Chapter.1
FAULT CURRENT MITIGATION

1-1 Introduction

Distribution systems are vital parts of the electrical power system studies. The majority of the distribution systems all over the world operate in a radial topology, which is a single power source feeds loads. This topology is very simple and their protection schemes are well understood. But due to the continuous growth of economic and development, the society should meet the rising power demand of the modern life. So, installed capacities of generation systems are increasing continuously, which result in gradually increase in number of independent power resources called Distributed Generation (DG). Besides that DG may be a one of the main solutions to decrease level of CO_2 in the air and its related pollution.

But DGs presence in the structure of distribution network is not without problems because the distribution grid structure is made more interconnected and then current flowing in the two directions [1]. A more connected power system means a stiff source with very high fault current capacity, which causes difficult network's operation and control that reduces reliability of a network [2]. Also, the grid sometimes operates near to its limits and then, with DG integrated with the grid, the fault current levels will overshoot the limits on several equipment like bus-bars, circuit breakers (CBs), and transformers which have to be replaced or at least upgraded. Otherwise, there is will be a growing in the frequency of fault occurrence and fault severity due to fault levels increasing [3].

In general, Faults in electrical power grids are uncontrollable events that happen due to two main reasons [4]: 1– Faults due to old age elements failures.

2–Faults due to grid external factors such as system overloading, winter lightning, or digging through power cables.

Faults have a great concern in power system studies ,due to it cause very high electrical currents which cause extra thermal stresses, electrical stresses and mechanical stresses on distribution power system equipment [4].

While fault duration, re-closer have to be closed to limit the fault risk of exceeding mechanical stress. Also, normally closed CB have to be opened with switchgear. Noticing that there is a severe risks on personnel if switchgear opening action fails during switching action [4].

So, a high fault level is undesirable only if the fault level is larger than the installed equipment's rating, which leads the protective devices to work wrongly and causes a transient faults to be changed into a permanent faults. This problem

impacts especially the circuit breakers because their interruption capacities are limited.

Then existed equipments in the interconnected system need to be protected against the short circuit currents and, in the same time, maintain an acceptable reliability level of the system [5].

Engineers all over the world have developed many detect fault currents schemes to activate isolation devices like CBs that interrupt the over-current amounts with a sufficiently rapid time before over-current amounts damage any part of the power grid. While these detect fault currents' schemes are effective, the levels of fault current increase gradually and exceed the interruption capabilities of the existing power system devices. This situation requires a fault level management against dangers of the occurred fault [6] .

There are two main fault current mitigation strategies, passive strategy and active strategy. Traditionally, the utilities have been using bus and grid splitting, high impedance transformers and current limiting reactors to maintain the acceptable values of fault currents. But the traditional mitigating devices remain in operation even during normal grid conditions, so they are a passive devices that have a fixed impedance on the grid, and therefore they are more power energy intensive and so reduces the system efficiency and stability [5].

This drawback can be avoided by using active or controlled mitigating devices.

The active fault current mitigating devices offer low impedance during normal operating conditions and during fault conditions it rapidly transit to high impedance state. So they have minimal losses because they are transparent to the system in normal conditions but they operate during fault only [6].

To decide an optimal effective mean of fault level management technique to be used for a specific power grid, a detailed study of some quantify parameters for the various options may be completed to compare the different solutions each to others from the financial and the operational perspectives, on the existing power grids. Also the energy loss and its cost has to be discussed in the detailed study for making a practical decision. However, This obtained conclusion could then determine the suitable fault current management method in that specific utility , but this obtained conclusion may not applicable for other grids [6].

While conventional fault current limiting techniques are assumed as passive techniques which are generally introduce additional costs on power system quality, operational complexity, stability, security of supply and reliability [4]. But it still applicable to be used in some cases, so they will be discussed in the

following section of the chapter beside discuss the concepts of DG and modern fault current limiting techniques called Fault Current Limiter (FCL).

1-2 Distributed generation

The maximum fault current tends to increase in a system for many reasons including the distributed generation sources which are added to an already existed system to accommodate with the power demand of load growth [7].

DG sources may be a mini turbines, wind farms, solar panels, or fuel cells up to 50MW [8] , and its major customers' applications are:

- Allowing customers to generate their own electricity continuously with all load operation periods,
- Improving system power reliability and quality by using DG to back up the main grid source,
- Reducing the amount of electricity purchased from the main grid during peak price periods, by generating a portion of electricity on site.
- Selling excess generation back onto the main grid when DG own loads are low, and
- Meeting all power needs of the customer's residential demand.

So, Egypt government welcomed the Japan's cooperation agency assistance in development of the renewable energy field for increasing the Egyptian renewable energy production to 20% of the total Egyptian power production by 2022 [9] & [10].

However, various studies have demonstrated that integration of DG in to existed distribution networks may create problems [11]which may lead to frequent power outages and then a customer dissatisfaction as a side-effect [12]. So, different utility protection aspects have to be carefully studied such as internal faults of the generation sources; fault currents supplied by the DGs; anti-islanding [13] [14] [15], and DG effects on already existing devices. Therefore all of these aspects are need to be carefully addressed when connecting DG to distribution networks.

Also, distribution systems are designed to have low impedances between generation and loads. So, this low interconnection impedance cause a high fault levels up to 20 times of system normal current. So, it is important for both good planning and operation of a distribution network to be reanalyzed after inserting

the DG , due to the change in the system nominal rated current and fault current [16].

Meanwhile smart grid is an important direction for future power grid development because its good characteristics of energy saving, efficiency, security and reliability. Also, in High Voltage DC (HVDC) section of the smart grid, when a fault happens at the DC side in HVDC with Voltage-Source Converters (VSC), then the current will surge within few milliseconds due to the DC-link capacitor discharge then AC main source feeds large currents into the DC side. So the power electronics may be damaged [17].

Therefore, the intense worldwide effort takes place to withstand the DG effect of growing threat of the short-circuit currents, so that replacing existing power grid infrastructure can be avoided or postponed. Thus, fault current limiting is an important indication to maintain the power transfer to be smoothly and continuously. Over the years, there has been important researches to develop a several fault limiting technologies which divided to traditionally fault limiting options shown in figure 1-1 will be discussed below in this chapter. And modern fault limiter options will be discussed in chapter (2).

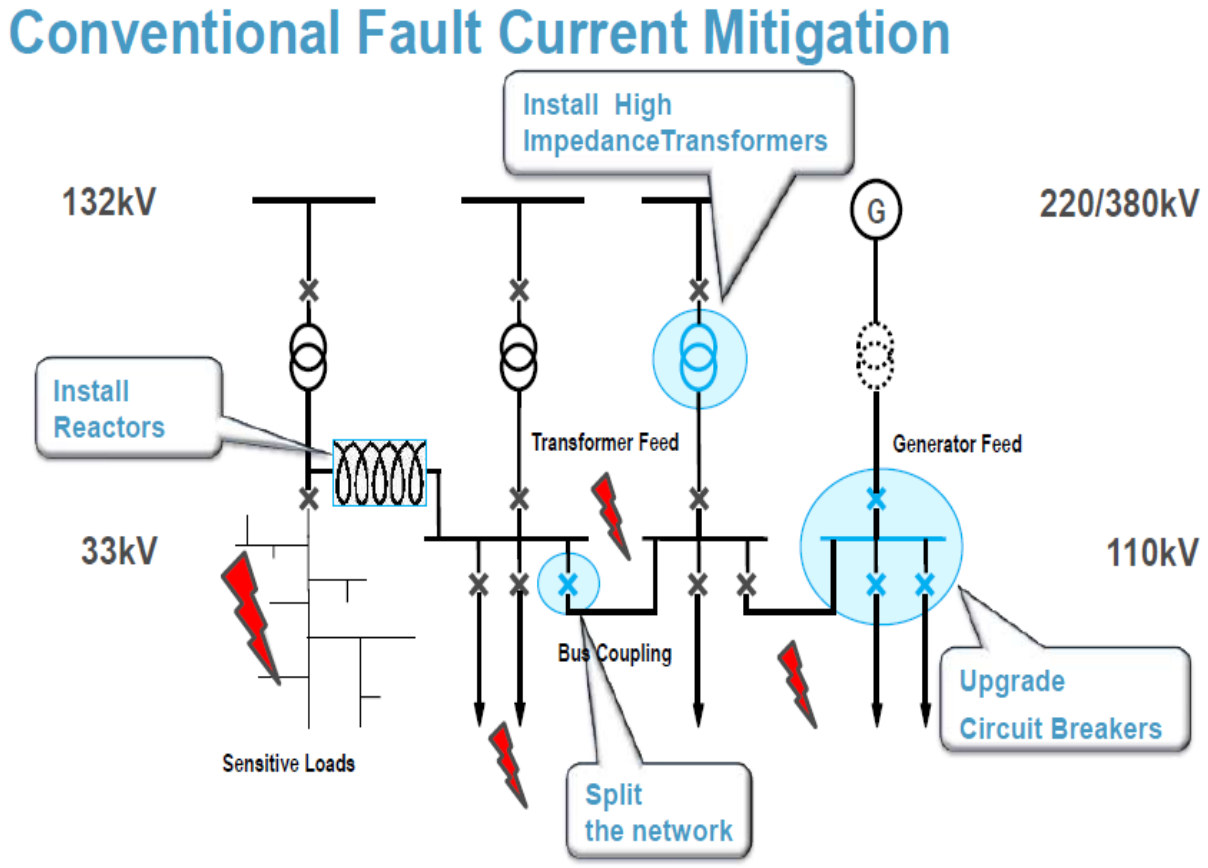


Fig 1-1 Conventional techniques of fault current mitigation [18]

1-3 Air core reactors

Air core reactors is a passive device was used in traditional grids for limiting fault currents to such a level less than the rated circuit breaker interruption capacity.

The air core reactors applications should consider its impact on other system equipment, such as its impact on CBs transient recovery voltage (TRV) [19]& [20].

Its interruption capacity will be rated according to substation current calculation, but rating in specific substation is preferred to be standard because it may reduce substation operation and maintenance costs [6] .

Its mean features can be summarized in the following advantages of [3]:

- Its technique, installed, and field tested has been well known for many years.
- It has a relative low cost and low maintenance compared with any of the other fault current limiting options.
- It has a small physical footprint.

However, it have many disadvantages like [16],

- It is bulky to handle and replacement.
- It is continuously connected in the system and therefore consumes considerable electrical power.
- It produces a voltage drop in steady state equals that of a transformer tap changer (which regulate the voltage on the MV bus-bars) [6] .
- It causes lagging power factor.
- It has fixed impedance, and therefore assumed as a continuous load during unfaulty situations.

1-4 High Impedance Transformer (HIT)

While standard transformers has an impedance around 10 %, however HITs are specified by 20% [21]impedance as a fault level management device. It is a passive mitigation device has the same theory of operation of the air core reactor, therefore it shares many of air core reactor's advantages and disadvantages.

But the high impedance transformer losses are technically not considerably high in case of the Medium Voltage (MV) bus-bar, because the transformer energy

loss depends on the current transfers through it, and MV current is almost low [5].

Although the high impedance transformers are considered as a costly option, device price via long term contracts will not higher than 6.4% of the standard transformers' price, so HIT can be assumed as a low cost fault current limiting option.

Therefore the high impedance transformer is an ideal option when new installations is a main future plane and there is no additional spaces in the electrical yard, but then substation has to consider the device additional costs for spare holding.

But its main disadvantage is introducing a power voltage drop and much increased steady-state power losses [4].

1-5 Equipment uprating

In the event of a rapid expansion in the grid and related rapid increasing in fault current levels at the substation buses. That fault current levels increase has a direct impact on the grid equipment like circuit breakers. Since, that fault currents observed at the buses exceeds the rated interruption capacity of circuit breakers so these under rated circuit breakers will have to be replaced with another uprated devices. Also, the all bus-bar related devices have to be re-evaluated in order to assure that if the new high short circuit forces can be withstood.

So, there are need for costly equipment upgrades or replacements.

In fact high fault current levels may be acceptable only when system equipment is approximately rated that new levels. But actually, many of the old substations was designed that a CB have to be replaced when fault current level has been exceeded or it is near the end of its service life.

Equipment uprating option is a high cost and time consuming option due to replacing all of the under rated devices with others that comply with the new current level specifications, however equipment uprating will eliminates the need for another fault level management methods.

So, this option is not a practical choice in many cases [6].

But in some cases, when substation components will be re-designed to be strengthened due to any technical reasons, then the equipment uprating option is

the optimum option because it has no increased maintenance or increased cost of the steady state losses.

1-6 Network reconfiguration (bus-bars splitting)

The last option of traditional fault current limiting management is splitting bus-bar. This option will reduce the fault levels and has a negligible cost. But splitting bus-bar leads to many problems in grid operation such as low power quality and undesirable low network reliability.

So it is not the optimum fault current limiting management in many grids [6].

1-7 Fault Current Limiter (FCL)

Due to continuous load growth in modern grids, Renewable Energy Resource (RER) are installed within the power network. So, fault currents may be exceed the existing circuit breakers interrupting ratings and then many CBs are underrated.

Many traditional aspects was discussed before to solve this problem, but all these aspects have performances that may not practical in many cases , so it have to achieve a modern device to be compatible with the modern grids and its modern specifications.

Such modern fault current limiting management is FCL devices which can be used to reduce the amplitude of fault currents to protect solid state components in modern grids and also to speed up both fault detection and fault interruption. Then FCL make the fault event in grid has less disturbance [22].

FCL is a viable modern alternative for fault level management that uses modern technologies to rapidly limit electrical surges that may occur on networks.

Besides that in modern grid, when short circuit connection happens at a presence of DG, the coordination between fuse and re-closer is mismatched and so decreases the network reliability. FCL is used also to solve this problem and generally to improve the reliability of the modern distribution networks [2].

Nowadays many different types of fault current limiters were installed on power grids all over the world, but three major FCLs types have been developed and commercially used which are Solid-State FCL, Superconducting FCL, and Electromagnetic FCL.

FCL different types will be discussed in details in the next chapter.

Chapter 2.

FAULT CURRENT LIMITER

2-1 Introduction

Although network interconnectivity improves power delivery reliability and meet the demands of increasing customer needs growth, but it also increases fault levels in the network as discussed in the previous chapter.

Damage from short circuit currents is a constant threat to any electric power system because it threatens the integrity of its generators, bus-bars, transformers, switchgears, and distribution lines. So in the modern systems it have to control the fault current level by a modern device.

One such modern solution is FCL which is a modern device has to control the new fault currents to a secure levels, which the already existed protection devices can operate safely with no extra cost or technical problems on the grid [23].

Also, FCL omits the network protection equipment's need for to be realigned to mitigate the fault currents created by DGs. This results in increasing the lifetime of system equipment.

The role of the FCL is to limit the fault current levels to a more manageable levels without a significant impact on the distribution system.

FCL may be located in several locations at the grid as implemented in figure 2-1 such as at transformer feed, generator feed, bus coupling, and at sensitive loads

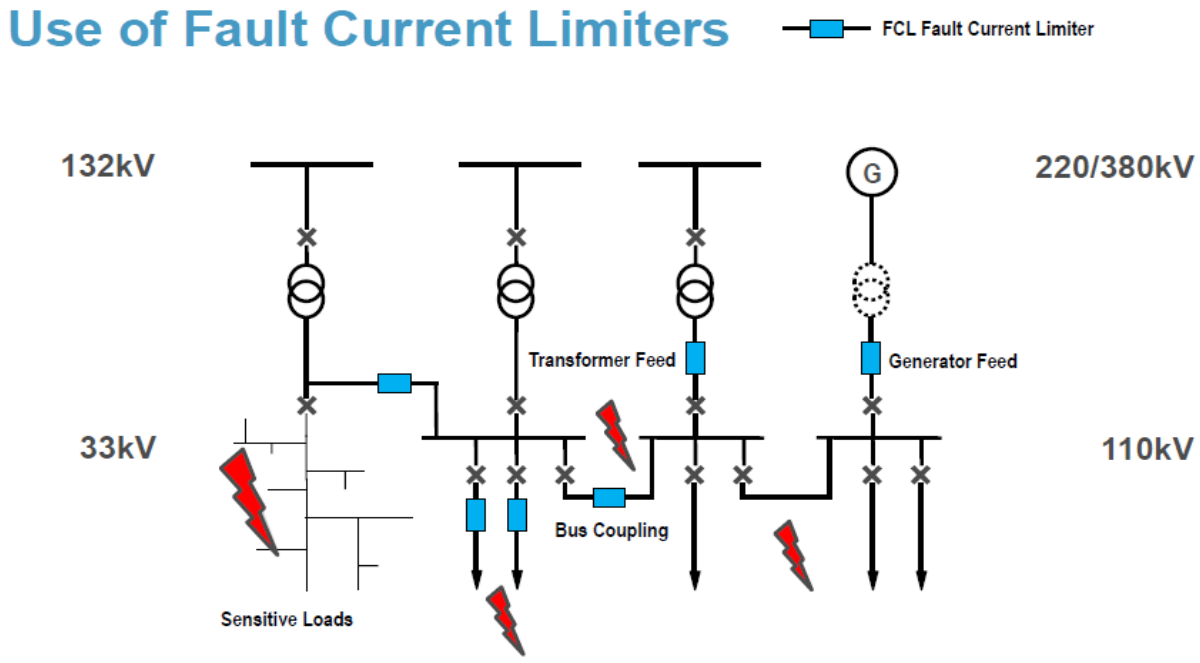


Figure 2-1 Usage of Fault Current Limiters according to its location [18]

The different FCL types will be assigned to the most applications in a grid such as: i) FCL installed at DG source which replace a circuit breaker with the advantage of maintaining system protection coordination correctly; ii) Fault Current Limiter may installed at distribution substations to mitigate the over current free of harmonic disturbance; iii) FCLs also have to be installed in transmission system which reduce fault current levels to that levels before install DG [22].
In brief, the presence of FCL device helps the power system to reduce inrush currents [24], improve grid power quality and power reliability [2].

Nowadays many different types of fault current limiters installed on power grids all over the world, but there are three FCL types actually are developed and commercially used which are solid-state FCL, superconducting FCL [25], and electromagnetic FCL. Some of FCL different types will be discussed below after listing the Ideal FCL characteristics

2-1-1 Ideal FCL characteristics

An ideal FCL should meet the following operational requirements [3] [26] [27].

- During steady state, it has low impedance causes zero voltage drop and little power loss across the FCL itself,
- During fault state, it has a fast-working within the first fault cycle (i.e. 20ms for 50Hz) and it can reduce the fault current to a desirable percentage in the next few cycles,
- After fault clearing, the automatic recovery of the FCL device to the pre-fault state happen without intervention of man work or external control devices,
- It capable of repeat mitigated operations for multiple faults in a short period of time,
- Has no impacts on voltage or angle stability in the utility,
- Has the ability to work up to the distribution voltage level classes,
- Has no impact on the normal operation of relays and circuit breakers,
- Maintenance free, small-size, and lightweight device,
- Has no danger for personnel usage, and
- Low bad impacts on the environment.

2-1-2 FCL main types

The FCL devices was divided in to different categories which have different particular characteristics. In general, FCL is assumed as an active device which its operation can be self-triggered or need another externally triggering device.

The FCL which was built using semiconductor switching devices is assumed to be an externally trigger device and the FCL which was built using superconducting materials is assumed to be a self- trigger device [5]

The self-triggered FCL devices use the material's physical properties for activation such as superconductors which was used to limit fault currents since the discovery of superconductor materials.

The superconductor limiting behavior depends on its non-linear performance when temperature, magnetic field, current density (T, B, and J respectively) vary. Changing value of only one parameter cause a superconductor material to transit between the zero resistance state (called superconducting state), and the high impedance state [7].

