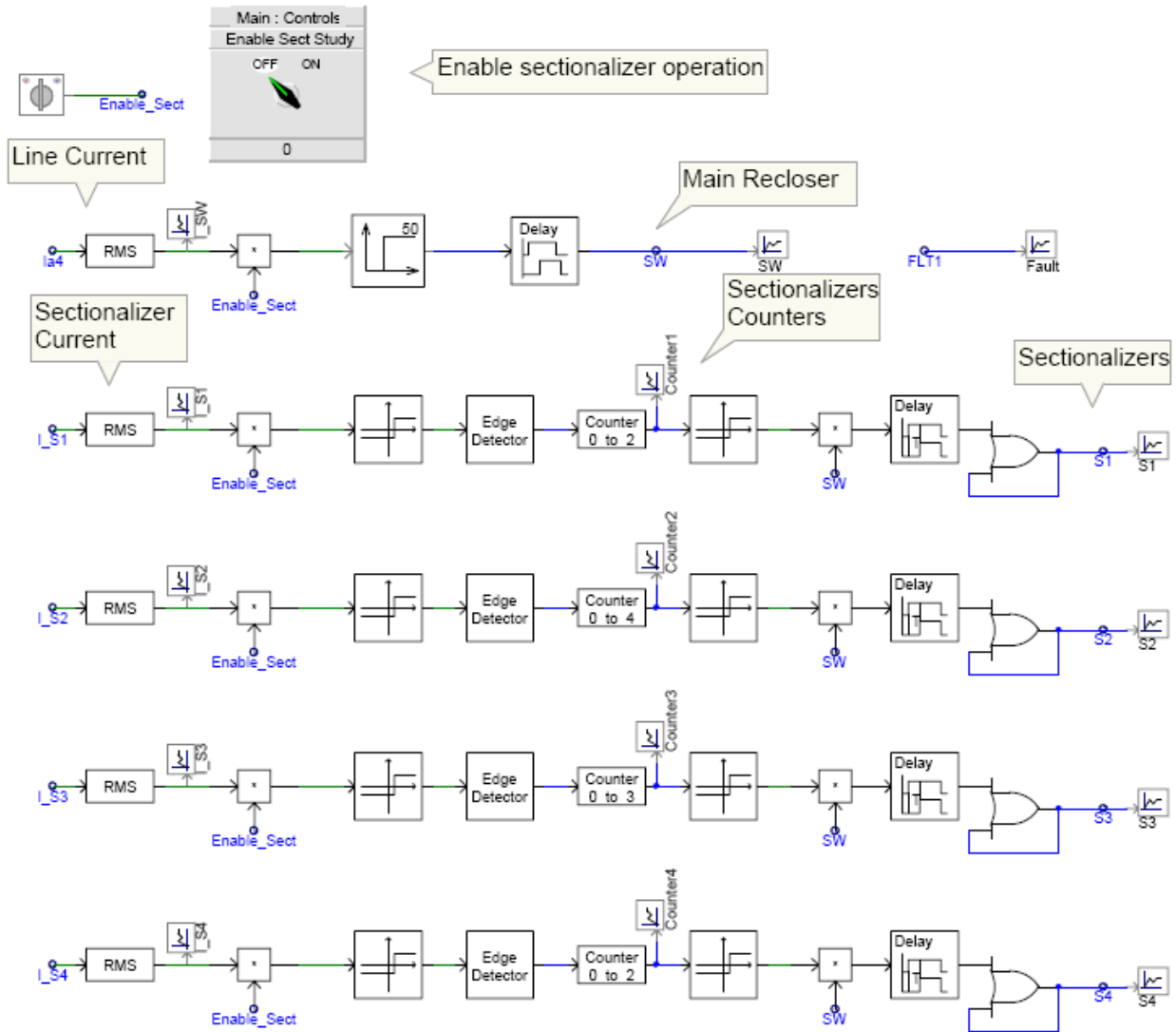


Figure B.9 Sectionalizer control and coordination

Appendix: C PSCAD[®] implementation of FCL – 2

This Appendix consists of the PSCAD[®] implementation of the solid-state FCL-2 model as delineated in Chapter 3, Section 3.3.