There are Fault Current Limiter's types do not depend on superconductors for the job of current limitation, such as fuses and solid-state FCL.
Practical tests on fault current limiters (FCLs) for AC systems 1000 V and above is described in details in [28] .

2-2 Superconductor Fault Current Limiter (SFCL) characteristics

Superconducting FCL limits the prospective short-circuit currents to lower levels. So, it improves grid stability and reliability by reducing the fault current levels. Superconductor materials lose their electrical resistance below certain critical values of temperature, magnetic field, and current density. SFCL can be classified into two main types [5]:

1- Quench SFCL type [29]& [30] which offers a low impedance in the normal operation but under fault conditions the device superconductor material transits to a high impedance and quench the fault current. Shielded core SFCL and Resistive SFCL are examples of SFCLs quench type.
2- Non-quench SFCL type which the device superconductor material is always in the superconducting state to offer a very low impedance. The fault is quenched by the iron core magnetic saturation state changes caused by the AC fault current. Saturated Core SFCL is an example of SFCL non-quench type.

SFCL is commonly recommended for its fast response and low power loss during normal operation depending on the superconductor material's performances. SFCLs use superconductor materials either to limit the fault level directly or to supply a DC current which saturate the device iron core [7]. Over the years, there has been substantial researches and developments in SFCL

several fault limiting technologies such as resistive type, shielded core type, transformer type.

2-2-1 Superconductor characteristics

While many SFCL designs are commercially being evaluated, the High Temperature Superconductor (HTS) was discovered in 1986, improved the economic usage of superconductors in FCLs. So in recent years, with the advancement in the fields of material science, the concept of HTS has been make its way to the forefront of SFCL technologies owing to their instantaneous and automatic reaction to faults, fast recovery and high reliability.

This is because of HTS ability to operate at 70K (-203ºC) with liquid nitrogen instead of Low Temperature Superconductors (LTS) which operates around 4K with liquid helium. This improvement have the advantage of about 20 times less costly in terms of both initial capital cost, operating and maintenance costs at refrigeration systems [7].

SFCL will be one of the important devices used for protection of the transmission and distribution grid because it reduces the effect of grid disturbances .SFCL has the ideal FCL's characteristics, such as a low impedance to current flow in normal operation and quickly increased impedance when fault short circuit occurs [31]. Also, SFCL performs two important functions during faults, first one is it limits the fault current and the second is that quickly recovering its impedance to its normal value after fault is removed [16].

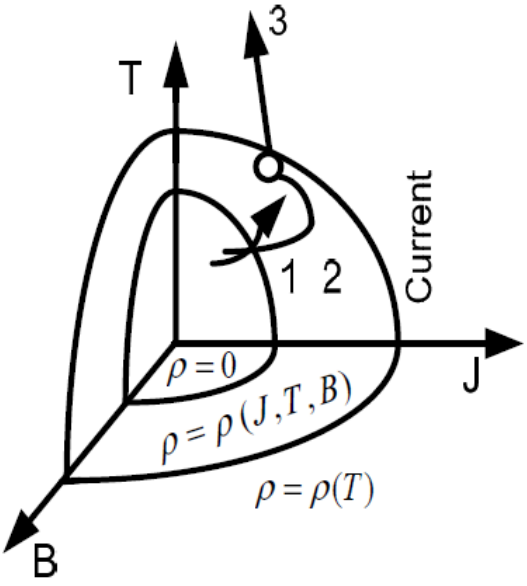


Fig 2-2 superconductor characteristics [16]

Figure 2-2 shows the (T), (B) and (J) characteristics of a superconductor material. It can be seen that the superconductor material can operate in one of the three states, 1, 2 or 3. The innermost surface-1 concerns with the zero resistance-(superconducting) state. The surface beyond surface-2 is the normal conducting state and the (transition) high resistance state is a particular state between surface-1 and surface-2.

So, when the current density exceeds the critical current density (Jc), the superconductor quickly reaches a very high resistance value, and then the fault current is limited to a lower values [16].

2-2-2 Superconductor quench phenomena

In faulty situations the current increases and then heat generated due to that high current cannot be locally removed, so it cause a section of the superconductor to become highly resistance and generates more and more heat. Then heat transfer all over the superconductor, so temperature increases on other adjacent sections also. Then, the combined high fault current and high generated temperature can cause these region to become extra ohmic value (region-2 state) and also generate heat.

That process is commonly called "quench" which describe the physical transition into the highly resistive state along the superconductor material, the quench process when initiated has a rapid action with uncontrolled procedure [7].

Though the quench process is uncontrolled once initiated, the superconductor material's temperature rising and the extent of the normal region in the superconductor materials can be predicted to determine the critical values of T, J, and B of each material.

The quench process is used in the SFCL design. There are many different theories for using this phenomenon to control the fault currents. But, there are only a few prototypes and practical designs. However, these designs still have many disadvantages such as device weight, reliability, behavior, cost, or recovery conditions after fault limitation [7].

2-3 Superconductor Fault Current Limiter (SFCL) types

There are many available concepts of SFCL in terms of impedance characteristics. Each type of SFCL has many of merits and demerits.

The SFCL cost depends mainly on SFCL rated continuous current, amount of fault current to be reduced, and system rated voltage [5].

In the following sections, many SFCL categories such as Resistive SFCL type; Rectifier SFCL type; Magnetic-Shielded core SFCL type; Saturated Core SFCL type [17] [31] will be discussed.

2-3-1 Resistive SFCL

In the resistive SFCL, the superconductor is directly connected in series to the line which has to be protected, while in the inductive SFCL concept the superconductor is magnetically coupled into the line [16].

Resistive SFCL is a device that 'engages' only when a fault is introduced to the power system. That device operates by allowing load current to pass through superconductor wire as the superconductor is the main current carrying conductor. Superconductor wire has to be cooled to below its critical temperature 'zero resistance state', therefore no steady state power loss to network [6].

The fault current density of superconductor in the resistive type SFCLs should exceed the critical current density Jc of the superconductor material.

The main advantage of the resistive SFCL is the automatically fault quenching and therefore a trigger mechanism is not essential [32]. But in the other hand the superconductor will burn out if it fails to quench.

As in figure 2-3, the resistive SFCL consists of a superconductor material R_{SC} and shunt elements R_{shunt} and L_{shunt}. Under normal conditions, superconductor R_{SC} offers almost zero resistance path to flow the nominal normal current.

Resistance of R_{SC} increases during fault situations according to the high fault current and related high temperature so it causes R_{SC} to act as an open switch, then shunt elements commutate the fault current. Shunt elements are selected to limit the high voltage across the superconductor material of R_{SC} during fault state [5].

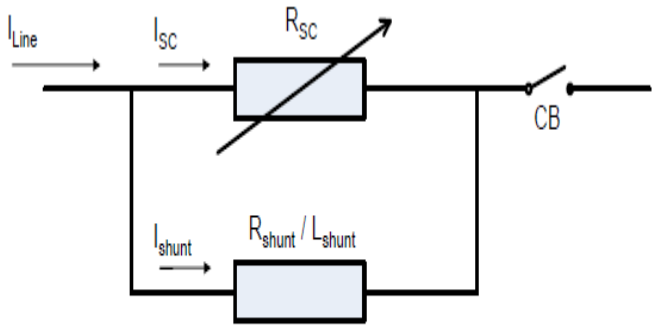


Fig 2-3 Resistive SFCL

During fault, the current increases above the superconductor material critical current density value which causes the superconductor wire to quench the high fault current by increasing the superconductor resistance exponentially. So, superconductor introduces a huge resistance into the system within the first cycle, thereby resistive SFCL instantaneously reducing the fault current [6].

These exponentially increase in the superconductor resistance produces a voltage across it. So, the superconductor resistance acts as a switch with milliseconds response and the fault current is limited [7].

The recovery in resistive SFCL delays because the quench process results extra heat has to be removed externally by cryogenic cooling system [33]from the superconducting wire.

Also, this extra heat causes a momentary temperature rise in the wire itself [34], which causes a loss of superconductivity state until the cooling system restore the superconductor temperature under its critical temperature again. This temperature restoring time, known as the superconductor material recovery time, is very important for electric power grid in the case of multiple fault events happened in small time interval, so it is an important comparative characteristic between the device types and detailed designs [7].

So, resistive SFCL can be modeled as a fast switch operates in a few milliseconds to limit the fault current in less than one cycle.

The resistive SFCL should be installed in series with a breaker (The CB interrupts the residual fault current and then the superconducting element will have a fast recovery) because if the resistive SFCL replaces the existing breaker, then the steady state flexibility would be reduced [6].

The operating costs of the resistive SFCL were determined using calculation of energy losses. While the main energy required for the resistive SFCL is for its cooling system during steady state and it is independent of the load current [6].

When the resistive SFCL insertion in South African power grid was compared to other traditional fault current mitigation techniques, it founded that the high capital cost of the resistive SFCL is a main disadvantage while its reduced operating cost over a 25 year service life is the main resistive SFCL advantage. So it is not the optimum alternative for fault level management in South African power grid. Whatever this conclusion may not be globally applicable [6].

in micro grid connection points with DG, although resistive SFCLs can successfully have a high current limitation level up to 80%, but SFCLs are devices of passive trigger which have not enough fast fault detection for some faults occurs in the transmission of a smart grid [22].

2-3-2 Shielded-Core SFCL

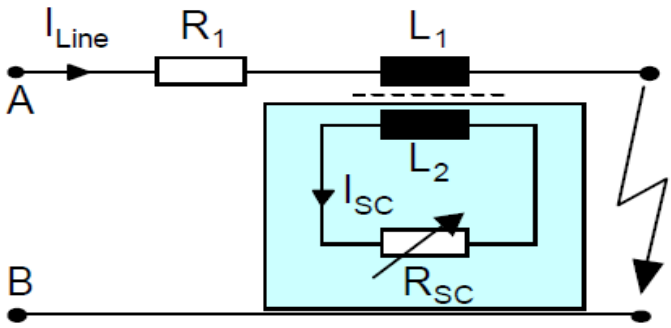


Fig 2-4 Shielded-Core SFCL principal [7]

The Shielded-Core SFCL resembles as a transformer with its secondary AC coil shunted with an HTS element (see Figure 2-4). So, it makes a mutual magnetic field coupling between the AC coils of the load line and with the HTS element [35].

During fault duration, the increased fault current on the secondary side causes the HTS element to quench, resulting in increased voltage across L1 coil which opposes the fault current direction.

A major benefit of the shielded-core SFCL type over the resistive SFCL type is the non-uniform hot spots along the superconductor material ,which can be avoided by some detailed equations for the AC coil turn's ratio to re-cool the superconductor after the limiting action.

But its major drawback is because it has nearly 400% the size and the weight of the resistive SFCL [7].

2-3-3 Hybrid SFCL

A hybrid SFCL is composite of a fast-acting switch connected in series with a resistive SFCL.
This switch job is to quickly isolate the superconductor material after most of the fault current transition to the resistive SFCL shunt elements. Then the fast-acting switch allow the superconductor wire to begin its recovery cycle while the resistive SFCLs shunt element limiting the fault current.
So allows the recovery time to be faster than that of a resistive SFCL only [7].
The switch can be opened during the quench process either using an electromechanical linkage, or by using a control system.

2-3-4 Saturated Cores Superconducting Fault Current Limiter (SCSFCL)

While shielded core SFCL and resistive SFCL depends on the superconductors quench to achieve the increased impedance during fault conditions, the saturated core SFCL has the advantage of non-quench.

SCSFCL has many other benefits like high reliability, negligible losses during un-faulted state, instantaneous response to faults, rapid recovery and high voltage withstanding so it has become popular in recent years [36].

SCSFCL basically is a variable impedance reactor connected in series with the grid. Under normal grid steady state operation, its impedance is low and the device is practically transparent to the grid. However, when a fault occurs, SCSFCL impedance extremely increases and preventing the short currents from rising to the full level of the system.

SCSFCL mainly consists of an AC coil wound on iron core and connected in series with the grid, presents low impedance to the grid when the current is within its nominal ranges.

But during a fault event, the rising current in the AC coil generates an AC magnetic field, which opposes the DC bias field. It drives the core out of its saturation state, leading to increase the permeability of the core section under the AC coil and hence increase the impedance then the fault current will be limited.

SCSFCL also was used in the High-Voltage Direct-Current transmission (HVDC) based on (VSC) systems of the smart grid to limit the DC short-circuit fault current, caused by the huge discharge current of the DC-link capacitor, to a relatively low level [17].

It is important to ensure that the SCSFCL behavior meets the specific requirements of various operation environments, and in the same time, it should have a small size and low cost. SCSFCL size and cost are determined by the size of iron cores, number of AC coil windings, and number of DC coil windings. The correlations of that three factors are investigated in [1] and [31].

Some papers analyze the responses of a SCSFCL for variations of different parameters, namely, the fault resistance, DC bias current, number of AC coil turns and number of DC coil turns. Further analysis is also done to study the SCSFCL's responses for different B-H characteristics of core materials using a mathematical model by a theoretical analysis method which is verified by experiments [1] [36] but it is not our main concern in this thesis.

Practical prototypes of SCSFCL were manufactured and installed in distribution and transmission power grids since 1980.The SCSFCL is the most developed inductive SFCL and has been put into use in several EHV AC systems [17].

The saturated core SFCL utilizes the large difference permeability of magnetic materials. High permeability materials allows a low impedance during normal

operation and a very high impedance during fault current events [37]. The SCSFCL perform current limiting action depending on its ability to change the iron core material magnetic state between saturation and unsaturation regions. So, SCSFCL can achieve the instantaneous reaction and return to normal operation immediately after isolating the fault [17].

So SCSFCL gaining more popularity than the other fault current limiting technologies in both transmission and distribution sectors [12]. But also it has many drawbacks as:

1-The induced high voltage on the DC coil during faults due to the transformer coupling forces will decreases the device efficiency and increases both cost and design complexity.

2-The two heavy iron cores per phase which are necessary for limiting the full fault cycle cause the SCSFCL to have large dimensions, large mass, and high cost .

3-The very expensive of using a cryogenic technology in SCSFCL in high-voltage grids.

Most of recent designs still suffer from one or more of the previous drawbacks and ways to overcome these drawbacks are still searched for.

Economically in smart grid applications, it cannot replace all under rated CBs. But only one SCSFCL is needed to be located at the interconnecting bus of transmission and distribution grids, also it keeps all already existed breakers within their interrupting ratings.

Actually, in 2009, one SCSFCL device was located at small distribution network in California, USA and, during a lightning-induced fault in 2010, that SCSFCL successfully limited the resulted fault current as expected [22].

2-4 Non-Superconducting Fault Current Limiter Technologies

The non-superconducting technologies FCLs are independent on superconductor materials to perform the current limiting action. But it depends on power electronic components which includes current limiting fuses and solid-state FCL devices.

2-4-1 Current-Limiting Fuses

Current-limiting fuses are commonly used for fault current mitigation in medium-voltage grids. Fuses limits the current by generating enough induced voltage across a gap after melting an element inside the fuse then a high-impedance path is provided for arcing and allow a low fault current flows after the melting action [7].
One of the commercially available fuses is the commutation fuse which interrupts the extra fault current by utilizing an explosive charge.
Another current-limiting fuse type is the standalone HV fuse which is one of the commercially available fuses and carry the current directly through a melting element inside the fuse.
The main benefit of using fuse technology is that it can be assumed as an inexpensive option compared with the other large capital cost fault current limiters discussed throughout this chapter.
But the main disadvantage of this device is it provides only one fault limiting situation then fuse will be damaged ,and replace a damaged fuse requires time of replacement with related interruption long time [7].

2-4-2 Solid-State FCL (SSFCL) (Figure 2-5)

The SSFCL's limiting action is based on the (on status /off status) change of semiconductor several devices and active controlled power electronics. The active controlled power electronics device's characteristics simulate a circuit breaker behavior because it switches the fault current into a limiting branch [7].
SSFCL have three main modes under fault conditions i) the off-state mode when SSFCL acts as a rapid CB; ii) the phase control mode when SSFCL limits the fault current flow; and iii) the reclosing mode when SSFCL ends its current limiting action [22].
The SSFCL sometimes can be assumed as a Fault Current Controller (FCC) because it is dynamically controlled through a power electronics.

There are some advantages of solid-state technologies such as it offers additional fault current control signals and have small geometries which not available with other FCL technologies.
While its disadvantages are the low reliability of switching electronics to sense fault level disturbances which may cause responds according to errors in fault sensing. Also, the continuous distortion in current waveforms due to switching electronics [7].

SSFCL Circuit Breaker (SSFCL-CB) is one topology of the solid-state FCL which cleared in the following figure, which is a device consists of a diodes and a commutating thyristors. Thyristors in this circuit are switched off during fault situations [7].

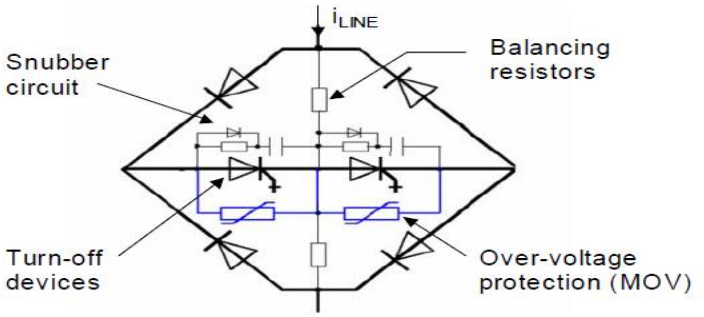


Fig 2-5 *SSFCL* Circuit Breaker [7]

In smart grid, SSFCL have many useful applications like [22]:

1- Where it installed at the connection node between the micro grid and the transmission network, then SSFCL will limit fault currents transfer between micro grid and the transmission network. So, that SSFCL should have high current limiting capacity.

2-SSFCL acts as a super rapid CB because it can quickly cut off the fault current provided by DGs and island the faulted micro grid. Otherwise the presence of DG fault current might disturb the Existing Protection Relay Scheme (EPRS) in a meshed structure transmission network [22].

3-SSFCL also when works in its phase control mode, then it allow a fixed limited fault level of current to flow and open downstream protective devices subsequently. This situation happens when power sources in a micro grid are off –grid.

4- SSFCL has the option to receive external signals by the communication feature of the smart grid, which helps the operator to know the whole smart grid status then operator can decide whether SSFCL should re- close its micro grid to the main smart grid or not.

5- In case of a fault may exist in transmission network, SSFCLs may be installed at Renewable Energy Resources (RER) terminals to maintain the correct protection coordination. This is because the communication system after detecting a fault, it sends out trigger signals to SSFCLs and off-grid DGs completely.

6- SSFCL device can replaces the large-capacity CB or re-closer and take the communication network advantage of the smart grid and then offer an intelligent protection at this locations. This is because of fast RERs reclosing with SSFCL fast action which improves the system transient stability and maintains a fast power availability after fault clearance [22].

2-5 A brief comparison between FCL technologies

In this section a comparison between FCL technologies will be cleared, and divided in two aspects which are the FCL techniques comparison and the FCL applications comparison.

2-5-1 Comparison between FCL Techniques

Table 2-1 is a brief comparison between the different FCL technologies which was discussed before. The main bases of this comparison are the steady state losses, the used triggering technique, the recovery time required after fault clearing, the distortion due to harmonics, cooling system required, activation time required before start limiting action, and current limiting rate. Device footprint is also included in this comparison because the FCL size and weight are a major concern to utilities.