A. Overall FCL Model (Ref: Section 3.3)

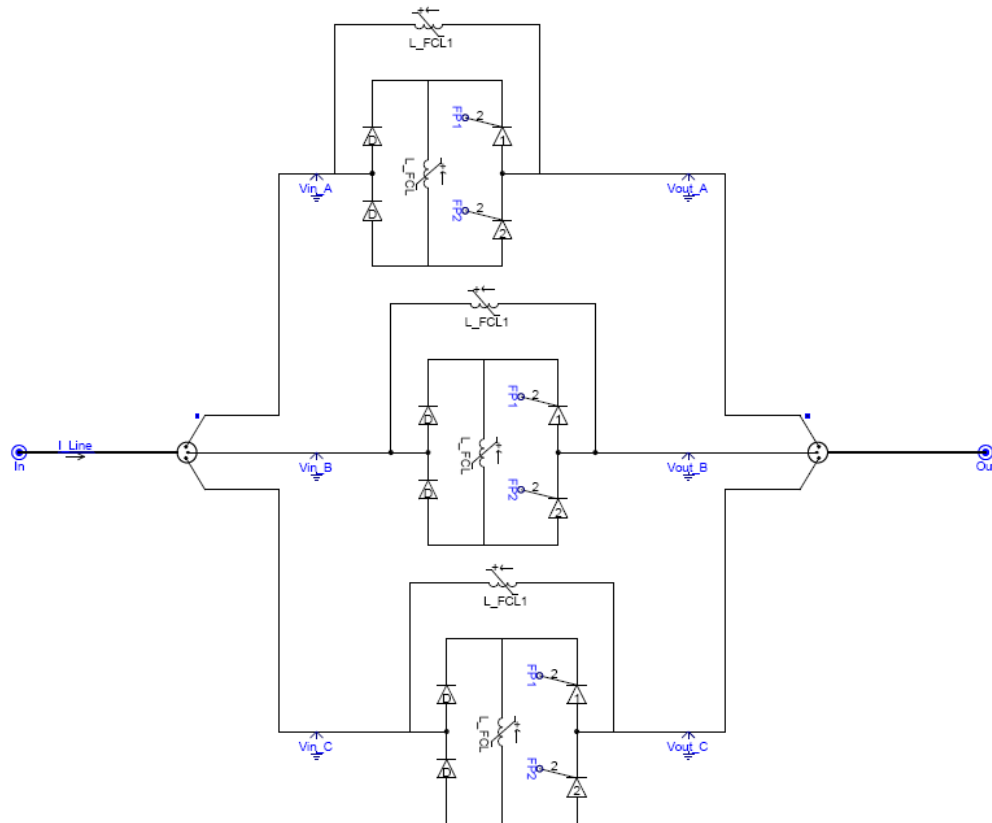


Figure C.1 PSCAD[®] FCL-2 Model (3-phase shown)

B. PSCAD implementation of power electronic switches

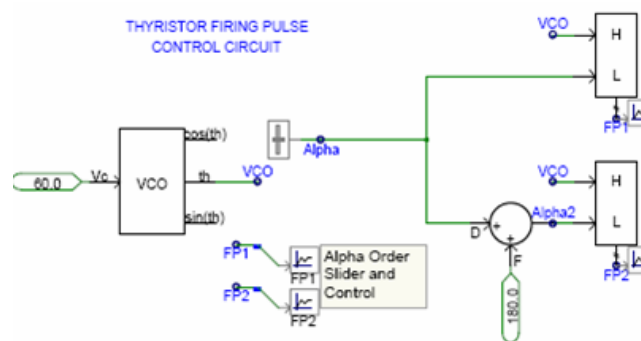


Figure C.2 Switch Firing Control (Courtesy PSCAD[®])

Appendix: D PSCAD[®] implementation of FCL – 3

This Appendix consists of the PSCAD[®] implementation of the Hybrid limiter FCL-3 model as delineated in Chapter 3, Section 3.4.

A. Overall FCL Model (Ref: Section 3.4)

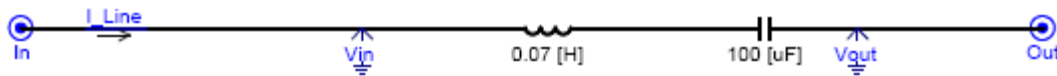


Figure D.1 PSCAD[®] FCL-3 Model (3-phase, bold line indicates three phase)

B. Rate of change of current monitoring

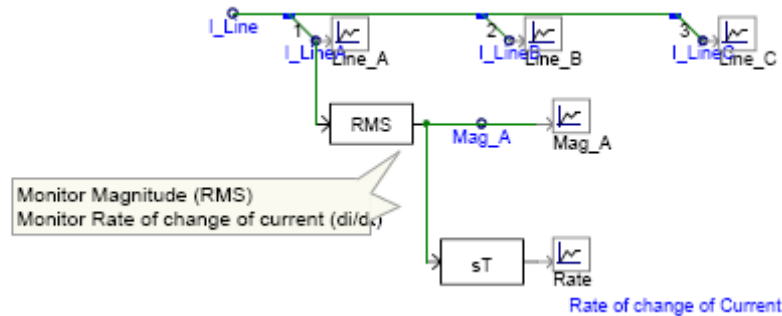


Figure D.2 Logic to monitor rate of change of current

C. Voltage difference waveforms monitoring (applicable to all FCL(s))

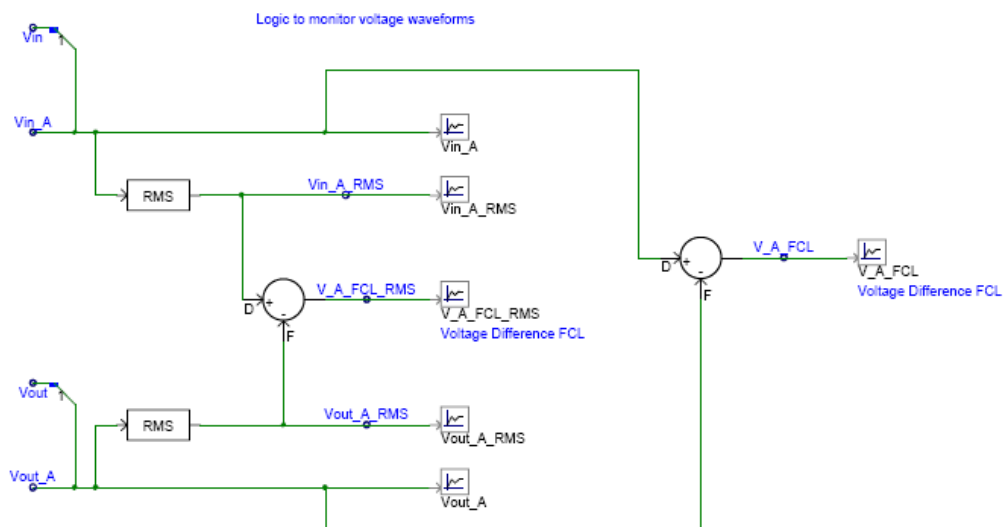


Figure D.3 Logic to monitor voltage waveforms

Appendix: E Utility survey

Company Name	Fault Protection and Sensor Technologies	Fault Location and SCADA Technologies	Other Technologies/ Future Work
Con Edision Company of New York		Using advanced fault locating software throughout the medium voltage distribution feeders and developing significant enhancements and extensions	
Aclara Technologies of ESCO	<p>The TWACS communication technology, which uses the electric energy delivery network as its physical communication medium, is currently used by many utilities for Automatic Meter Reading and other utility functions and has the following unique characteristics: 1) All electric metering transponders can be reached by the TWACS communication system. 2) The TWACS communication path to the customer premises is the same as the phase, feeder, and bus serving the feeder electric energy delivery path to the customer premises. Hence an outage at the customer also de-energizes the metering transponder and the transponder cannot respond to an outbound command. 3) These characteristic features can be used to identify outages. Transponders responding to polling commands are assumed connected to an energized part of the electric circuit. The ones which do not respond are assumed to be connected to part of the circuit that is de-energized. This isolation is due to the disconnecting action of a protective device. 4) The protective device works in a selective coordinated fashion with other protective devices following a hierarchical order. This method is used by utilities to isolate faults and to minimize the effects of a fault on the total network. 5) By selecting a few metering transponders beyond each protective device for polling, the outage mapping function can be accomplished through TWACS communication and polling.