Table 2-1 comparison of FCL technologies [7] [22]

Type / performance	Resistive SFCL	Hybrid SFCL	SCSFCL	Shielded-Core SFCL	SSFCL	Fuses
Steady state Losses	HTS Material cooling	HTS material cooling	core and conductors	HTS material cooling	Similar amount as that of resistive	Negligible
Triggering	Passive	May be Passive or Active	Passive	Passive	Active	Passive
Recovery	necessary HTS Re-cooling	Much faster than resistive SFCL	Immediate	Faster than resistive	Immediate	Never ,One use only
Size and Weight	small	more than Resistive SFCL	400% of Resistive SFCL	Much more Resistive SFCL	Similar to resistive SFCL	smallest one
Harmonics	first fault cycle	Mainly first fault cycle	all fault cycles	first fault cycle	all cycles	None
Cooling?	Need	Need	Need	Need	Controllable	No Need
Activation Time	< ¼ cycle	Faster than Resistive	Immediate	Immediate	µs level	Immediate
Current limiting rate	< 80%	< 80%	30 % – 45%	< 80%	Can be Controlled	100%

2-5-2 Comparison between FCL applications

There are some important notices have to be addressed when comparing the applications of the different FCL types in smart grid which can be listed as [22]:

1- RER new installed at smart grid may cause the fault level to exceed the existing circuit breakers' capacity, so many CBs may be underrated even at normal operation conditions due to changes in load. Economically, it cannot replace all the under rated circuit breakers on the smart grid.
   But one SCSFCL only is needed to be located at the interconnecting bus will keep all already existed CBs within their capacities.
2- FCLs located at distribution grid have to allow a flow of an acceptable limited fault current to trip the system protective devices during the fault event. So, resistive SFCL and SCSFCL are used successfully for large substations. While SSFCLs are not recommended at this site for large-capacity substations, because SSFCL device must operates under the mode of phase control which produce high current harmonics that disturb the sequence of over-current relays.
3- When there is a new hundreds of MWs RER integrated into a smart grid, Resistive SFCL and SCSFCL are the successfully techniques of FCL at this situation, because they are commercially fabricated to high-voltage ranges and internally triggered by heat or current increasing. Also, they have the advantage of the devices' low steady state power loss and low steady state impedance so, it have negligible effect on transmission network load ability or on transmission network stability.
   But in the other hand, using of Resistive SFCL and SCSFCL devices, some parts of the grid have to be redesigned and reprogrammed because the FCL effective impedance must be taken into consideration [22].
4- While the main application of SSFCL in smart grid is to receive an external trigger signals then operator can monitor the smart grid as a whole and take important accurate decisions.

Chapter 3.
Saturated Cores
Superconducting
Fault Current Limiter (SCSFCL)

3-1 Introduction

In the residual chapters of this thesis, the Saturated Cores Superconducting FCL (SCSFCL) will be discussed in details because it is a practical device proven its advantages in many actual applications all over the world.
This device has significant attention from both electricity utilities and researchers because it has a major advantages like providing instantaneous fault current mitigation and instantaneous recovery state [38].
SCSFCL is a device placed in series with a DG utilizes the permeability change of the iron cores between saturated and unsaturated states. The cores permeability changing provides a low steady state impedance and extra fault transient impedance at current limiting conditions [39].

3-2 SCSFCL Working Principle and Characteristics

- The SCSFCL concept was suggested firstly by B. P. Raju group in early 1980's [26].
- The schematic configuration of one phase SCSFCL closed core type is clearly showed in Figure 3-1, which consists of two symmetrical magnetic iron cores, two symmetrical AC coils, and one superconductor dc bias coil for each phase.

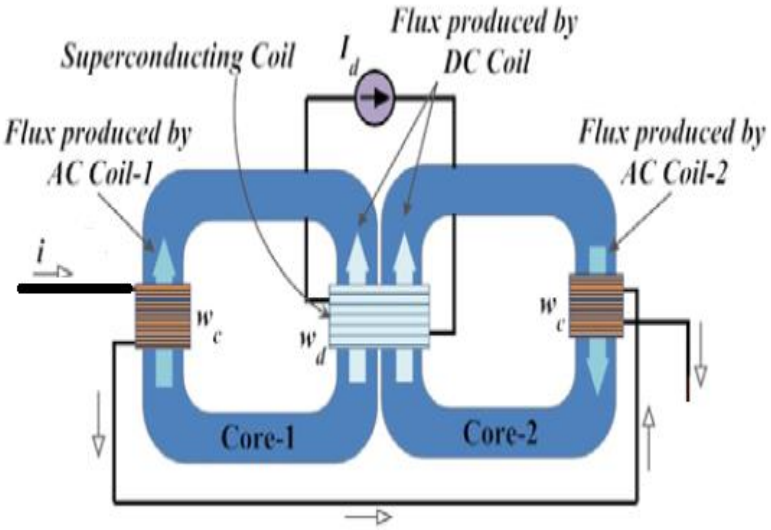


Fig 3-1 configuration of single phase SCSFCL [36]

3-2-1 SCSFCL Working Principle

- The superconducting coil is used because of its low operating power loss and its little induced voltage during normal operation, which makes the windings are more compact [7].
- The AC windings are made of copper conductors and wrapped around the cores to form an inductance in series with the AC grid line to carry load current. The number of ampere turns of one AC coil is equal to the other

one but wounded in opposite direction to one another [1]. Two AC cores and coils are necessary to limit the both negative and positive half fault current cycles [38].

- The DC current supply is adjusted such that both cores are driven into deep saturation region.
- The direction of ampere-turn of DC coil is the same as the direction of one AC coil and opposite to the other coil, which means that always one core flux opposes the DC flux and the other core flux support the DC flux [36].
- The two cores are labelled as core-1 and core-2, respectively, and the number of turns of the AC winding and DC winding on each core is N_c and $N_{d,}$ respectively.
  The cross-sectional area of the iron core is A, and the mean magnetic path length is ℓ while I_d is the DC bias current. Then, we can obtain the following equations [36].

$$N_d I_d + N_c i = H_2 \ell \quad (1)$$

$$N_d I_d - N_c i = H_1 \ell \quad (2)$$

$$B=\mu H=\mu_\circ \mu_r H, \qquad ,\mu_\circ=4\pi\times10^{-7} \quad (3)$$

Where B in ($wb/m^{2)}$ & H in (A.T/m) & μ is the permeability of the iron core [17].

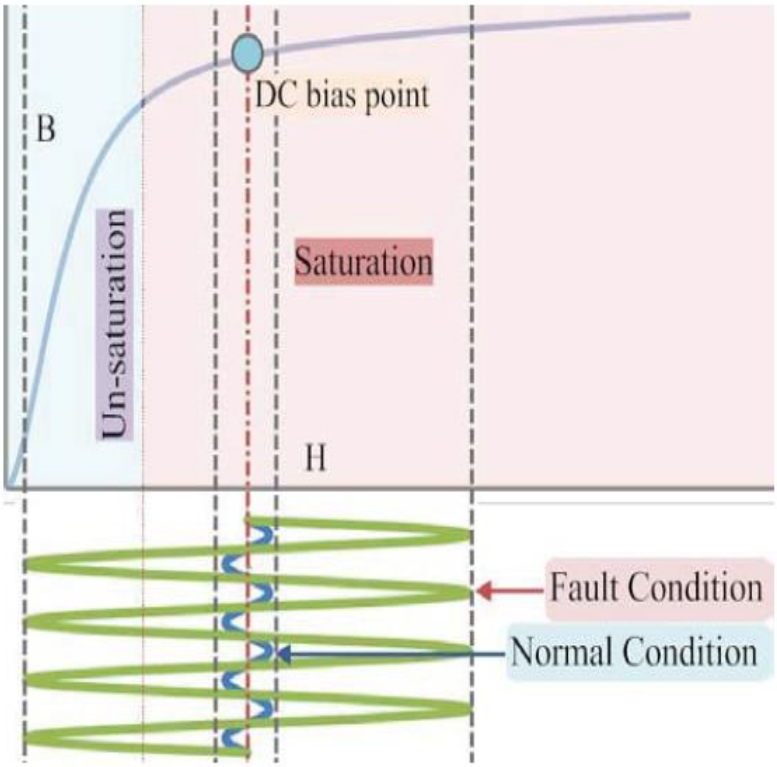


Fig 3-2 operating zones of SCSFCL [36]

- Figure 3-2 shows the operating zones at B-H curve of an iron-core of SCSFCL. The curve is composed of un-saturation zone, where B changes quickly with the change of H, and a saturation zone, where B changes only slightly with the change of H [26].
- Designers stated that, Sac< Sdc <Sy, which are the cross section areas of AC, DC and yoke iron beams, respectively. So the DC magnetic effect in

AC iron beam is strong, while the AC magnetic effect in DC iron beam is weak [1].

3-2-2 SCSFCL normal steady-state conditions

Under normal steady-state conditions, a DC superconductor is used to drive the iron cores into the deep saturation region (normal condition).
Positive AC flux shifts the core operation further into the saturation region due to the magnetic field of one AC coil that in the same direction of the existing DC bias, while the other AC coil has an opposite effect on the DC bias but iron core still works in the saturation region [40].
In this case, the two iron cores behave like a standard air core reactor which has a relative permeability ($\mu_{r)}$ equal one. So, the magnetic permeability (μ) of the both cores is approximately equal to permeability of air and so, SCSFCL behaves as if there were no iron-core resulting in a very low SCSFCL effective impedance.
While the normal AC current is too small to affect the saturated status of the cores.
Also, because the AC fluxes opposing each other, then voltage drops on the AC windings are low [17] [26].

3-2-3 SCSFCL short-circuit conditions

When short-circuit fault occurs, the greatly increased fault current of the power system causes increased AC coils' current which increases the AC ampere-turns to become a big magnitude comparable with the DC bias.
So, the operating points at the B-H curve is transitioned through high slope regions, which are the regions of high core inductance [40].

- Therefore, for one half cycle, the core where its AC flux opposes the DC flux will decrease the effective flux and then saturated status of this iron core will be ended. So it results in a higher core relative permeability and related inductive reactance becomes very large and the short-circuit current is mitigated for this one half cycle. While the other core reaches a further saturated state as its AC flux adds to the DC biasing flux [36].

Similarly, the situation reverses in the next half-cycle.

- In general, the generated voltage across an AC series coils always depends on the flux changing with time. The high fault current through SCSFCL causes a very large change of the flux, then the total generated voltage (E) across the series coils is the sum of both

voltages which are generated across each coil, resulting in a high (E) value.

- This high generated voltage also is able to slow the fault current evolution and then able to reduce the level of fault current [40].
- The device current limitation reactance can be compared to that of a transformer's reactance when its secondary current is kept constant [26].
- During action of limitation, the core dynamic action is moving instantaneously in and out of the saturation region, so iron cores produce harmonics in the current waveform. However, under normal operation, the voltage and current waveforms are unaffected by the saturated core SFCL harmonics [7].Which clearly appears in our current wave form simulations in the case study.

3-2-4 SCSFCL recovery conditions

- After fault clearance, the system current return again to its steady state level, so SCSFCL device return into saturation region again.
- Because SCSFCL operation depends only on the change of the cores permeability, does not depends on the superconductor material quench, so the detection time for a fault and recovering time are much faster than that of other FCLs types which employing quench superconductors such as resistive FCL and Shielded-Core FCL [12].
- The minimum SCSFCL impedance or the SCSFCL steady state insertion impedance is the SCSFCL impedance during unfaulty operation when the ferromagnetic cores is saturated [12].
- The maximum SCSFCL impedance is the SCSFCL impedance during the fault insertion, which means that when one SCSFCL core is unsaturated [12].
- Unlike resistive SFCLs, which require cooling time between succession limiting actions to cool the superconducting components, the saturated core approach can manage several limiting actions in short time because the superconductor does not quench [7].

3-2-5 *SCSFCL general characteristics*

From the above discussion, it is observed that the SCSFCL general characteristics are as follow [36],

1) Because the magnitude of the system maximum fault current decreases with the increase of the system fault resistance, so the inclusion of the SCSFCL in to a grid decreases the system fault current magnitude considerably because SCSFCL increases the system fault resistance.
2) During normal operation, the more increased DC current the more saturates cores, then the corresponding voltage drop of ferromagnetic cores will be decreased.
   But during fault conditions, fault current causes a high opposing AC flux of one core to un-saturate this core completely, then the voltage across the SCSFCL increases. Also, the voltage across its DC coil increases according to transformer action [36].
3) The SCSFCL AC steady state currents increases according to the DC coil turns' increase, but this increase will be negligible if DC biasing current adjusted to be high enough to saturate the two cores.
4) The AC SCSFCL steady state current does not affect with B-H cores' characteristics, while AC SCSFCL fault current affects with B-H cores' characteristics considerably.
5) B-H curve at its steepest slope indicates a high relative permeability cores, which offers the highest mitigation levels, and so this high relative permeability develops a high voltage across the SCSFCL device during fault [36].

3-2-6 *SCSFCL general equation:*

SCSFCL general equation depends on the physical features described above. An inverse tangent function may approximate the B-H characteristics.

The magnetic field linkage by one AC coil in the core is obtained by the following equation [40]:

$$\boldsymbol{B(i_{ac}) = \frac{-2\,B_{sat}}{1+tan^{-1}\left(K\pi-\frac{\pi}{2}\right)}\left(1 + tan^{-1}\left(K\frac{\pi}{I_d}(I_{max} - i_{ac}) - \frac{\pi}{2}\right) + 2\,B_{sat}\right)} \quad (4)$$

Where $\boldsymbol{i_{ac}}$ is the instantaneous AC line current, I_{max} is the maximum steady state line current which maintains the cores fully saturated, at which point the average magnetic field is B_{sat}. While K is a constant determines the line currents' range where the cores' magnetic state are actively changing from saturated to unsaturated behavior. The K value is depending on the device dimensions, core relative permeability, μ_r, and number of the AC turns. The equation is scaled when

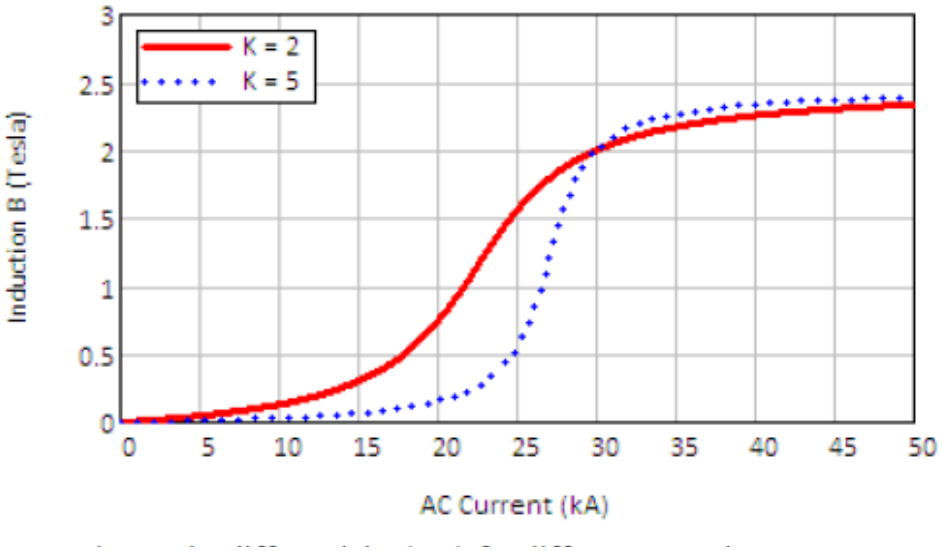


Fig 3-3 (B/i_ac) relation @ Bsat=2.2T& Imax=30KA [40]

B = Bdc_bias and $\boldsymbol{i_{ac}}$ = 0.

- The relationship between flux density (B) and current ($\boldsymbol{i_{ac}}$) Can be obtained for different values of K, and is shown in Figure 3-3.

3-3 SCSFCL Design problems:

While SCSFCL device has significant attention from both electricity utilities and researchers because it has a major advantages, but it still suffers from some design problems such as:

- The magnetization states of the two iron-cores are not identical, so flux produced by the AC coils in the two iron-cores is not completely cancelled during steady state operation.
- Designers stated that the ratio of the SCSFCL DC turns to its AC turns is 10 or greater. Therefore fault condition causes AC magnetic flux to be changed largely in a very small times, then it causes a very large induced voltage in the DC winding, that very large induced voltage may damages the DC magnetization circuit [12].
  But damage of the DC magnetization circuit can be avoided if the DC circuit is switched to open when a short-circuit fault takes place [26].
- The SCSFCL device is generally expensive due to its large size and heavy weight.
- The good behavior device need a sufficiently low impedance during steady state power transmission, which needs a powerful DC bias coil to enable the section of an iron-core housing the AC coil gets saturated.
- The SCSFCL uses an insulation level which permits the maximum voltage required for SCSFCL operation, but without a breakdown of its DC windings, which determine the suitable cryogenic system used [12].
- A significant amount of power is absorbed by the SCSFCL itself. This power absorption generates heat that is controlled by a cooling apparatus.

- The height and width of iron core window is determined by insulation distances and the ratio of cross sectional area of AC iron beams, yoke and DC iron beams [31].
- Voltage drop of the SCSFCL itself in normal state should to be no more than 1.5% at the rated operational current [31].

3-4 SCSFCL typical applications

Simulation results in [31] proved that the current limiting impedance is proportion to the number of AC coil turns. Also, the impedance has least value when the diameter of AC iron beam increasing, and the impedance reduces with the DC current.

While, it cannot replace the under rated circuit breakers all over a smart grid. One SCSFCL only is located at the interconnecting bus between the transmission and distribution networks will keeps all already existed CBs within their interrupting ratings. Actually, in 2009, a SCSFCL device was located at small distribution network in California, USA and, during a lightning-induced fault in 2010, the SCSFCL device limited the fault current as expected [22].

Many companies around world are manufacturing FCL devices, so the typical commercial applications of SCSFCL of two companies will be discussed here.

3-4-1 **Innopower typical** ***applications:***

By Innopower superconductor cable company limited, China, two SCSFCLs at 35 kV/90 MVA and 220 kV/300 MVA have been manufactured and put in live grid operation in 2008 and 2012 respectively [1].

Figure 3-4 explains the possible applications of an SCSFCL which is generally one of the following cases which will be also summarized in table 3-1 [26]:

a) At the secondary side of a transformer in a single source distribution network.
b) At the intersection of two HV transmission networks;
c) At a branch of a multisource distribution network ;and
d) At a complex EHV transmission network.