</p>		<p>Provide automatic fault location for distribution systems</p> <ul style="list-style-type: none"> o Identify 100% of solid faults (i.e. the vast majority of all main line faults) o Provide advanced monitoring applications/diagnostics to assess outages/faults and geographically map such events to show the extent of an outage. • A device which continuously monitors all currents for all phases at all feeders and provides intelligence to capture a fault and identify the feeder and phase(s) where the fault occurs. o The System will be able to detect any solid fault that causes a protective device on the medium voltage to trip. This would include down to a low-voltage fault that would cause the high-side fuse of the service transformer to blow. • Autonomous notification to the Master Station System to start Polling to quickly identify outages. o The System will generate alarm messages that identify the specific feeder and phase(s). These alarms will trigger the System to ping to a canned group of meters for each feeder/phase identified in the alarm message. • The overall time required to complete the outage assessment is expected to be within two to three minutes, depending on the system configuration and size. • Additional desirable Goals / Next Phase o Identify network switching events and autonomously update the system's communication path to all affected end-points (meters).
Gujarat Energy Transmission Corporation		<p>1) On 11 KV Distribution systems we use vacuum circuit breakers for fault interrupter. We do not use fault current limiters on 11 KV systems. The old electrometrical relays are being replaced by numerical relays which record the fault current of the circuit. Communicating protective relays & advanced fault locator are still not adopted.</p> <p>2) For 66/132/220/400 KV transmission systems, numerical relays with fault locator are being adopted by M/s GETCO which has facility of disturbance recording for fault analysis. We are using equipment diagnostic kits for power factor measurement of transformers & C.T's & P.T's, Circuit breaker analyzer, Thermo vision camera, Leakage current monitoring of L.As, Sweep frequency response analysis etc. for condition monitoring of EHV class equipments</p>	
Alliant Energy - Interstate Power & Light Co	Not Doing any Research	Not Doing any Research	Not Doing any Research

Company Name	Fault Protection and Sensor Technologies	Fault Location and SCADA Technologies	Other Technologies/ Future Work
Consumers Energy	<p>1) <u>Advanced protection for distribution systems</u>: No projects currently.</p> <p>2) <u>Integration of adaptive protection with distribution automation</u>: <u>Project</u>: We do not presently have a project to automatically locate faults on the distribution system but we have been using a manual process on both our distribution and sub-transmission systems with very promising results. We have had preliminary talks with personnel at Progress Energy on what they are doing on this topic and are planning on having follow-up discussions. <u>Products</u>: MehtaTech digital fault recorder, SEL relays, Cooper Form 6 (and earlier) and GridSense LineTrackers.</p> <p>3) <u>Communication approaches for monitoring systems and/or protection system implementation</u>: <u>Project</u>: Our communications plan is to leverage the AMI communications infrastructure as much as possible for use with the Smart grid. <u>Products</u>: We are testing several of the major AMI meter manufacturer's system and also looking at alternative communications backhaul using various communications options such as cellular, BPL and WiMax.</p>	<p>1) <u>Advanced data management and data processing for distribution monitoring systems, especially related to disturbance monitoring for fault location, fault prediction, and equipment diagnostics</u>: <u>Project</u>: We are still in the process of getting automated data collection installed and still using manual data collection/management/processing. As we expand our data collection capabilities we will need to implement more advanced systems, this is on our radar screen and will be addressed at the appropriate time.</p> <p>2) <u>Data warehousing of circuit information for advanced monitoring applications</u>: <u>Project</u>: We have just implemented several of the SAP suite of applications along with a new SCADA, OMS and GIS system. We are still in the process of optimizing these systems and are planning on integrating the AMI/SG data into them. In addition, we have taken a preliminary look at some of the Distribution Management Systems that are available and are planning on evaluating these in the near future. <u>Products</u>: The vendor that we are using for the AMI data warehousing is OSIssoft and we will be following up with them to try and integrate their system with our SCADA and OMS systems. We have also been participating in AMI@SAP.</p>	<p>1) <u>Sensors for monitoring on distribution systems</u>: <u>Project</u>: As part of our AMI pilots, we are looking at installing some additional line monitoring to assist in determining system losses (both technical and nontechnical). The issue that we are having is that for determining losses we will need to have monitoring devices that are capable of metering accuracy. Most of the devices that we presently have out there are relay accuracy or less. <u>Products</u>: Presently we are using substation protective device controls (SEL & Cooper) along with devices (LT40 LineTrackers from GridSense) out on the distribution lines. For our sub-transmission system we use MehtaTech digital fault recorders. We are also looking into MetPOD from FieldMetrics for both substation exit and line monitoring.</p> <p>2) <u>Sensors for fault indication or fault location</u>: <u>Project</u>: We have mostly installed multi-functional sensors that are capable of determining several system conditions (voltage, load current, fault current, power factor, etc.) and as such monitoring and fault indicating would be one and the same.</p>
Hydro-Quebec Distribution	<p>Hydro-Québec will start a joint study (fall 2008) with an equipment manufacturer to evaluate how the new protection technologies can be applied to the distribution system to improve actual protection schemes. This work will involve new MV equipment concept and new protection logic possible through the latest protection controllers. First results to be available in 2009/2010. Some possibilities to detect high impedance faults are available in newest generation of substation numerical protection relays. Although the project is not yet structured, Hydro-Québec may want to try this feature to evaluate how it performs. There is no schedule yet for this one.</p>	<p>Hydro-Québec has its own fault location project based on voltage signature from dispersed monitors. This innovative approach to locate faults is made through a Voltage Drop-based Fault Location (VDFL) technique using remote power-quality measurement devices. This technique accurately locate faults on feeders using few decentralized PQ sensors (3 to 5 per feeders), providing voltage drops signatures, that could be already be part of another system such as Advanced Distribution Automation or Automatic Metering Infrastructure. VFDL is a good example of integrating an application into these advanced system at low cost. A collaboration has been agreed between EPRI and Hydro-Québec on this project. Tests are being made in Québec and in the USA combining Hydro-Québec's and EPRI's approaches on fault location. First results to be available in 2009.</p>	<p><u>Data Management</u>: Nowadays, several manufacturers offer intelligent electronic devices (IED) or intelligent controllers to improve network performance. In order to achieve these goals, the actual distribution system infrastructure (especially remotely controlled IED) shall be used to gather as much information as possible related to network, equipment and product (i.e. power quality) to improve the distribution system overall performance. Hydro-Québec is conducting several projects to qualify and quantify the type of data that can be gathered from major distribution equipment including substation digital protection relays and Distribution reclosers. A paper was presented at the IEEE /PES GM in 2008.</p> <p><u>Telecommunications</u>: A study by Hydro-Québec's Telecommunication department is undergoing to evaluate the most appropriate telecommunication technologies to apply to the several Distribution automation applications in the Québec's telecommunication environment.</p>
Energy and Environmental Economics, Inc	<p>Their Response consists of a 127 page PDF titled "Value of Distribution Automation Applications" submitted to the California Energy Commission (CEC)</p>	<p>Their Response consists of a 127 page PDF titled "Value of Distribution Automation Applications" submitted to the California Energy Commission (CEC)</p>	<p>Their Response consists of a 127 page PDF titled "Value of Distribution Automation Applications" submitted to the California Energy Commission (CEC)</p>