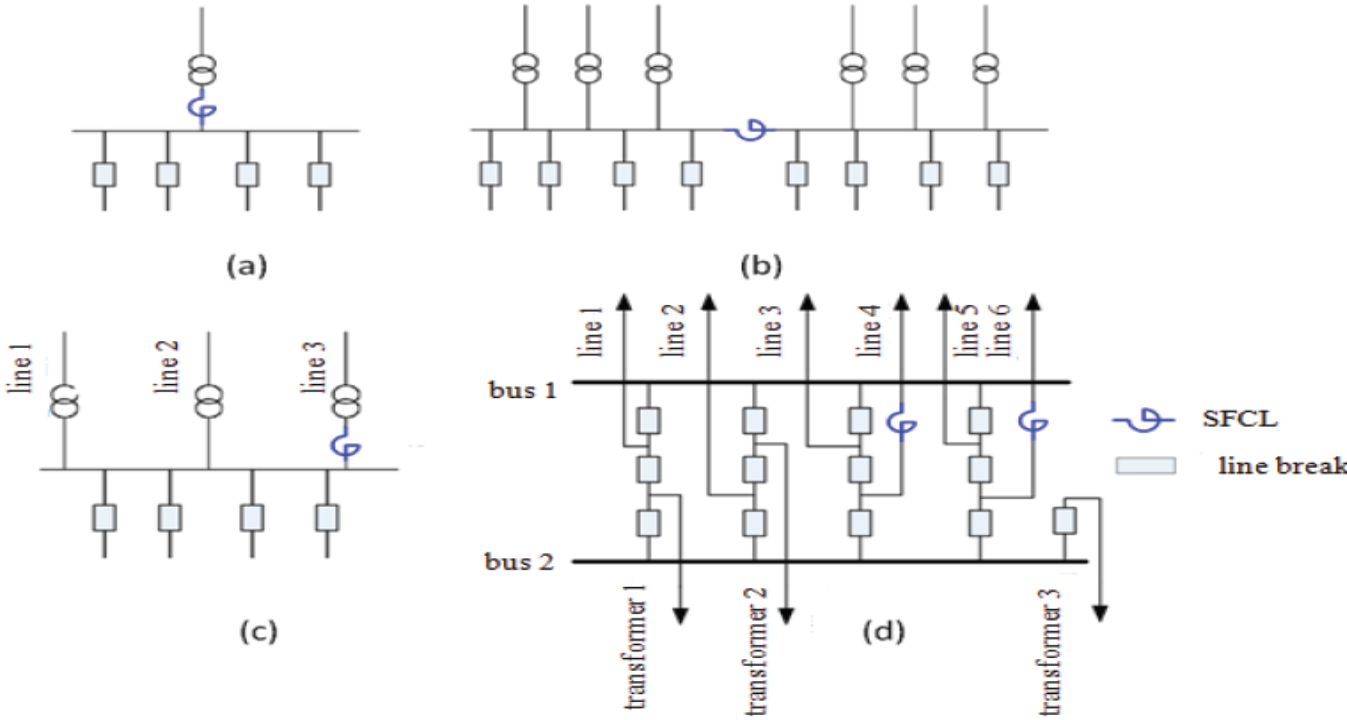


Fig 3-4 Examples for possible applications of SCSFCLs [26].

Table 3-1 summery of SCSFCLs indices in possible applications

Case	current limiting impedance	fault current reduction rate
(a)	0.5-2.0Ω	> 30%
(b)	2.0-5.0 Ω	> 20% at the bus for a single installation
(c)	4.0-8.0 Ω	> 20% for the interconnected network
(d)	5.0-20 Ω	>5% at the bus for a single installation

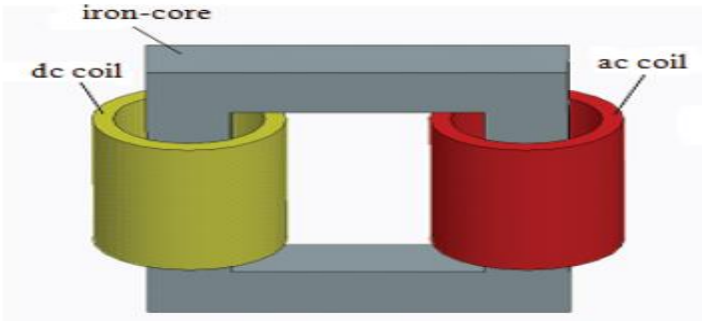


Fig 3-5 practical HV- SCSFCL [26]

While Figure 3-5 shows the practical configuration of the coils and the iron-core of a SCSFCL for HV applications. The iron-core having differential cross-sectional areas according to the well-known design rule of

Sdc≥Syoke> Sac, where the Sdc, Syoke, and Sac are the cross-sectional areas of the section housing the DC coil, the yoke, and the section housing the AC coil respectively. The ratio of Sdc: Syoke: Sac is 1.5:1.5:1 for the iron-core used.

- a **35 kV /90MVA SCSFCL** with dry-type electrical insulation and a **220 kV/300MVA SCSFCL** with oil electrical insulation were manufactured and installed for live-grid operation at Puji substation, Kunming, China in 2008 and at Shigezhuang substation, Tianjin, China in 2012 respectively [26].

The SCSFCL DC coil is made of Bi-2223 HTS tapes (4.2 mm width, 2.1 mm thickness, Ic is in the range of 120-180A, 77 K, self-field). The AC coils are constructed with copper wires.

Fig 3-6 SCSFCL medium-size prototype

- Figure 3-6 describes the medium-size prototype of SCSFCL, number of dc coil is 400, and dc current is 120 A. The cross section area of AC beam is 706 cm^2, the cross-section ratio Sdc:Syoke: Sac is 2:1.8:1, the height of iron core window is 0.5 m, the width of iron core window is 0.37 m and length of magnetic path l is 3.48 m [1].

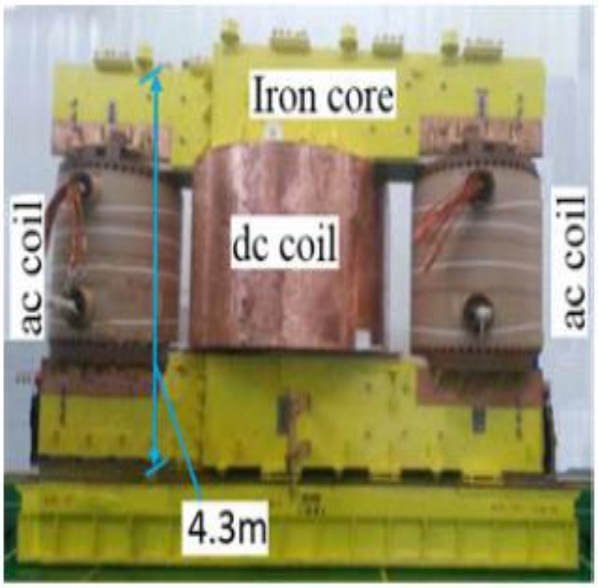


Fig 3-7 SCSFCL one phase 500 kV

- Figure 3-6 is the prototype of one phase 500 kV SCSFCL. There are two performance requirements of the prototype from the power grid. First 65KA short circuit current should be limited to 35kA, which means the current limiting impedance must be no less than 4.5Ω when ac current is 35kA. Second, voltage drop of the prototype in normal state should be no more than 1.5% at the rated

operational current 2.5 kA, which means the steady state impedance should be no more than 1.73 Ω.

- Considering the engineering practice, the iron core window is fixed with 1985 mm height and 1465 mm width, which means the magnetic path length of SCSFCL becomes longer with diameter of AC iron beam increasing [1].

3-4-2 Grid ON company typical applications:

The SCSFCL utilizes copper AC coils wound onto iron core to present very low impedance during normal current operation. After fault clearing, the FCL immediately (<1ms) returns to its low impedance again in normal condition and so the SCSFCL ready to protect the grid against any faults [41].

A) As SCSFCL was located after a transformer, it offers a reduced fault levels in substation and accommodates switchgear ratings.
In this location, it can install one or more FCLs depending on the required fault current reduction.
In this location, the FCL can be included in the transformer protection zone, with no additional protection devices.
Also The FCL is used to improve load balancing between different rated power feeder transformers. So, FCL enables increasing the capacity on existing grids [41].

B) FCL may be connected in a bus-tie location and offers the advantages of grid interconnectivity, flexible arrangements and increased power quality.
Also in this location, one or more FCLs may be installed, depending on the bus topology and fault current reduction required, with small changes on settings of existing protection devices.
It can parallel the FCL with the existing bus-tie circuit breaker, with no additional protection devices [41].

Chapter 4
SCSFCL PROPOSED MODEL SIMULATION AND RESULTS

4-1 Introduction

The SCSFCL behavior has been characterized through experimental and mathematical simulations. Both these techniques are accurate but fail to demonstrate the SCSFCL behavior in the actual electrical grids, due to the iron cores complex nonlinear magnetic characteristics. So, there is an increasing demand for developing a flexible accurate model of the SCSFCL that can be easily inserted into transient network analyzers to demonstrate the SCSFCL effects on the other equipment of the network [38].

This chapter presents the development of a flexible SCSFCL model, which accurately describes the nonlinear magnetic properties of the iron cores. The proposed model is tested in simulation package to assure that its behavior is most close to the theoretical working principle and characteristics, which was discussed in the previous chapter.

In this chapter, all simulations were carried out using PSCAD software. Firstly, a PSCAD model for a SCSFCL will be proposed in details. Notice that the developed SCSFCL model will be discussed here is a behavioral model, which aims to simulate the operation of a real SCSFCL.

After discussing the obtained results, it can be concluded that the proposed SCSFCL model behaves very closely to its theory of operation . So, the FCL model can limit current effectively.

4-2 PSCAD/ EMTDC version 4.5.0

To study the effects of SCSFCL model, author choose the simulation method, because building a prototype then test it physically is a high time consuming and cost. While, simulation method is a quick and easy way to model SCSFCL and test its effects on a distribution system.

PSCAD/ EMTDC version 4.5.0 (available at faculty of engineering, Mansoura University) is chosen as the used systems software. Because it enables us for simulating the instantaneous responses of test system [15].

4-3 Proposed PSCAD Model

4-3-1 Major circuital components

The SCSFCL can be modeled as an inductor wounds with superconductor HTS wire combines with two thyristors and one variable resistor as shown in Fig 4.1.

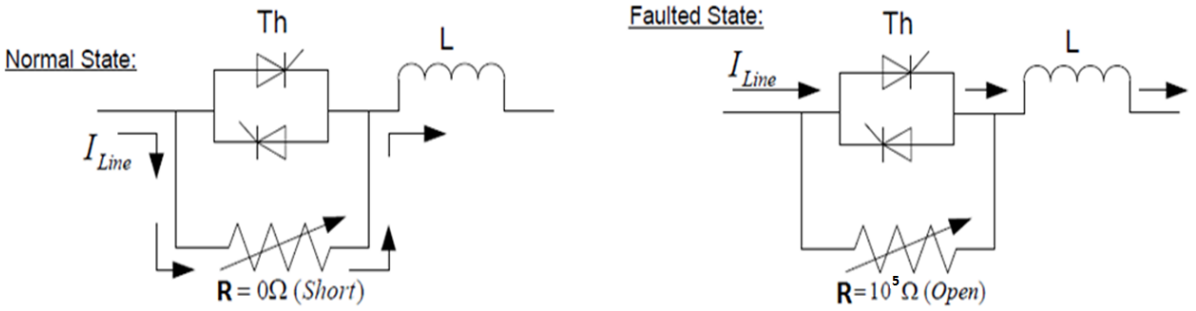


Fig 4-1 SCSFCL model circuit diagram

The model's components are as follows [3]:-

a) **The inductor (L)** is wounded with a High Temperature Superconductor (HTS) wire which has to be cooled by a cryogenic system. Faulted situations insert over current that causes the HTS impedance to be increased sharply in microseconds to provide the current limiting feature.
The inductor was chosen in these model because the current cannot change instantaneously in it.
The inductor magnitude will be adapted to catch the optimum performance of the SCSFCL model.

b) **The phase controlled AC thyristor switch (TH)** [42]
Practically, harmonics will be injected into a SCSFCL circuit due to three mean reasons:
    1) SCSFCL iron core,
    2) SCSFCL Switching components, and
    3) Any SCSFCL non-linearity components.

Thyristors are inserted in the model to model the SCSFCL real device harmonic component.
If we use any other power system components except thyristors, it may have adverse effect in the proposed model due to harmonics effect.
Thyristor switch off only every half cycle, after a zero current, so it have to use two thyristors.
.

c) **Linear variable resistance (R)**

(R) Models the HTS resistance sharp increasing from zero to 100000Ω during fault.
.

4-3-2 Model operation sequence [3]

The model operation sequence is described in figure 4.1

a) At grid normal state, THs are switched off and R is close to 0Ω, so all of the line current flows through the resistance R then flows through the inductor L.
   HTS wire has no significant impedance and its voltage drop is very low.
b) During faulted states only, THs are fired on, in a reverse sequence one to other, so they act as a source of harmonic injections.
   While resistance R is sharply increased and can be considered as an open circuit. Then all of the fault current is commutated through TH and L components.
c) When the fault cleared, R is ramped down to 0Ω again, and THs both will be switched off, so SCSFCL obtains its normal state again.

4-3-3 Automatic Fault Detection Technique [3]

Automatic fault detection means there is no any external trigger devices for activation SCSFCL model to start limiting action. So SCSFCL model detects line currents only to predict a fault situation as the actual SCSFCL device.

In fact, after power system achieves a steady state current (normal current), a fault occurs externally of SCSFCL device. Then, the magnitude of the line current changes instantaneously and achieves a new steady state value (i.e. fault current).

But many faults come and go instantaneously for many reasons, such as a tree in windy weather touching the power line, an animal or bird locates between two lines, or an in-rush current due to machine starting.

So, SCSFCL goal is triggering only during a fault. Then, it may be has to insert a delay time of 2 cycles at least before triggering a SCSFCL model. A similar delay time can be used before switching off the SCSFCL then ramps SCSFCL impedance down.

There are two methods to detect faults:

- Monitor the magnitude of line (I_{rms}). But the FCL might be falsely triggered for many reasons like inrush currents.
- The other alternative is to check the rate of current change (di/ dt).

4-3-4 the Proposed SCSFCL Model

After studding the SCSFCL operation carefully and SCSFCL model which was proposed in [2], author success in this thesis to propose a new SCSFCL model in PSCAD/EMTDC environment which its complete PSCAD/ EMTDC version 4.5.0 logic can be founded in figure 4.2.

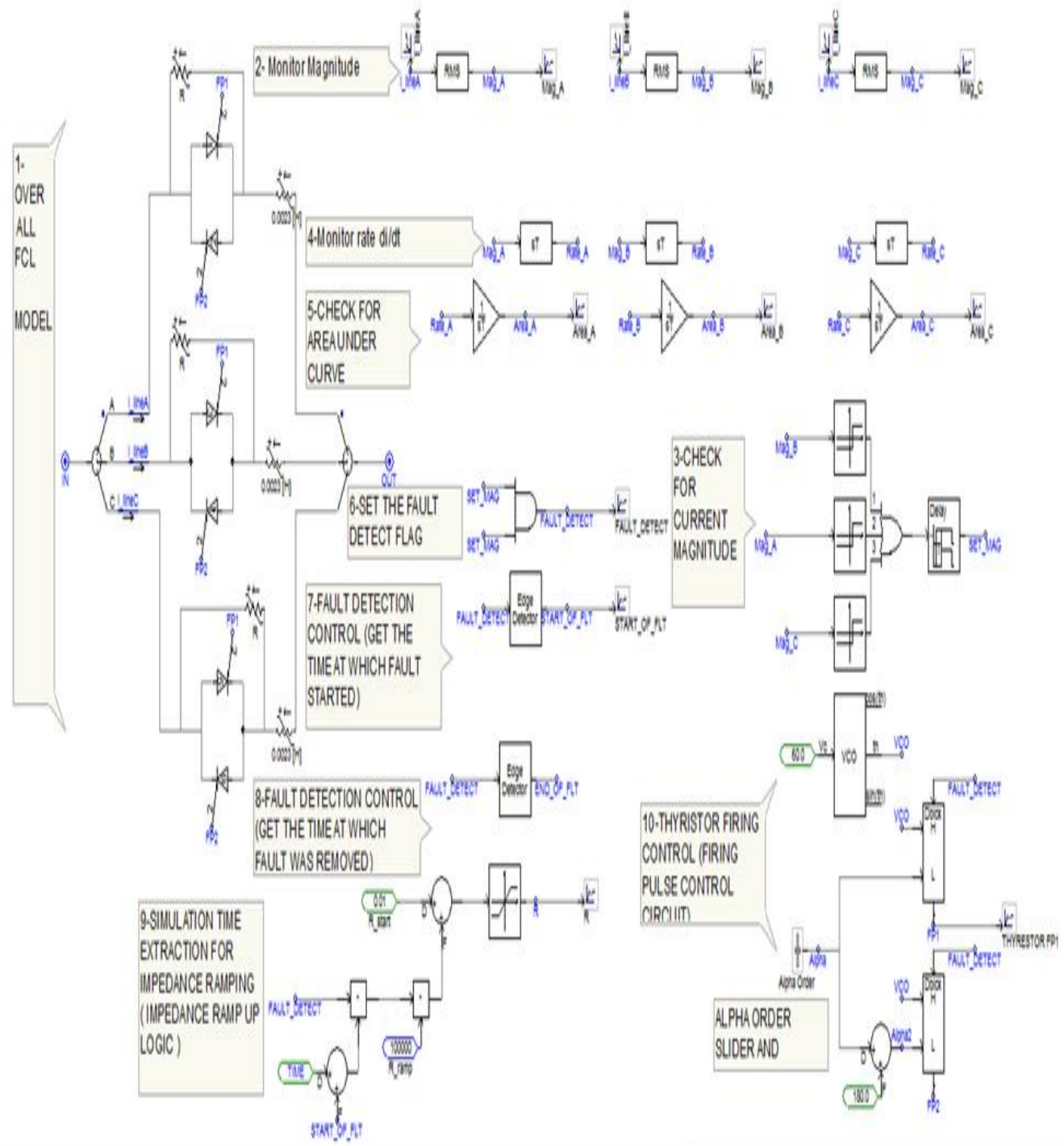


Fig 4-2 SCSFCL PSCAD proposed model

In the proposed model, the impedance of the SCSFCL increases sharply during fault periods. The impedance ramp rate can be adjustable.

4-4 Test system overview

Figure 4.3 represents the configuration of Tanta city distribution system with DG and SCSFCL [8] , which was used in this thesis for all simulation studies. The studied distribution system consists of 15 buses. Bus 1 is 66/11 transformer. F1, F2, F3, and F4 are the expected fault locations while CB1 and CB2 are two circuit breakers.

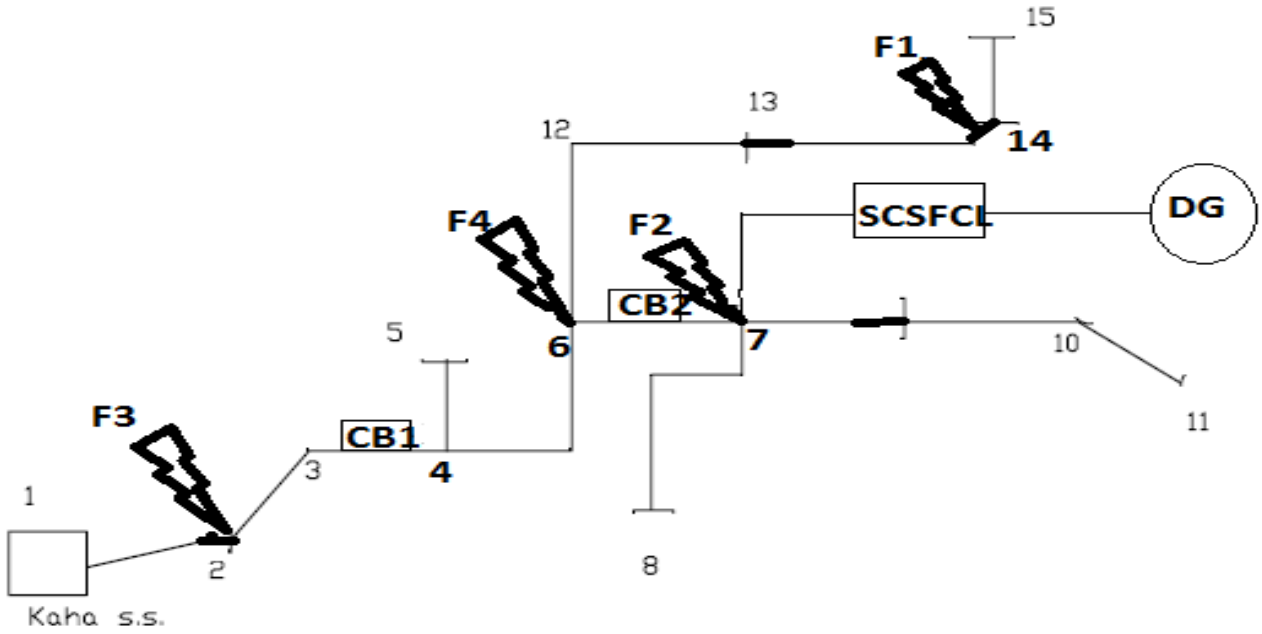


Fig 4-3 single line diagram of Tanta city distribution system with DG and SCSFCL

Table 4.1 presents the system line data while the reference base system shown in appendix A, It is found that the best DG location is at bus 7 [8].

- Because most new sources used are wind turbine and solar panel and its exact output value cannot be determined, so it has to treat such sources output [2]. Here DG simulation as an ideal source asymmetrical at load angle 30º and rms phase to phase voltage is 10.27 kV at 50 Hz and DG series parameters are 0.08829 Ω & 15.92 mH [8].
- As in many researches, the optimal location of SFCL is at the integration point of two generating sources. It is the point of combination of the DG with the power grid for both distribution and customer grid [16].

- Simulations were performed for three different faults – three-phase to ground, single-line to ground and double-line to ground.

Table 4-1 main line data of test system [8]

bus	line		length km	Line parameters	
	from	to		R Ω/km	X Ω/km
2	1	2	0.078	0.163	0.0892
3	2	3	0.85	0.266	0.0949
4	3	4	0.22	0.569	0.1062
5	4	5	0.05	0.569	0.1062
6	4	6	0.33	0.569	0.1062
7	6	7	0.2	0.569	0.1062
8	7	8	0.04	0.569	0.1062
9	7	9	0.65	0.266	0.0949
10	9	10	0.15	0.569	0.1062
11	10	11	0.1	1.113	0.1172
12	6	12	0.44	0.569	0.1062
13	12	13	0.15	0.266	0.0949
14	13	14	0.45	0.266	0.0949
15	14	15	0.2	0.266	0.0949

The total simulation time is 3 seconds and the fault will be inserted for 50 cycles from sec 1 to sec 2.

Six case studies are considered cases as follow sequence:

1) Check current waveforms in the distribution system with and without an SCSFCL cases, then check efficiency of the SCSFCL to regains the fault current levels in the distribution system to that levels before inserting the DG in the grid, which is the theoretical SCSFCL behavior.
2) A comparative study between “no DG, with DG and (with DG and SCSFCL)” fault cases.

- The bolted three phase-to-ground faults are not the only faults used in all thesis simulations, despite it are the highest value and the worst case scenario for any distribution system fault current. But in this thesis it was simulated different fault types and locations to assure that the SCSFCL

mitigates the fault current during any type of fault at any point in the system.

- While The PSCAD simulation of the test system shown in appendix B, but because it may be unclear it will be divide into 4 detailed figures (4-4, 4-9, 4-12 &4-14), each figure details the components of a section of the system.

4-5 Adaptation of the proposed SCSFCL inductance.

The main objective of a SCSFCL is to mitigate the fault current changes due to DG insertion in to the grid.

Building on this base, insert a bolted L-L-L-G fault at position F1 as shown in figure 4.4 which is a detailed PSCAD/EMTDC simulation for fault (1) location.

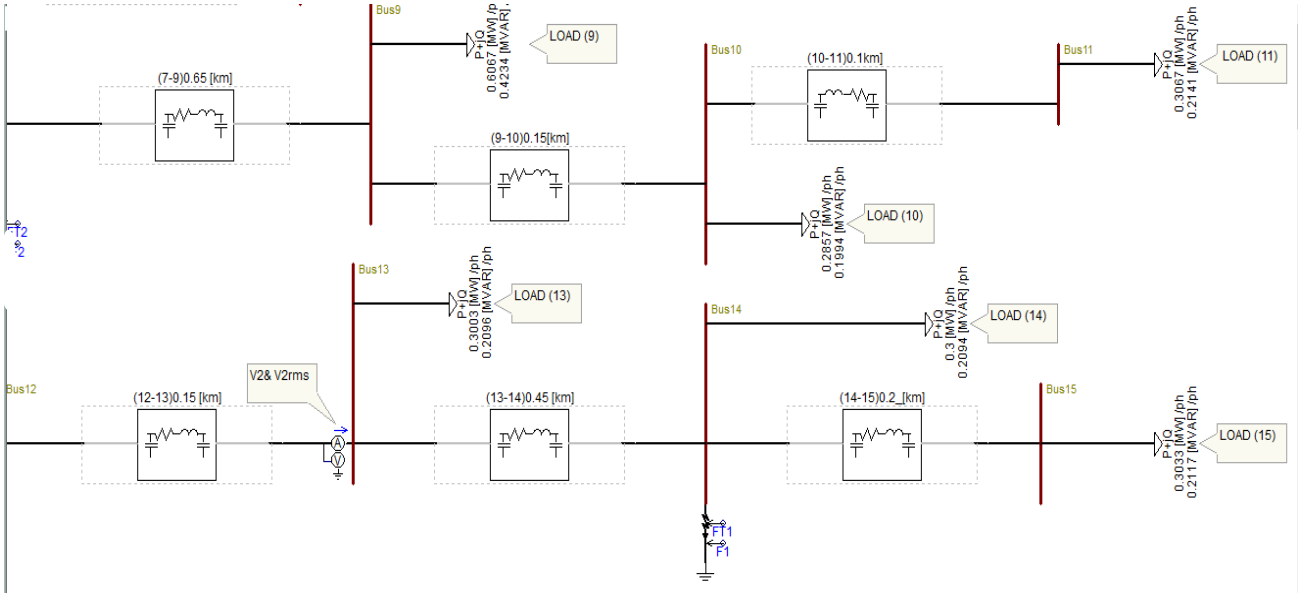


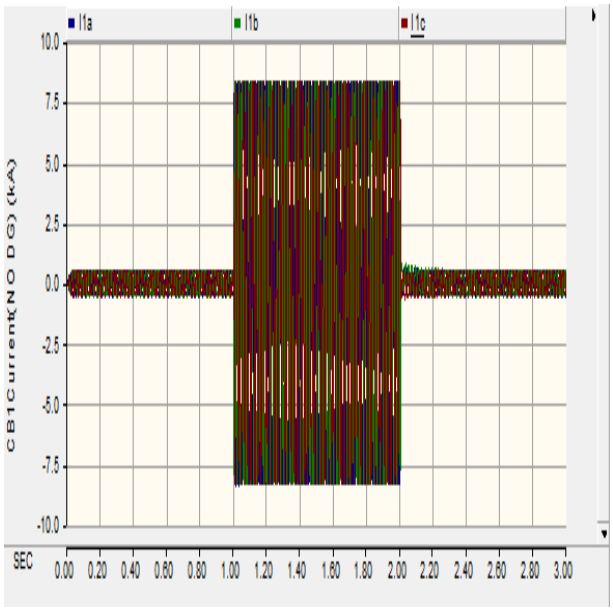
Fig 4-4 1st PSCAD/EMTDC section of the test system (fault at F1)

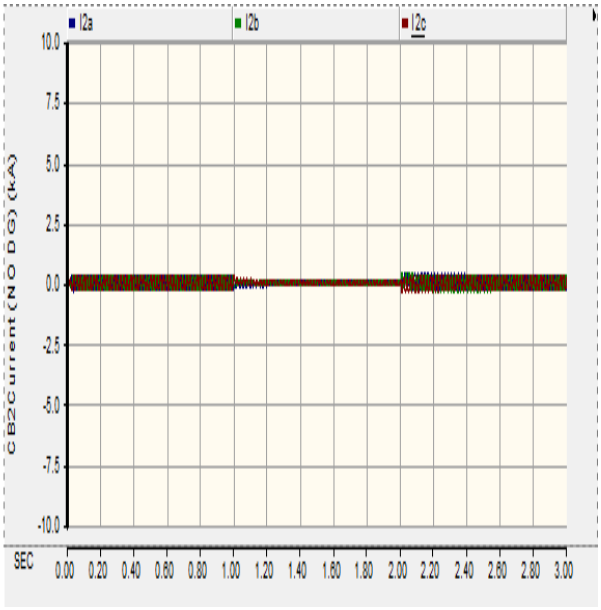
The plot of the CBs current's waveforms is shown in figure 4-5. It is describe the all-time current in the following scenarios, test system with no DG, test system with DG, test system with the presence of the DG in series with the proposed three-phase SCSFCL model respectively.

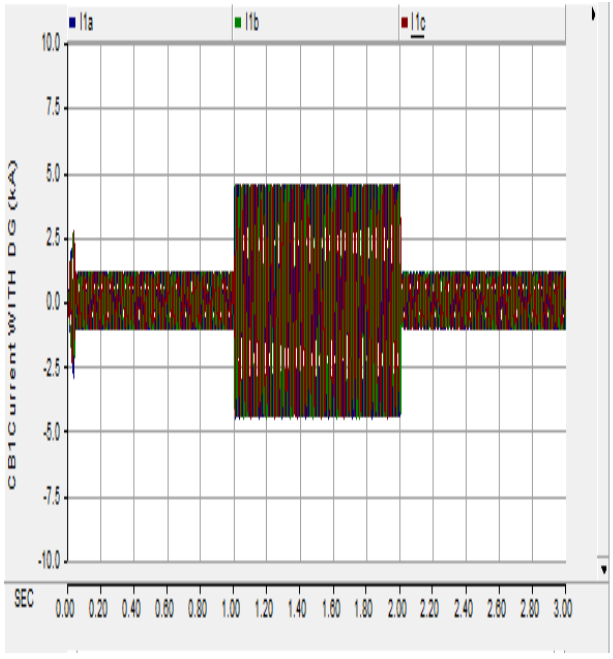
The ideal SCSFCL model simulates the faulted current levels of the "no DG" case, and in the same time, simulates the normal current levels after inserting

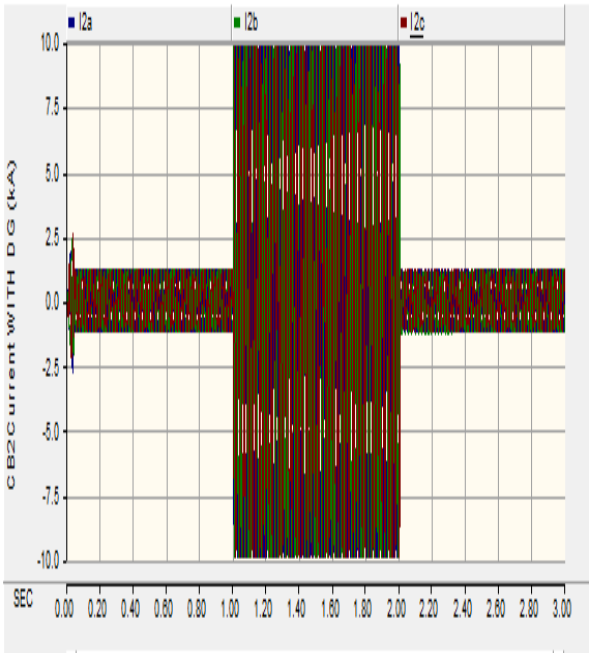
the DG, referred as "with DG " case. So the last scenario which is to insert the DG in series with the SCSFCL was repeated for variable values of inductance L as shown in figure 4.5.

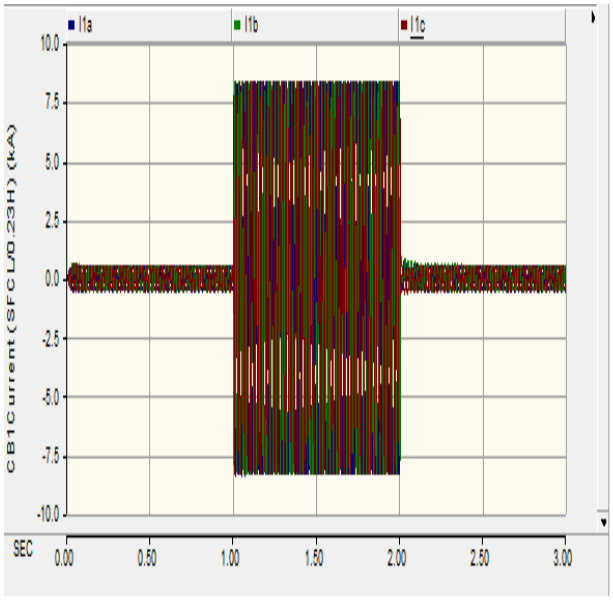
Observing that change the value of (L) should have corresponding change in the comparator factor in Appendix (B) which is a part of the proposed SCSFCL model

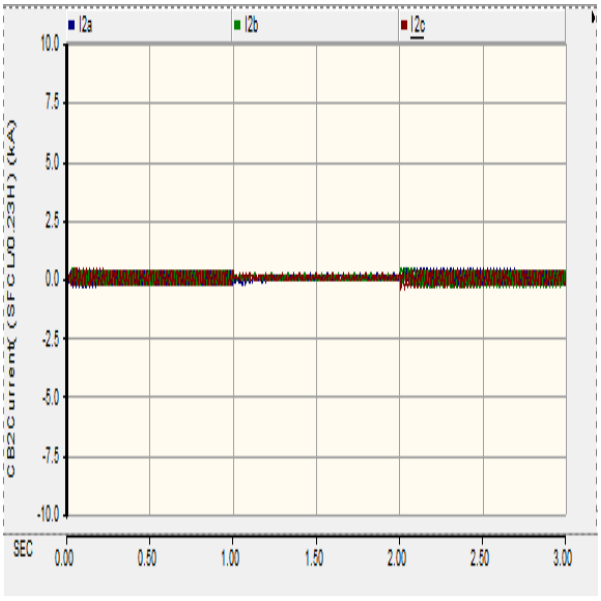


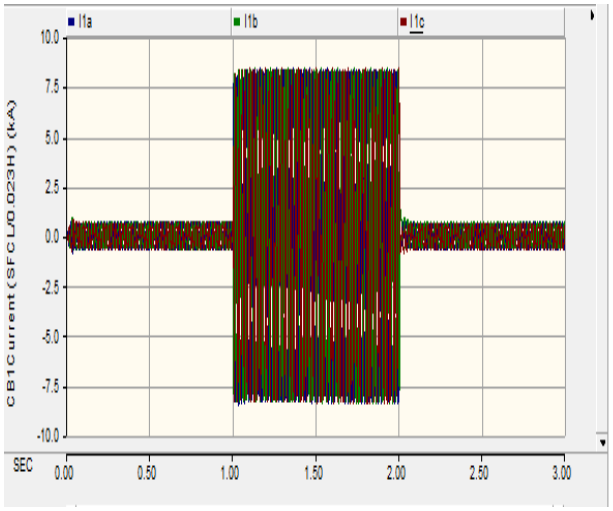


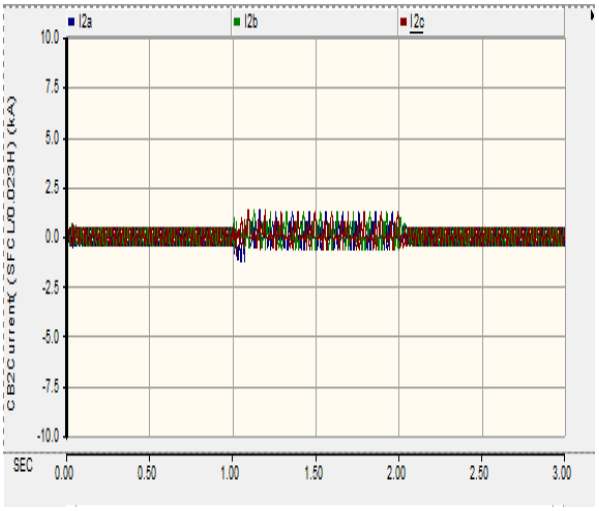


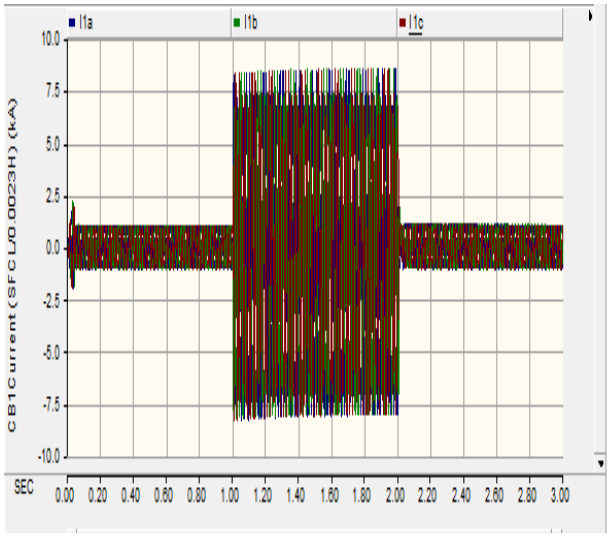


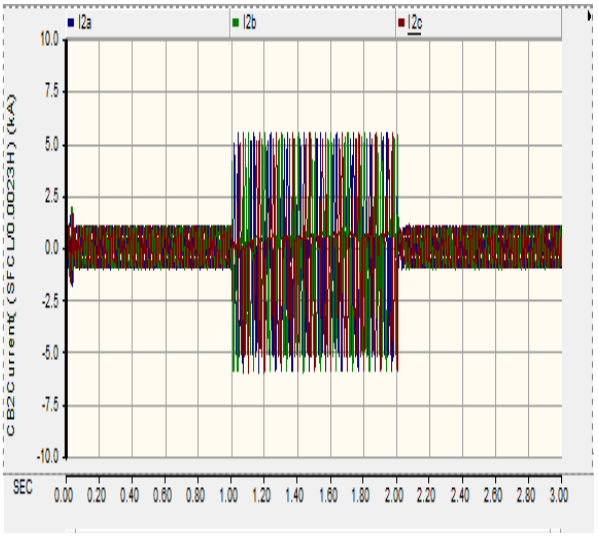

I1a
I1b
I1c
CB1Current (SFCL/0.23H) (kA)
SEC


I2a
I2b
I2c
CB2Current (SFCL/0.23H) (kA)
SEC


I1a
I1b
I1c
CB1Current (SFCL/0.023H) (kA)
SEC


I2a
I2b
I2c
CB2Current (SFCL/0.023H) (kA)
SEC


I1a
I1b
I1c
CB1Current (SFCL/0.0023H) (kA)
SEC


I2a
I2b
I2c
CB2Current (SFCL/0.0023H) (kA)
SEC

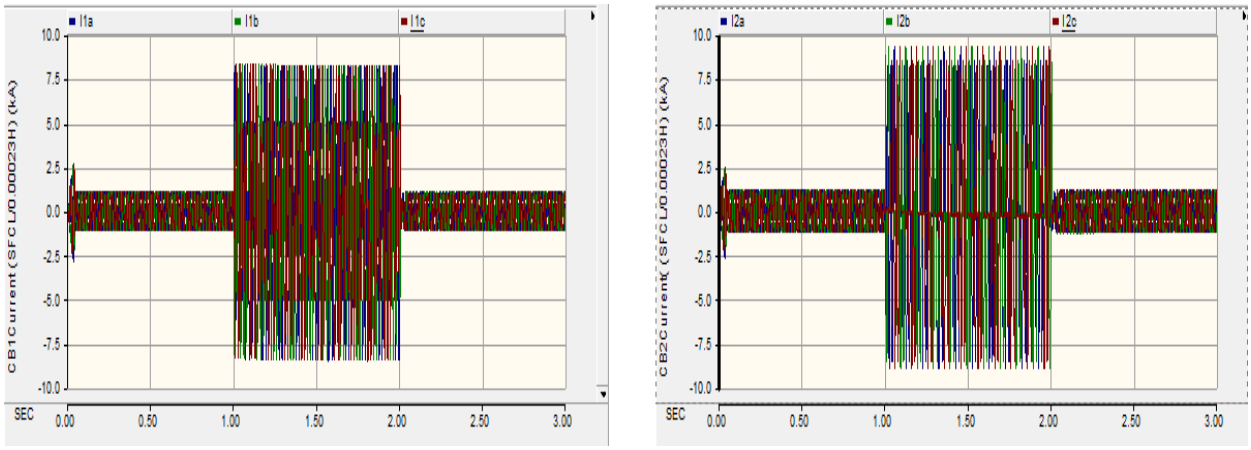


Fig 4-5 CB1&CB2 currents (no DG, with DG, with DG and SCSFCL/0.23H, with DG and SCSFCL/0.023H, with DG and SCSFCL/0.0023H, with DG and SCSFCL/0.00023H)

As described earlier during a limiting action, the dynamic action of the core moving instantaneously in and out of saturation produces harmonics in the current waveform however, under normal operation, the current waveforms are unaffected by the saturated core SFCL [7].