Company Name	Fault Protection and Sensor Technologies	Fault Location and SCADA Technologies	Other Technologies/ Future Work
Southern Company/ Alabama Power Co	<p><u>Advanced protection for distribution systems:</u> 1) The IDMS Short Circuit Analysis application will calculate on a real-time basis the maximum short circuit current available for a phase to ground or phase to phase fault at any point modeled in the electric distribution system. 2) The IDMS Short Circuit Protection Coordination application checks coordination of protective devices with the next upstream protective device.</p> <p><u>Integration of adaptive protection with distribution automation:</u> In the Distribution SCADA/Distribution Automation initiatives, APC utilizes micro-processor based protection relays to manage the protection and coordination of the electric distribution circuits. The IDMS short circuit analysis and protection coordination tools will support adaptive relay setting changes to ensure effective coordination of the electric distribution circuit as the circuit configuration dynamically changes</p> <p><u>Sensors for fault indication or fault location:</u> In the Distribution SCADA/Distribution Automation initiatives, APC utilizes Distribution Line-Post Sensors for Distribution line fault detection. A fault condition is reported on a per phase basis when line current exceeds a pre-set magnitude threshold for a pre-set duration of time.</p>	<p><u>Automatic fault location for distribution systems:</u> Fault location is a future application development initiative for the SoCo/APC IDMS project. The initial approach will be to utilize data from digital relays that are being installed on APC's electric distribution feeder breakers and line reclosers.</p> <p><u>Other advanced monitoring applications, such as equipment diagnostics based on monitoring:</u> 1) The SoCo/APC IDMS Unbalanced Load Flow analysis will be utilized to determine the power measurement parameters at each point modeled in the electric distribution system and to identify line and equipment overloads. 2) The SoCo/APC IDMS Optimal Volt/Var Loss Management application recommends circuit reconfiguration to reduce distribution losses by a quantifiable amount with the capability, if enabled, direct Distribution SCADA control actions to controlled devices to achieve the recommended configuration. 3) The SoCo/APC IDMS Power Quality application utilizes harmonic content measurements to identify potential circuit conditions such as voltage distortion in excess of IEEE 519 limits, blowing of capacitors from excess current due to harmonic current flow, conductor overload, voltage unbalance, etc. 4) The SoCo/APC IDMS Contingency Analysis application analyzes various single contingencies based on the present state to determine if the contingencies can be remedied or if there will be loss of customer service for a substantial period of time.</p>	<p><u>Communication approaches for monitoring systems and/or protection system implementation:</u> In the Distribution SCADA/Distribution Automation initiatives, APC utilizes MAS Communications (licensed 952-926 MHz radio system) to support deterministic system-wide communications with distribution substations and distribution line devices</p> <p><u>Advanced data management and data processing for distribution monitoring systems, especially related to disturbance monitoring for fault location, fault prediction, and equipment diagnostics:</u> The SoCo/APC Distribution Feeder Fault Anticipation project is an EPRI-sponsored multi-year project that is conducted by Texas A&M, and utilizes digital monitoring to anticipate failures and faults before they cause outages or other reliability problems in the electric distribution system</p> <p><u>Data warehousing of circuit information for advanced monitoring applications:</u> The SoCo/APC IDMS Data Archiving will support future data mining techniques to effectively manage, verify and quantify the benefits of the future Green Circuits</p> <p><u>Sensors for monitoring on distribution systems:</u> In the Distribution SCADA/Distribution Automation initiatives, APC utilizes Distribution Line-Post Sensors for Distribution line fault detection. The line-post sensor facilitates detection per phase line voltage, current, Megawatts and Megavars. The sensor outputs are used to calculate MVA and power factor on a per phase basis.</p>
CANMET Energy Technology	<p>Implementation of advanced fault detection technologies, in the context of advanced distribution system protection with DG. It will assess whether special consideration is required when implementing advanced protection technologies into systems with DG as well as how multi-functional relays can be used to facilitate the integration of DG, particularly when there are a number of DG on a given feeder. As the first stage, we have proposed to partner with ENMAX and analyze the impact of DG on their IntelliRuptor system.</p>	<p>Advanced fault location technologies have shown promising initial results, enabling location of faults to within 100's of meters, even on lines of greater than 20 km. However, the impact of DG on the accuracy of these methods has yet to be determined. In this project, it is proposed to partner with Hydro-Quebec and investigate how DG could impact their fault location approach. If complications are encountered the development of mitigating solutions will be pursued.</p>	
CPS Energy		<p><u>Automatic fault location for distribution systems:</u> The Distribution Management System (DMS) has a fault location application that is integrated with the distribution system Supervisory Control & Data Acquisition (SCADA), but it is currently being used in the manual method until it can be automated. Microprocessor (i.e. SEL) relays are required to determine an expected distance from the source, but fault current is retrieved when necessary and then CYME studies are run to determine approximate location. This is predominately a manual process.</p> <p><u>Other advanced monitoring applications, such as equipment diagnostics based on monitoring:</u> By the second quarter of 2009, the DMS SCADA system will monitor all distribution Intelligent Electronic Devices (IED's) such as reclosers, switches, capacitor banks, and voltage regulators. The DMS will monitor status values such as open, close, and alarms; analog values such as voltage, current, watts, Vars, and VA; and remote control.</p>	<p><u>Communication approaches for monitoring systems and/or protection system implementation:</u> A licensed and unlicensed radio system is used for communicating with IED's. CPS Energy is researching other communications options.</p> <p><u>Data warehousing of circuit information for advanced monitoring applications:</u> CPS Energy is using OSI Soft Inc. PI Processbook and PI DataLink for data warehousing of circuit information.</p> <p><u>Sensors for monitoring on distribution systems:</u> Reclosers and motorized gang operated switches will monitor current and voltage levels. Power Quality meters will monitor feeders. Manual fault locators are placed on circuits suspected of having problems.</p>