Depending on this discussion and as shown by the previous curves in figure 4.5, it founded that the accebtable wave current shape is in scenario '**SCSFCL with DG&SCSFCL/0.0023H'** which optimize the following :

1- its normal current waveshape nearly same as the normal current waveshape of 'with DG' scenario,
2- its fault current waveshape nearly same as the fault current waveshape of no DG' scenario, and
3- has a minimum harmonic available.

But it may have to check the performance of that FCL by carry out various simulations

4-6 Performance verification of the used model (L=0.0023H)

For checking the performance of the internal components of the proposed SCSFCL model it may simulate '**SCSFCL with DG&SCSFCL/0.0023H'** scenario again but concentrate on the rms phase current (Mag_B), the resistance (R), fault detection period (FAULT_DETECT), instantaneous phase current through the resistance (I_R_A), and the Thyristor's operation (Thyristor FP1) which shown in figure 4-6 in all of the simulation time.

Discussing the obtained figures as follow.

4-6-1 rms Phase Current (Mag_B)

For checking the rms phase current in the proposed SCSFCL it can choose phase B as an example. From the figure 4-6 it can obtain that:

1- During normal operation, before sec 1 and after sec 2, the current does not change except at the start time.
2- During fault operation, between sec 1 and 2, the current rises suddenly to nearly 800% of the normal current, so it can determine value of (2 KA) as indication of faulted situation.
3- After fault, after sec 2, the current return again to the normal current value but after nearly 0.1 sec. which called the delay time.

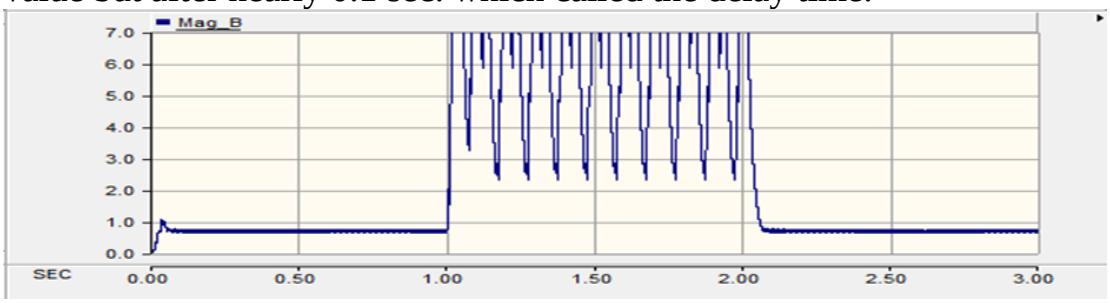


Fig 4-6 internal SCSFCL model component performance (Mag_B)

4-6-2 the resistance (R)

To check the performance of the resistance (R) in the proposed SCSFCL, it can be considered that R referred to a single phase resistance which is symmetric for the three phase. From the figure 4-7 it can obtain that:

1- During normal operation, before sec 1 and after sec 2, resistance R constant and equals 0.01Ω (the start value) except at the start time.
2- During fault operation, between sec 1 and 2, resistance R rises suddenly to 200000Ω and ramps from 100000Ω to 200000Ω.
3- After fault, after sec of 2, the resistance R ramps down again to 0.01Ω after nearly 0.1 sec., after sure that fault was cleared.

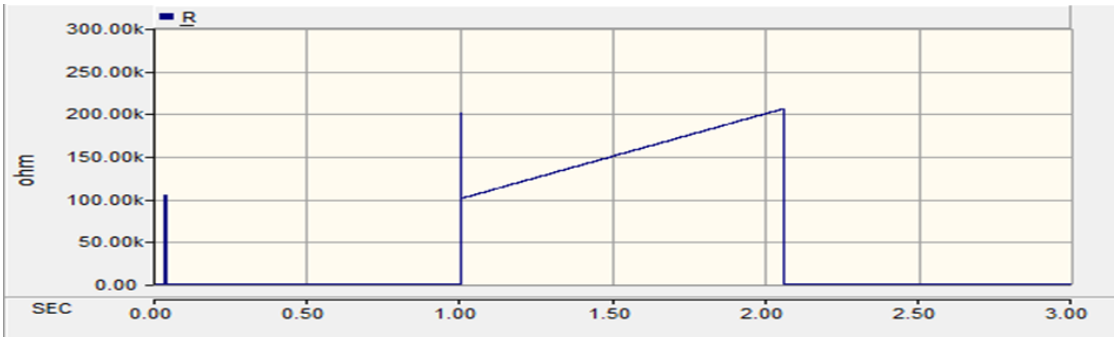


Fig 4-7 internal SCSFCL model component performance (R)

4-6-3 fault detection period (FAULT_DETECT)

To check fault detection period (FAULT_DETECT) in the proposed SCSFCL, from the above figure 4-6 it can obtain that:

1- During normal operation, before sec 1 and after sec 2, there's no fault detection, magnitude of detection equals zero.
2- During fault operation, between sec 1 and 2, fault is detected correctly.
3- After fault, after sec of 2, after nearly 0.1 sec., there's no fault detection, magnitude of detection equals zero, after sure that fault was cleared.

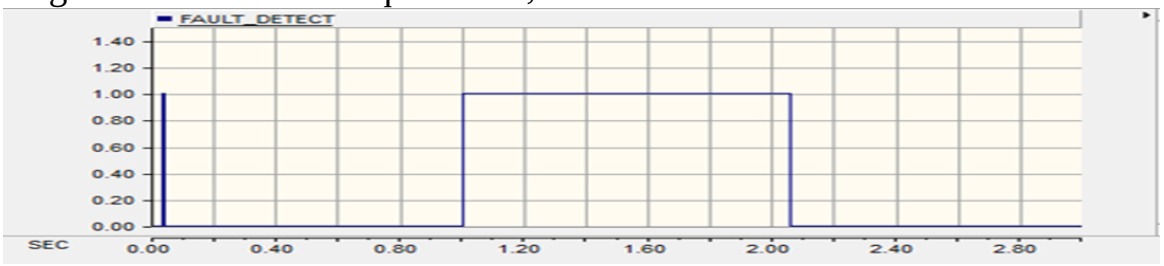


Fig 4-8 internal SCSFCL model component performance (FAULT_DETECT)

4-6-4 the instantaneous phase current through the resistance (I_R_A)

For checking the instantaneous phase current through the resistance (I_R_A) in the proposed SCSFCL model it can choose phase A as an example. From the above figure 4-6 it can obtain that:

1- During normal operation, before sec 1 and after sec 2, the current is the normal current magnitude of nearly 1000A, as same as in normal current of rms phase (B) current. So this behavior assures that all the line current goes through the resistance R which is the theoretical SCSFCL behavior.
2- During fault operation, between sec 1 and 2, the current equals zero. It means that the resistance R acts as an open circuit during a fault which is the theoretical SCSFCL behavior.
3- After fault, after sec 2, the current return again to go through resistance R in the normal current value but after nearly 0.1 sec. which called the delay time.

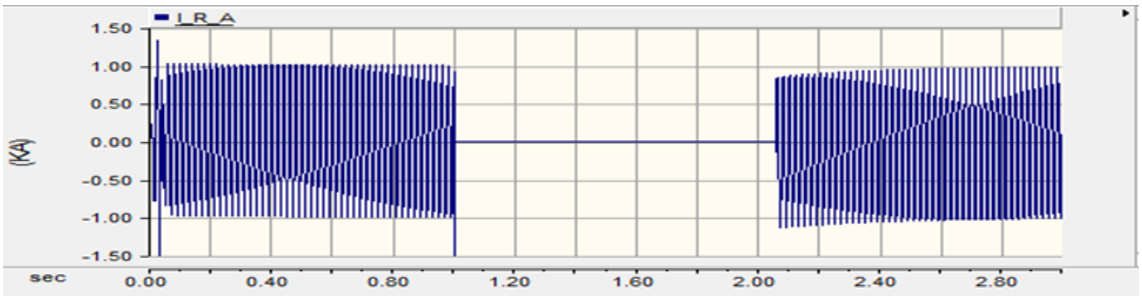


Fig 4-9 internal SCSFCL model component performance (I_R_A)

4-6-5 the Thyristor's operation (Thyristor FP1)

For checking the Thyristor's operation (Thyristor FP1) in the proposed SCSFCL it can choose phase FP1 as an example. From the above figure 4-6 it can obtain that:

1- During normal operation, before sec 1 and after sec 2, Thyristor is off
2- During fault operation, between sec 1 and 2, Thyristor is ON then OFF in continuous sequence. This means that Thyristor 1 is ON when Thyristor 2 is OFF and vice versa in a continuous sequence during fault duration only, which is the theoretical SCSFCL behavior.
3- After fault, after sec of 2 and a nearly 0.1 sec., Thyristor is OFF operation again.

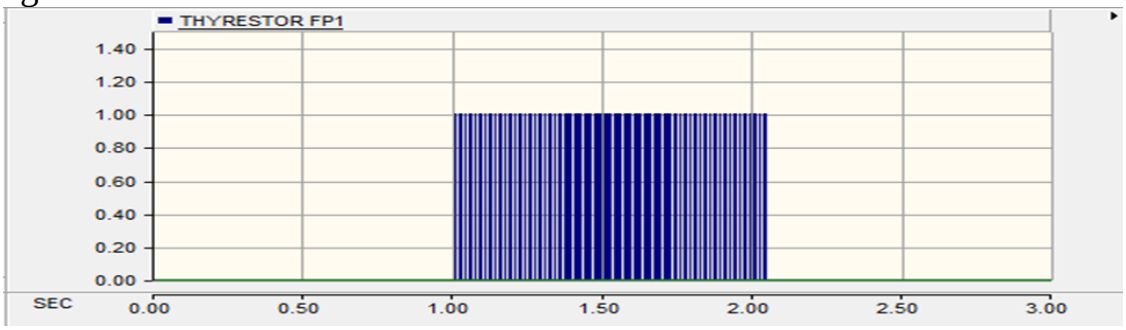


Fig 4-10 internal SCSFCL model component performance (Thyristor FP1)

Chapter 5
TEST SYSTEM SIMULATIONS AND RESULTS

5-1 introduction

The FCL device which located in series with a DG improves failure rate of protective devices. Generally, failure rate of protective devices is depending on different parameters, one of this parameters is the short circuit current passed through it. Because short circuit current is decreased at presence of FCL then failure rate is decreased, resulting in more reliability of the network [2].

The following sections present the results of the FCL insertion in series with a DG in a typical distribution system. The goal of these simulations is to show the effectiveness of the SCSFCL in limiting the fault currents in different fault types and locations. all fault types, namely single-, 2- and 3-phase symmetrical faults will be discussed in details, also four fault locations F1, F2, F3 and F4 are sequentially inserted into the system. In every case, a comparative simulation study between "no DG, with DG and (with DG and SCSFCL)" fault scenarios was obtained and discussed.

All simulation results worked out in different scenarios prove that the SCSFCL works well despite the fault locations and fault types according to:

1- The SCSFCL affects the faulted phases only.
2- SCSFCL design may not be affected when change its location in the distribution system.

5-2 FAULT POSITION (1)

The PSCAD/EMTDC simulation was previously showed in figure 4-4

5-2-1 three phase to ground fault:

It was previously cleared in section 4-5

5-2-2 single phase to ground fault at phase A:

As it is clear from figure 5-1, the fault was successfully limited by the device. The fault current is limited by about 50% through circuit breakers 1 and 2.

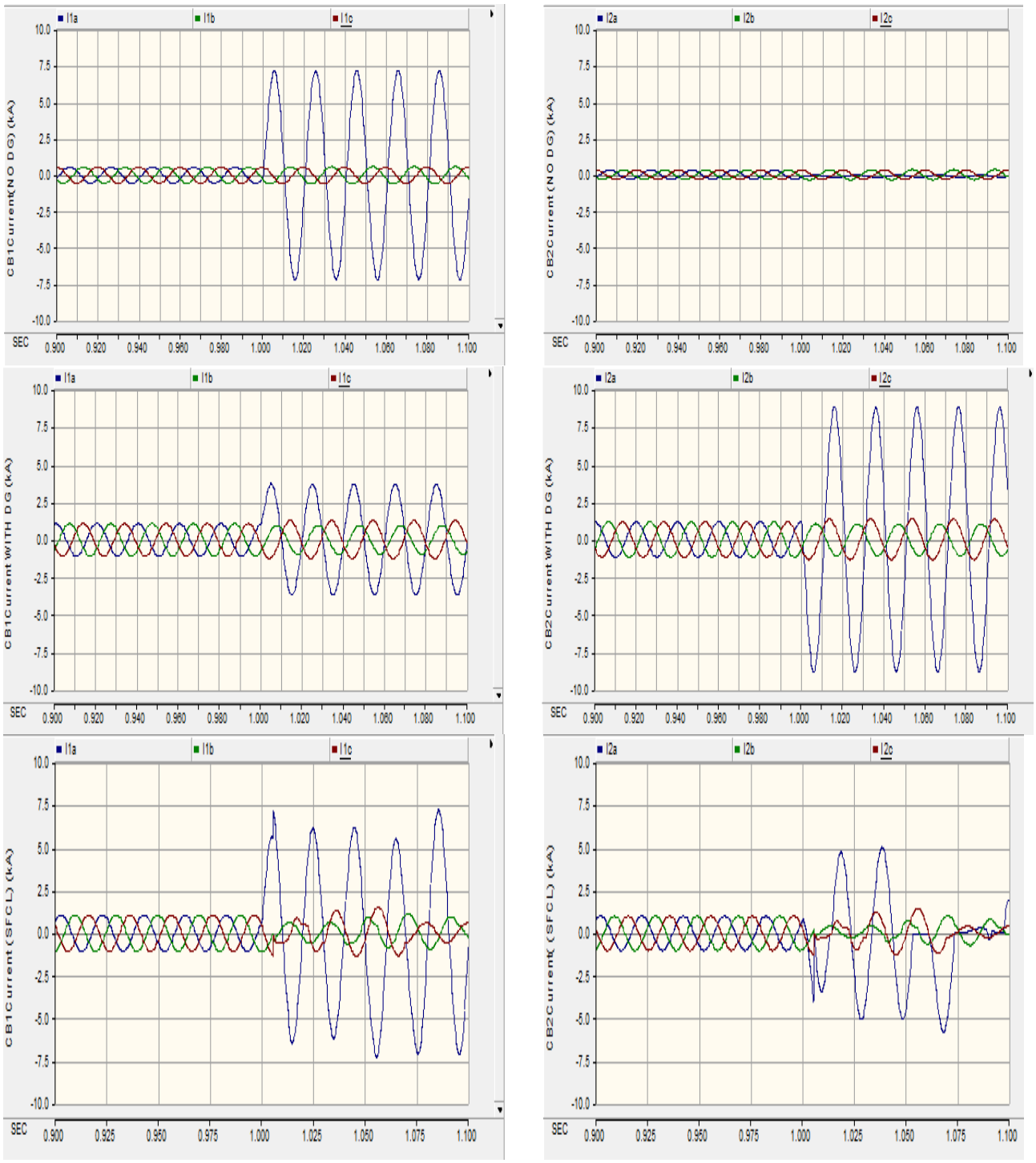


Fig 5-1 current wave shapes in (no DG, with DG, with DG+SCSFCL) scenarios, single phase fault (A)

5-2-3 L to G fault at B:

As it is clear from the figure 5-2 .Similarly to the previous case in section (5-2-2), phase B current only is very high value.

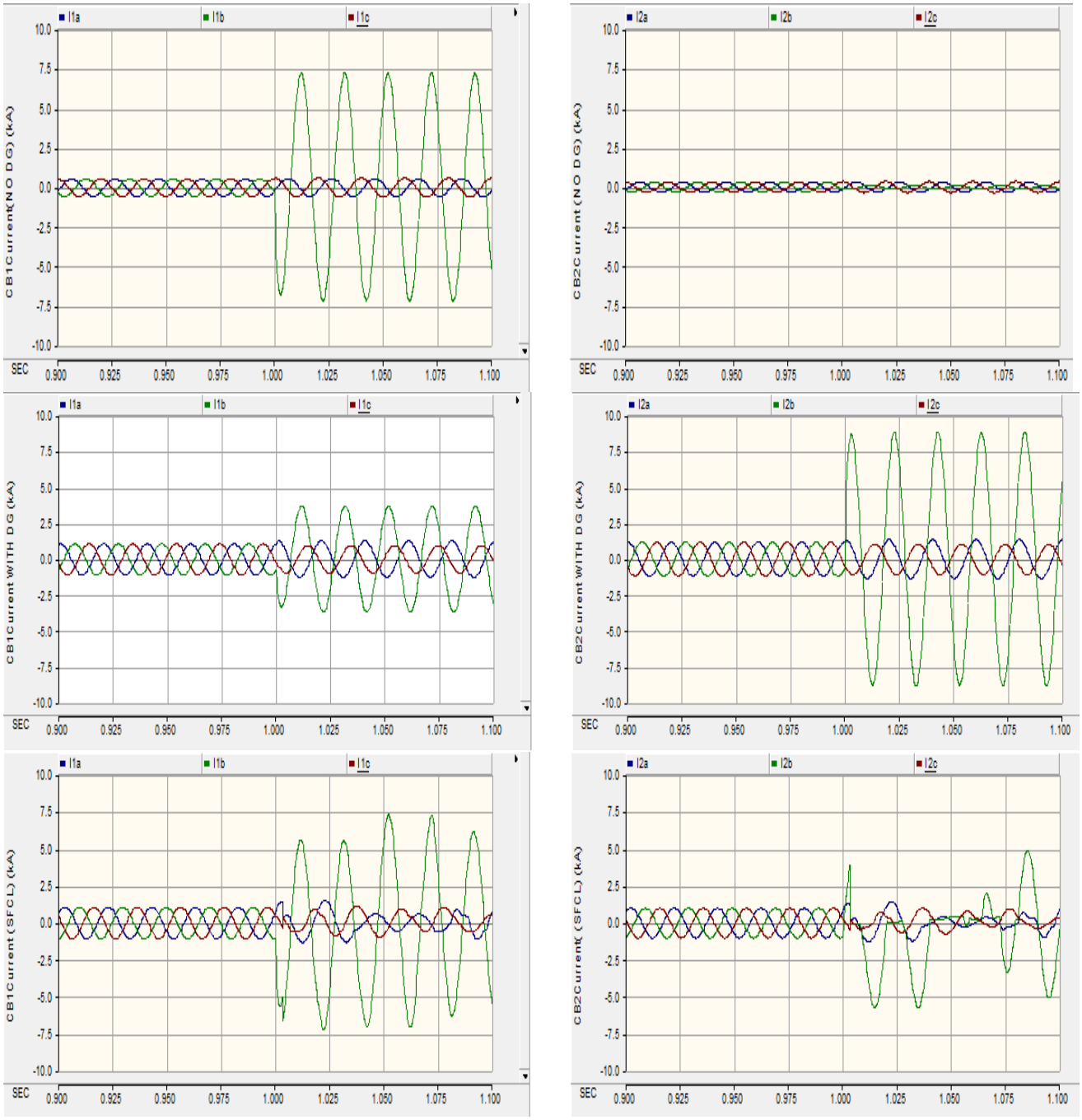


Fig 5-2 current wave shapes in (no DG, with DG, with DG+SCSFCL) scenarios, single phase fault (B)

5-2-4 L (A)-L (B) - G fault

Last PSCAD simulation at F1 was phases A & B fault. Figure 5.3 shown that the fault currents at A & B is almost the same high value.

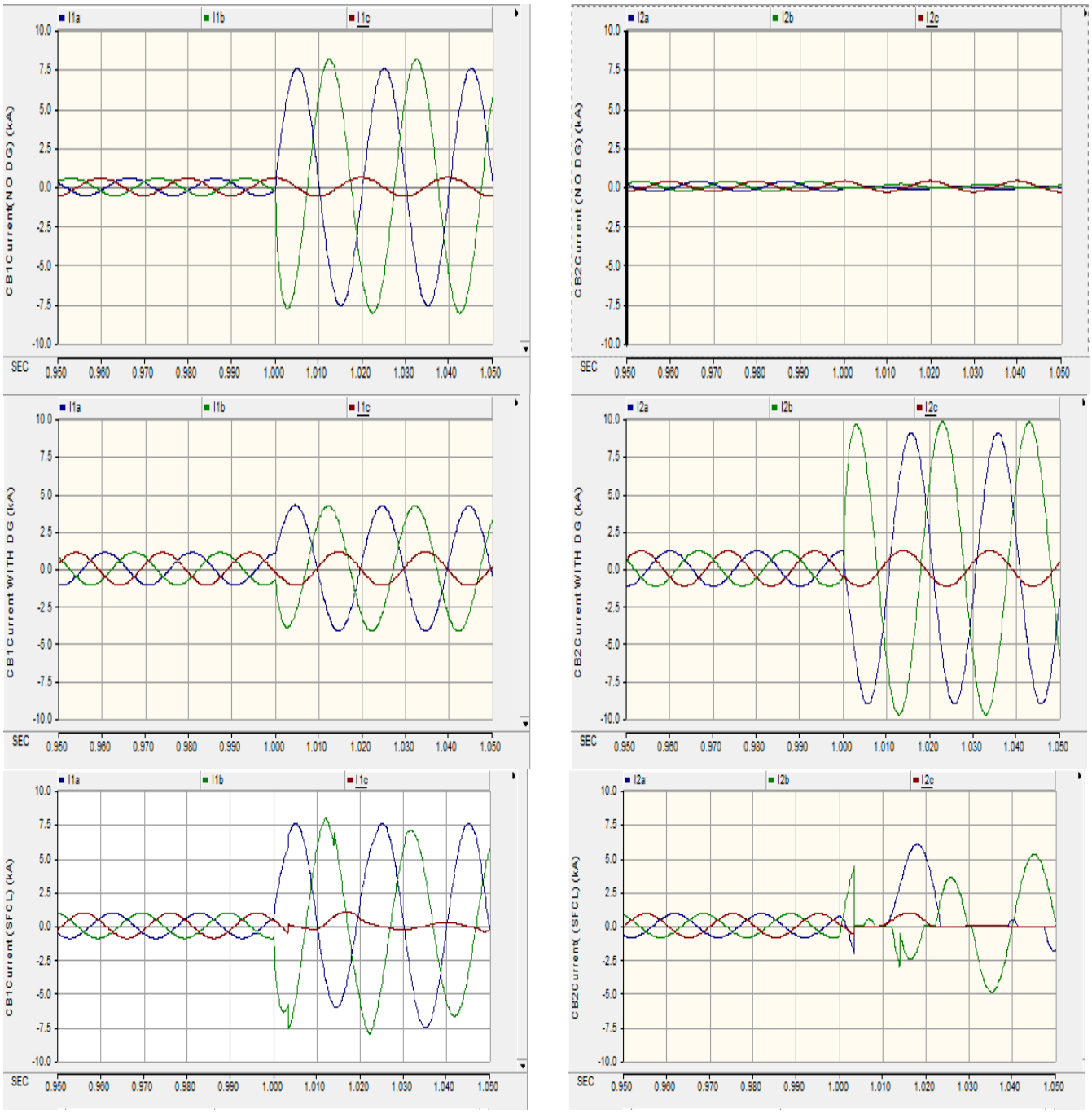


Fig 5-3 current wave shapes (no DG, with DG, with DG+SCSFCL) scenarios in two phases (A and B) fault

5-2-5 phase to phase to ground fault with changing SCSFCL location:

It is very clear that CB2 should be replaced because it will have at least 5KA short circuit current which its 5th rated fault current before adding DG. So, fault currents may damage some equipment in both bus (6) and bus (7).

So we suggest that to change the SCSFCL location to be sited before CB2 and then simulate again the previous fault case L-L-G at A & B at F1.

From the following figure 5-4, it is founded that the instantaneous phase (A) current (I_R_A) which go through the resistance (R) has similar shape as that previously was obtained and discussed in section (4-6-4).

Also, the instantaneous phase (A) current through the SCSFCL has a similar values and wave shape as it was obtained by figure 5-3 'with DG+SCSFCL) scenario'.

So, it can prove that when changing the location of the SCSFCL in the distribution system, there is no change on its performance and so, no change required in its parameters.

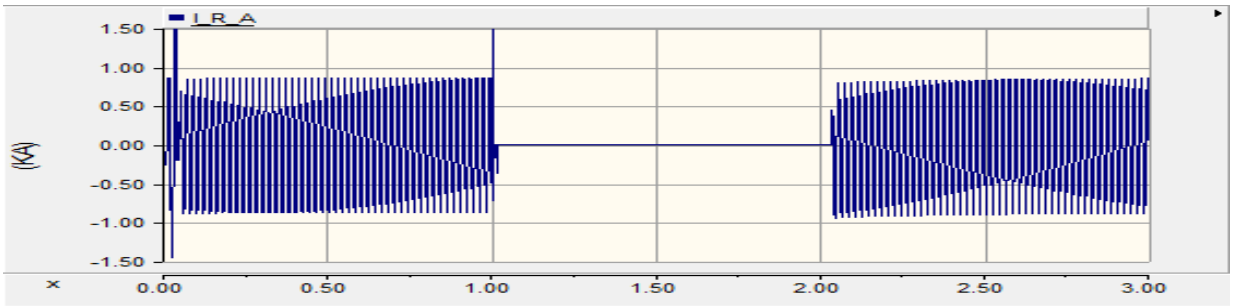


Fig 5-4 the instantaneous phase (A) current through the model's resistance

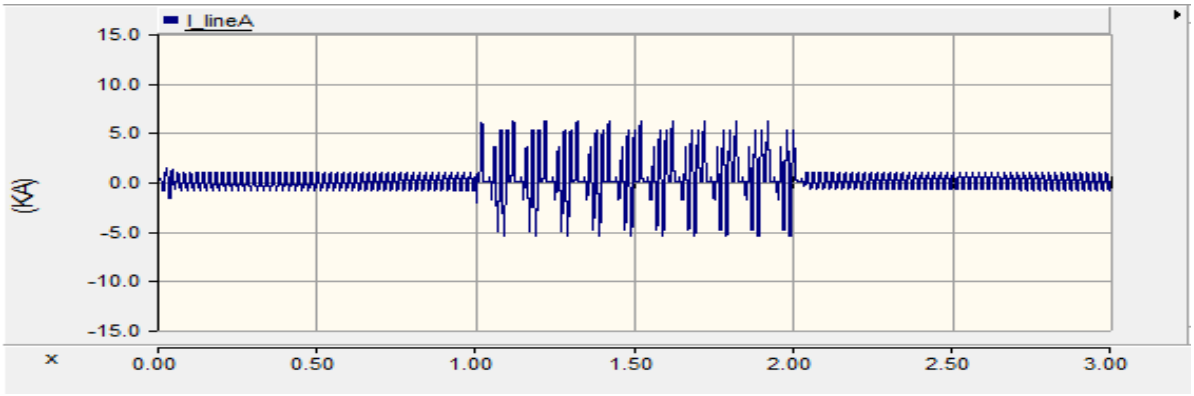


Fig 5-5 the instantaneous model line current through the phase (A)

From the above figures, we can obtain that SCSFCL design may not be affected when change its location in the distribution system.

5-2-6 phase to phase to ground fault (A and C):

Another phase to phase to ground fault simulation was obtained, but with change the faulted phases shown in figure 5-6. This simulation verified that the proposed SCSFCL always mitigates the fault current only in the faulted phases.

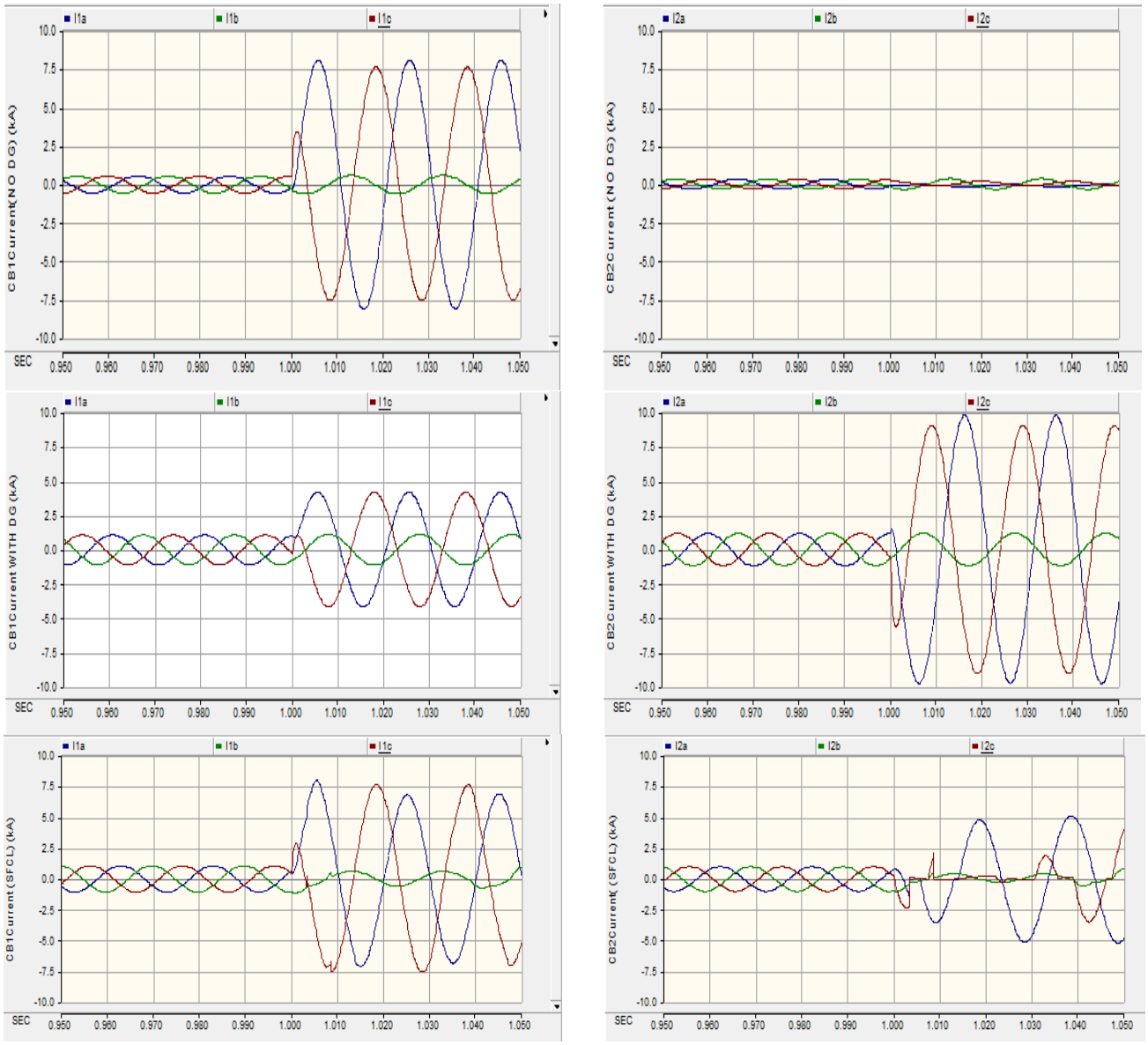


Fig 5-6 current wave shapes (no DG, with DG, with DG+SCSFCL) scenarios in two phase (A and C) fault

5-3 FAULT POSITION (2) & (abc-g) fault

The previous section 5-2 assures that the SCSFCL successfully mitigates the fault current in all fault types (single phase, two phases and three phases to ground faults).

Building on this base, in this section it has to assure that the SCSFCL successfully mitigates the fault currents in all fault locations in the distribution system.

So, Insert a bolted three phase-to-ground fault at position F2 as shown in figure 5.7 which is a detailed PSCAD/EMTDC simulation for fault location(2).

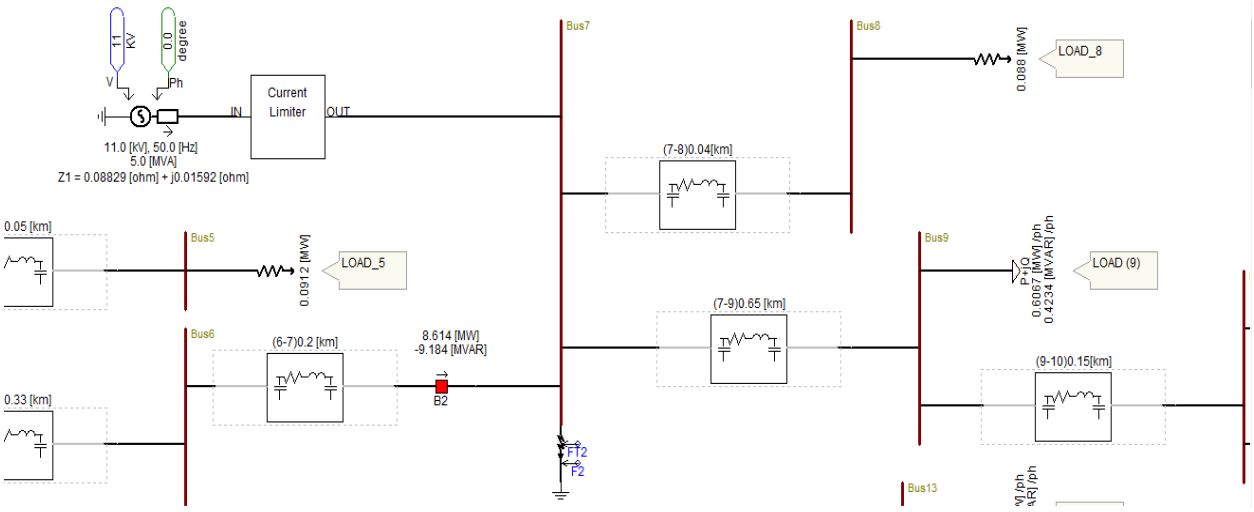


Fig 5-7 2nd PSCAD/EMTDC section of the test system (fault at F2)

From the simulation results in figure 5-8 observe that SCSFCL does not affect the steady state current, because it has a low steady state impedance.

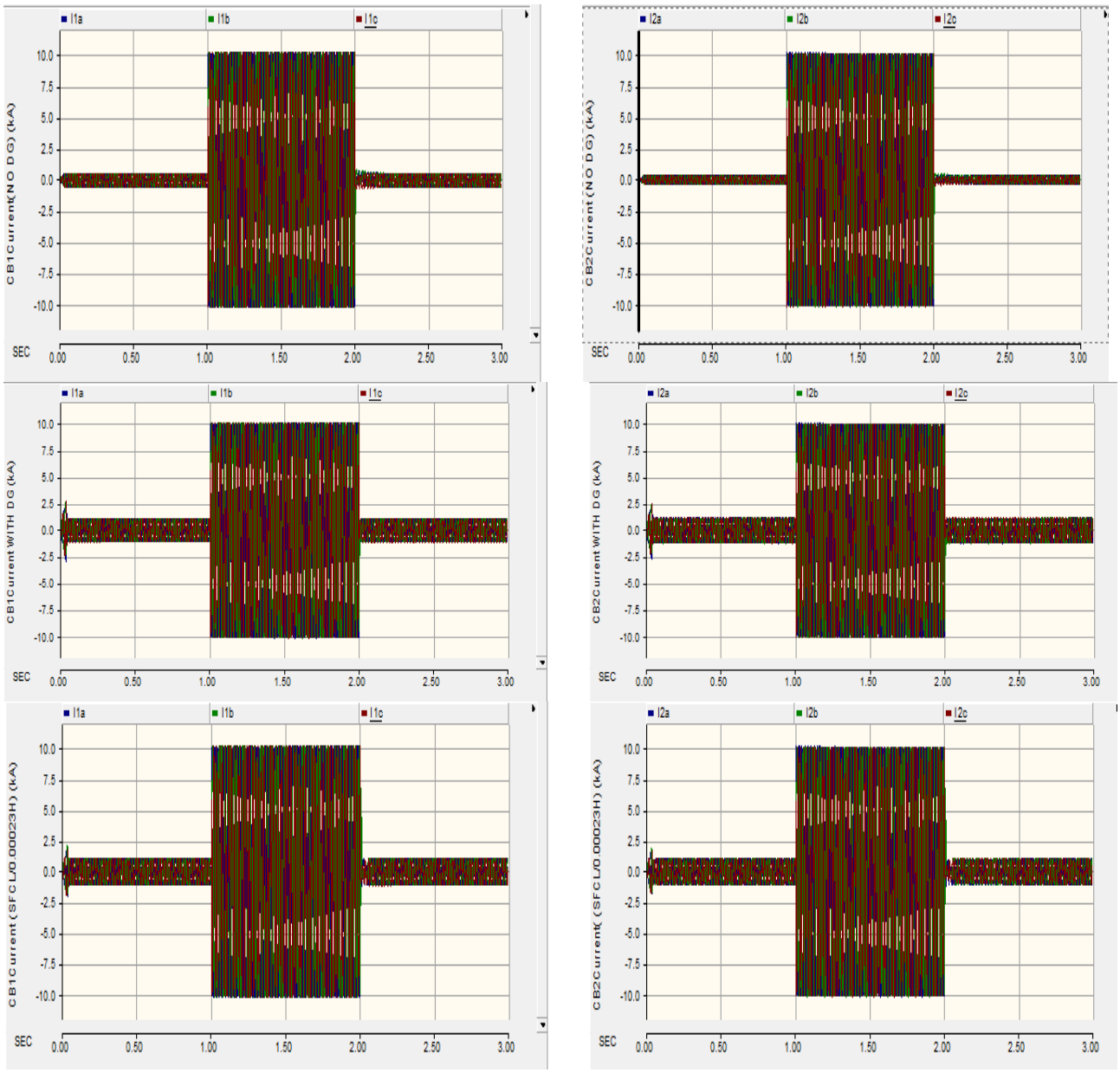


Fig 5-8 current wave shapes in (no DG, with DG, with DG+SCSFCL) scenarios in F2

Also it does not affect the faulty current because the DG insertion in the grid has no effect on the fault currents.