Company Name	Fault Protection and Sensor Technologies	Fault Location and SCADA Technologies	Other Technologies/ Future Work
Center Point Energy	<p><u>Advanced protection of distribution systems:</u> We have improved fault detection and better coordination using microprocessor based feeder breaker relays. We have attempted fault location but had mixed results.</p> <p><u>Integration of adaptive protection with distribution automation:</u> We have piloted this type of protection, but do not have it system wide.</p>	Not Doing any Research	<p><u>Sensors for monitoring on distribution systems:</u> Tried Lyndsey current/voltage sensors</p> <p><u>Sensors for fault indication or fault location:</u> Tried Lyndsey current/voltage sensors</p>
San Diego Gas and Electric	<p><u>Advanced protection of distribution systems:</u> SDG&E is developing protection schemes required to protect the integrity of the Western Interconnection. Remedial Action Scheme (RAS) devices are in place and are currently being tested. Each scheme has specific requirements related to timing and back up power supplies and redundant protection. In addition, SDG&E has an additional scheme known as Overload Scheme (OLS), which is used for local SDG&E area grid protection. SDG&E has been replacing obsolete electromechanical relays with modern microprocessor based relays. In 2005, a project was initiated to replace the obsolete relays on the transmission lines based on reliability, failure rate, parts, and maintenance issues. So far, 40% of obsolete relays have been replaced with the microprocessor relays.</p> <p><u>Integration of adaptive protection with distribution automation:</u> SDG&E has installed a decentralized application of Feeder Automation System Technology (FAST) in 2007. FAST is an automatic switching scheme that will restore service following an outage event. This approach uses a switching logic programmed in the controller of the centrally located SCADA Master. Upon a system disturbance, a master system takes information from the remote site, such as analog voltage/current and status indications/alarms, and will perform the appropriate action.</p> <p><u>Sensors for monitoring on distribution systems:</u> SDG&E is installing fiber optic cables with the power conductors to transmit real time temperature data which will be used to calculate a real time ampacity for the conductors. This will allow for maximum equipment utilization, static, and ultimately, dynamic ratings for conductors. New hardware and software technology is being developed to measure the condition and performance of distribution equipment. This technology is utilizing sensors to provide diagnostic information to facilitate increase capacity utilization of transformers. SDG&E has installed power quality instruments in substations to collect data and monitor disturbances in the system. These instruments will provide information to indicate a fault and potentially have a way to anticipate a fault by identifying short duration faults in the system. SDG&E is currently targeting the installation of 1.5 field SCADA devices on every 12 kV circuit. Typically, 1.5 switches per circuit is comprised of a mid-point SCADA switch, and a SCADA tie switch that is shared with an adjacent circuit.</p>	<p><u>Automatic fault location for distribution systems:</u> Under the Advanced Metering Infrastructure (AMI) program, SDG&E will be installing smart meters that will interface with the outage management system (OMS) to use real time and historical information, including last gasp notification, to precisely assess an outage size and location. There are many events that occur in the system that are not faults but are picked up by power quality instruments. Those specific events are being examined and researched in the goal of fault anticipation. SDG&E is researching the characteristics of a fault that last for two or less transient cycles and developing an algorithm to correlate that location as a possible prediction of a future fault.</p> <p><u>Other advanced monitoring applications, such as equipment diagnostics based on monitoring:</u> Under the Condition Based Maintenance (CBM) program, SDG&E is developing hardware and software technologies that will measure the condition and performance of transformers and circuit breakers in T&D substations to make better maintenance decisions. Diagnostic analytics will be used to detect potential problems before they occur. SDG&E is working with a company in a pilot project to detect electromagnetic emissions or failure signatures caused by arcing in faulty equipment on the distribution system. The instrument detects an arc source and captures data that is analyzed to identify equipment that may potentially fail in the near future. Testing and data gathering has been conducted and locations of potentially faulty equipment have been identified. SDG&E is investigating the locations and evaluating the cost effectiveness and reliability of this equipment and the associated data analysis methods.</p>	<p><u>Communication approaches for monitoring systems and/or protection system implementation:</u> SDG&E is installing a pilot project in 2008 with a scope of 5000 Smart Meters in a particular community. In residential communities, the smart meters can communicate the location of a fault faster than the current "call in" method where SCADA is not present. Smart meters will also have the ability to communicate with SDG&E its time based energy consumption and demand data which can be utilized to monitor system demand and resource availability. SDG&E uses SCADA that has a communication infrastructure that operates on a 900MHz channel. A SCADA switch would send status and analog data to the remote terminal unit (RTUs), which then converts the data to digital data, and sends it to the supervisory control station via a 900MHz channel. In return, the supervisory station is capable of communicating control commands to the SCADA switch via the same medium.</p> <p><u>Advanced data management and data processing for distribution monitoring systems, especially related to disturbance monitoring for fault location, fault prediction from PQ instruments to predict future faults by analyzing patterns of events leading up to a fault.</u> The data is loaded into an application developed by SDG&E and EPRI to perform applications such as coding system disturbances, analyzing specific customer/system issues when prompted by a user, identifying and supporting additional monitoring sites, and generating a monthly and yearly analysis of the distribution system performance. SDG&E is developing a new OMS/DMS tool that will provide more detailed information about customers affected by outages and automatically calculate reliability statistics for the outage. The new OMS will be capable of interfacing with smart meters to utilize real time and historical information to precisely assess outage size and location. This will expedite the determination of outage causes and eliminate the confusion that arises when multiple faults occur. The new DMS tool will allow scenario analysis, and it will generate switching orders to support planned or unplanned outages.</p>

Company Name	Fault Protection and Sensor Technologies	Fault Location and SCADA Technologies	Other Technologies/ Future Work
American Electric Power	<p><u>Integration of adaptive protection with distribution automation.</u> Pilot projects are proceeding in decentralized and distributed intelligence systems that enable fault isolation and restoration to alternative sources based on available system capacity. S&C IntelliTeam with Scada-mate switches and Cooper Cybectech SMP controllers with reclosers are the DA focus areas at this time. Centralized DA control/overlay is also being studied for potential DA application and enhancement. All DA schemes have the requirement of interfacing with SCADA.</p>	<p><u>Automatic fault location for distribution systems.</u> AMI interface to outage engine, monitoring to enable the following real-time SCADA information: <u>Other advanced monitoring applications, such as equipment diagnostics based on monitoring.</u> GE M2 Hydran monitors being installed on select transformers + temperature monitoring to enable the following real-time SCADA information: Fault Gas reading (H₂, CO, etc.). Moisture in oil, top oil temperature, winding current reading – all three phases, winding hot spot reading – all three phases, insulation aging – all three phases, moisture content of cellulose winding insulation, bubbling temperature of insulating oil.</p>	<p><u>Communication approaches for monitoring systems and/or protection system implementation.</u> 900 MHz Spread Spectrum radio systems interfacing with SCADA</p> <p>Mesh networks and directional communication schemes with preference for mesh dynamic routing. <u>Data warehousing of circuit information for advanced monitoring applications</u></p> <p>Utilization of AMI products for time interval loading and voltage information as well as momentary/sustained outage reporting</p> <p>Storage of this information for circuit studies and importing into various applications. <u>Sensors for monitoring on distribution systems</u> Remote monitoring and control of distribution capacitors - radio or digital cellular communications. <u>Sensors for fault indication or fault location.</u> Fault detection devices manufactured by Cooper Power Systems and Schweitzer are in the process of being field tested. Fault indication is provided via digital cellular interface.</p>

Figure E.1 Table of industry survey responses