5-4 FAULT POSITION (3) & (abc-g) fault

In this section continue to assure that the SCSFCL is successfully mitigating the fault current in all fault locations in the distribution system.

So, Insert a bolted three phase-to-ground fault at position F3 as shown in figure 5.9 which is a detailed PSCAD/EMTDC simulation for fault location(3).

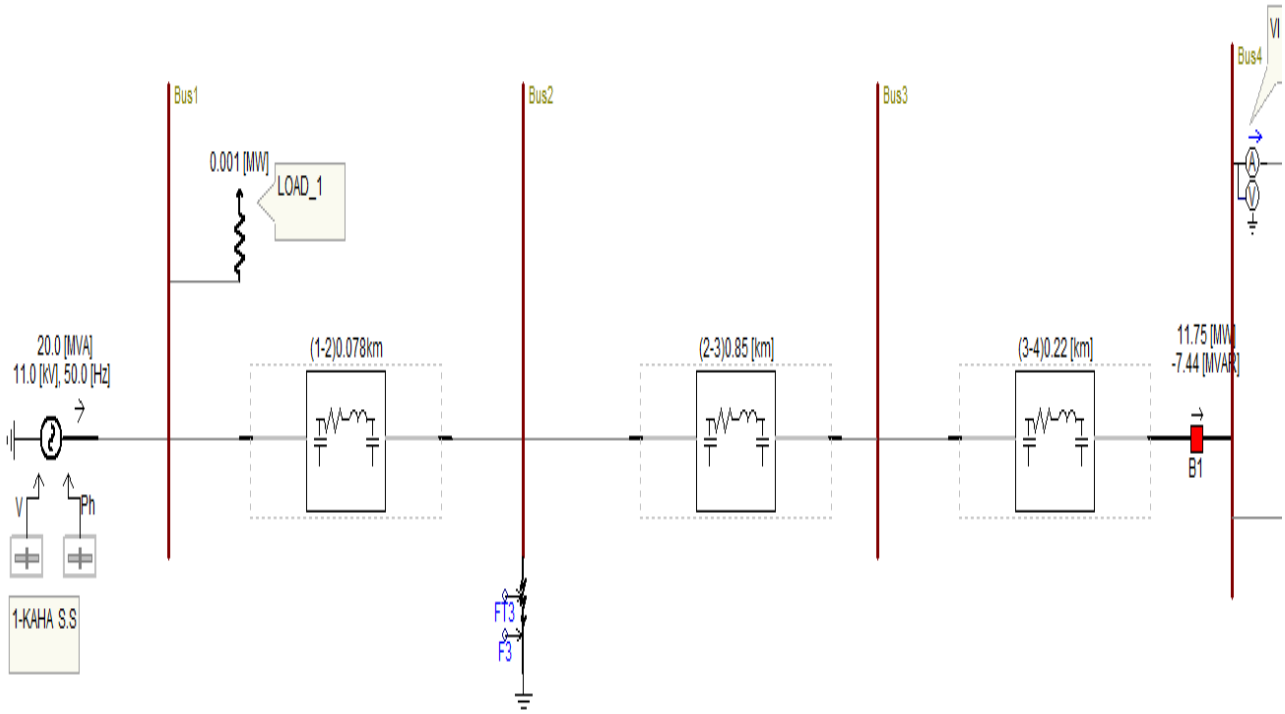


Fig 5-9 3rd PSCAD/EMTDC section of the test system (fault at F3)

The results of the simulation will be shown in figure 5-10. From this figure it can obtain that, if fault was inserted at location (3), then the two circuit breakers (CB1, and CB2) in the test system will observe the same amount of currents. So the SCSFCL mitigates the fault currents of CB1, and CB2 in the same range (from 8.75kA to 6.25 kA).

Also, harmonics will be observed during the fault only.

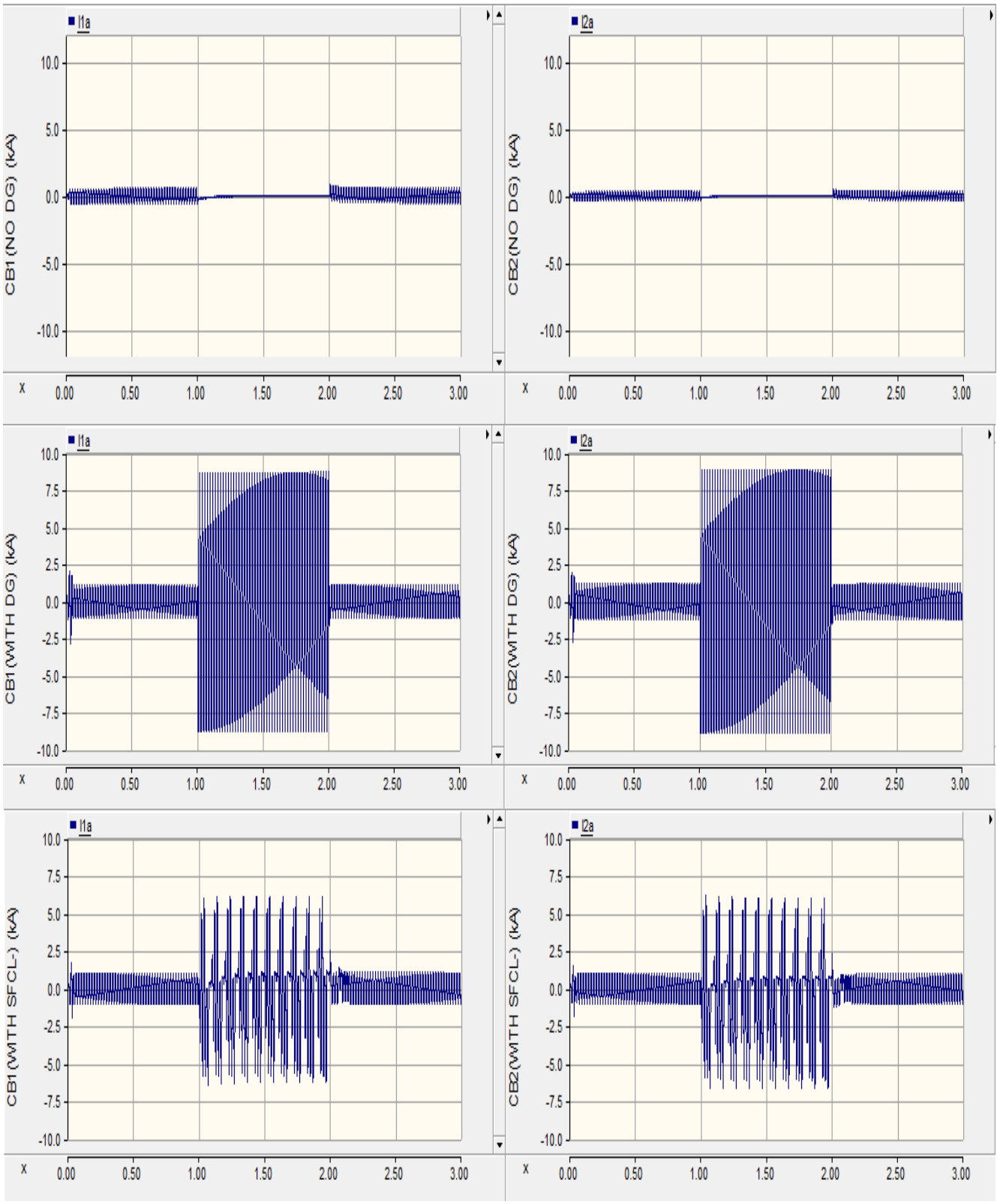


Fig 5-10 single phase current wave shapes in (no DG, with DG, with DG+SCSFCL) scenarios in F3

5-5FAULT POSITION (4) & (abc-g) fault

In this section the last simulation to assure that the SCSFCL is successfully mitigates the fault current in all fault locations in the distribution system.

So, Insert a bolted three phase-to-ground fault at position F4 as shown in figure 5.11 which is a detailed PSCAD/EMTDC simulation for fault location(4).

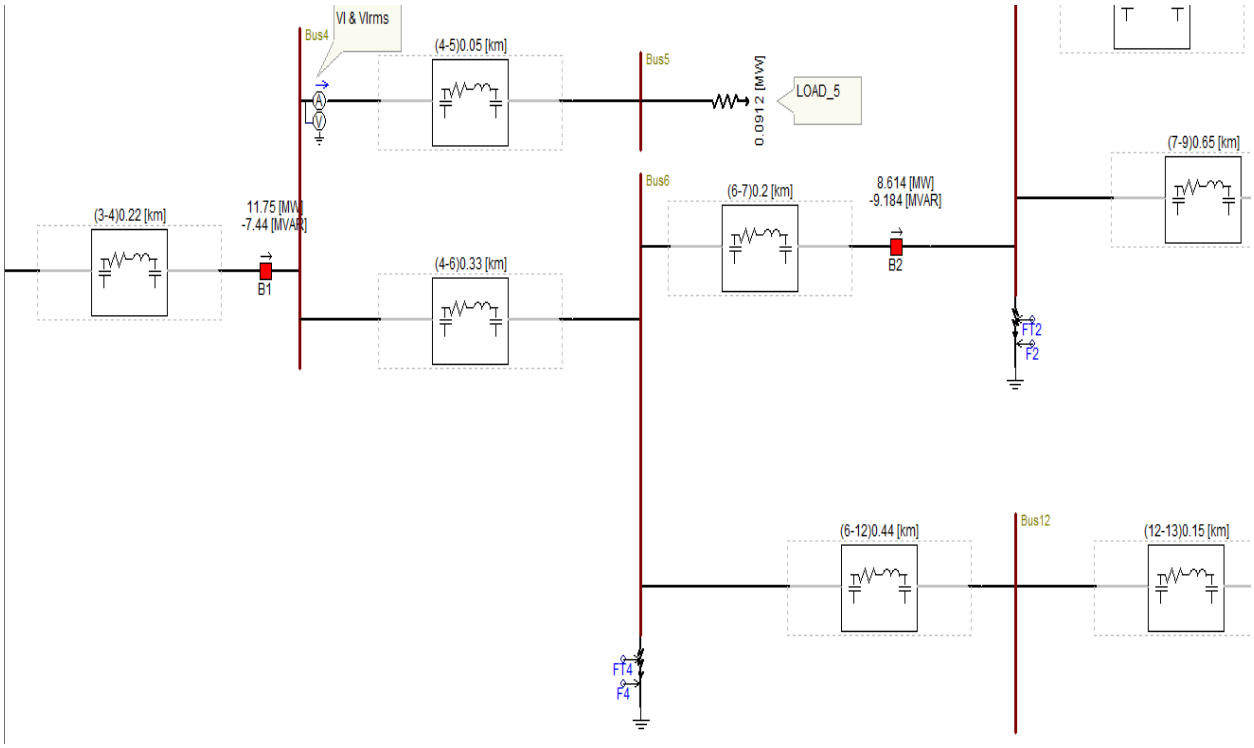


Fig 5-11 4th PSCAD/EMTDC section of the test system (fault at F4)

From simulation results which shown in figure 5-12, The SCSFCL limited the fault current through CB2 from 30 kA to 10kA with 33% reduction rate , while the three-phase fault current in CB1 does not mitigated at all because this fault current through CB1 does not change by inserting DG in the test system.

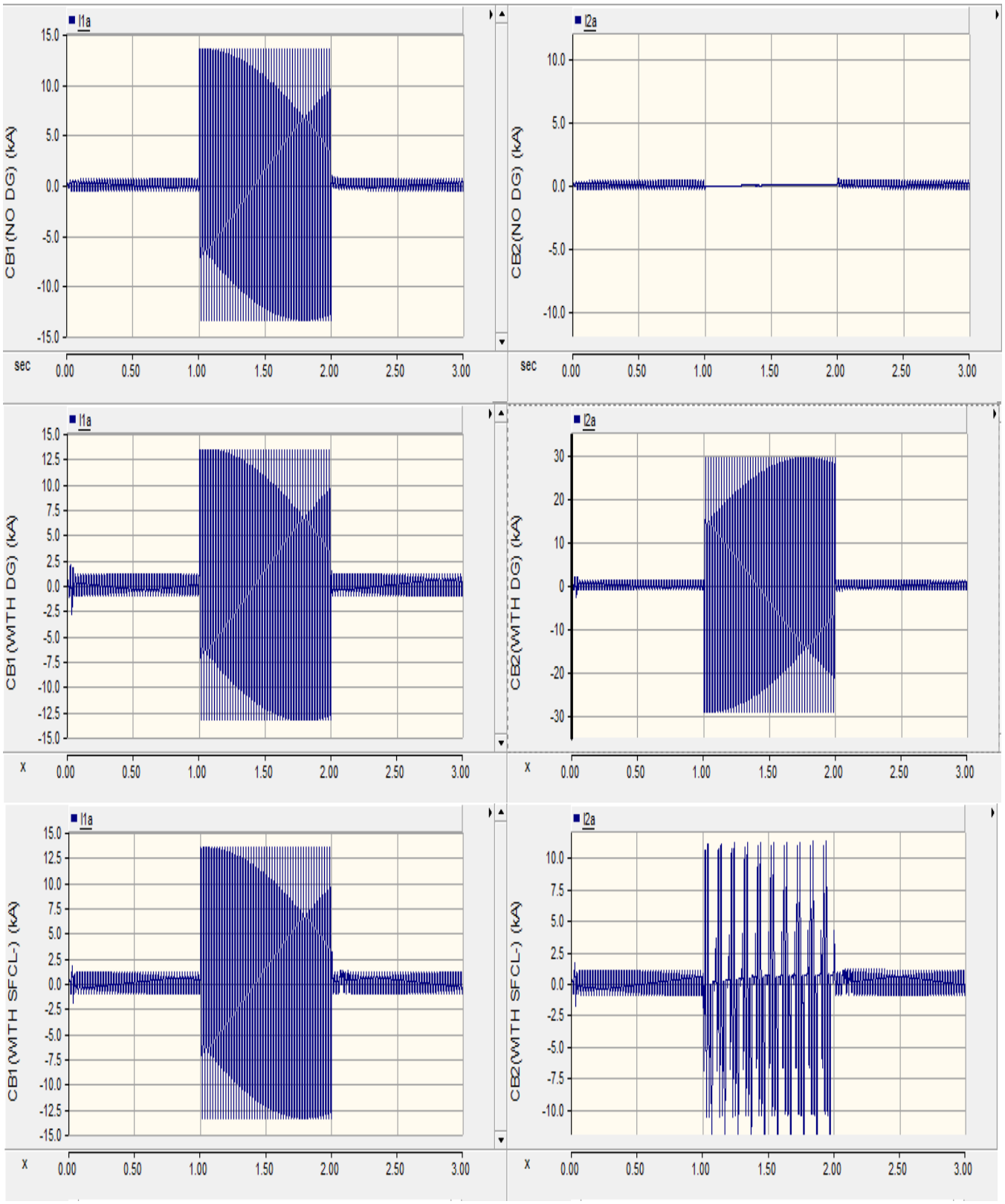


Fig 5-12 current wave shapes in (no DG, with DG, with DG+SCSFCL) scenarios in F4

Chapter 6. CONCLUSION AND FUTURE WORK

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

Summary and Conclusions of thesis

Due to continuous load growth in modern grids, Renewable Energy Resource (RER) are installed within the power network. So, fault currents may be exceed the existing circuit breakers interrupting ratings and then many CBs are underrated.

Many traditional aspects was discussed to solve this problem, but all these aspects have performances that may not practical in many cases , so it have to achieve a modern device to be compatible with the modern grids and its modern specifications.

Such modern fault current limiting management is FCL devices which can be used to reduce the amplitude of fault currents to protect solid state components in modern grids and also to speed up both fault detection and fault interruption. Then FCL make the fault event in grid has less disturbance [15].

Besides that in modern grid, when short circuit connection happens at a presence of DG, the coordination between fuse and re-closer is mismatched and so decreases the network reliability. FCL is used also to solve this problem and generally to improve the reliability of the modern distribution networks [2] [43].

The FCL devices was divided in to different categories which have different particular characteristics. In general, FCL is assumed as an active device which its operation can be self-triggered or need another externally triggering device.

Nowadays many different types of fault current limiters were installed on power grids all over the world,

The FCL which was built using semiconductor switching devices is assumed to be an externally trigger device and the FCL which was built using superconducting materials is assumed to be a self- trigger device [5]

The self-triggered FCL devices use the material's physical properties for activation such as superconductors which was used to limit fault currents since the discovery of superconductor materials.

- The resistive SFCL should be installed in series with a breaker (The CB interrupts the residual fault current and then the superconducting element

will have a fast recovery) because if the resistive SFCL replaces the existing breaker, then the steady state flexibility would be reduced [6].

- When the resistive SFCL insertion in South African power grid was compared to other traditional fault current mitigation techniques, it founded that the high capital cost of the resistive SFCL is a main disadvantage while its reduced operating cost over a 25 year service life is the main resistive SFCL advantage. So it is not the optimum alternative for fault level management in South African power grid. Whatever this conclusion may not be globally applicable [6].
- The non-superconducting technologies FCLs are independent on superconductor materials to perform the current limiting action. But it depends on power electronic components which includes current limiting fuses and solid-state FCL devices.
- Unlike resistive SFCLs, which require cooling time between succession limiting actions to cool the superconducting components, the saturated core approach can manage several limiting actions in short time because the superconductor does not quench [7].

While, it cannot replace the under rated circuit breakers all over a smart grid. One SCSFCL only is located at the interconnecting bus between the transmission and distribution networks will keeps all already existed CBs within their interrupting ratings.

Actually, in 2009, a SCSFCL device was located at small distribution network in California, USA and, during a lightning-induced fault in 2010, the SCSFCL device limited the fault current as expected [15].

Many companies around world are manufacturing FCL devices,

The SCSFCL utilizes copper AC coils wound onto iron core to present very low impedance during normal current operation. After fault clearing, the FCL immediately (<1ms) returns to its low impedance again in normal condition and so the SCSFCL ready to protect the grid against any faults [41].

- As SCSFCL was located after a transformer, it offers a reduced fault levels in substation and accommodates switchgear ratings.
  In this location, it can install one or more FCLs depending on the required fault current reduction.
  In this location, the FCL can be included in the transformer protection zone, with no additional protection devices.

Also the FCL is used to improve load balancing between different rated power feeder transformers. So, FCL enables increasing the capacity on existing grids [41].

- FCL may be connected in a bus-tie location and offers the advantages of grid interconnectivity, flexible arrangements and increased power quality.
  Also in this location, one or more FCLs may be installed, depending on the bus topology and fault current reduction required, with small changes on settings of existing protection devices.
  It can parallel the FCL with the existing bus-tie circuit breaker, with no additional protection devices [41].

This thesis introduced an efficient solution of the problem of increasing the fault current short circuit levels in the electrical grid due to their extensions by using a proposed SCSFCL. The proposed SCSFCL was modeled and simulated in PSCAD environment.

An 11 KV west delta Egyptian distribution system Tanta region was modeled as a typical network with the proposed simulated model. The studied distribution system consists of 15 buses. Bus 1 is 66/11 transformer. F1, F2, F3, and F4 are the expected fault locations while CB1 and CB2 are two circuit breakers.

The variation of FCL inductance was analyzed to find the proposed value.

Six different cases are simulated and discussed to test the system. The proposed FCL was capable to mitigate the faults current level to be nearby their values without DG.

The model parameters were adapted by the author to restore the fault current levels to their values before the integration of the DG. It founded that the acceptable wave current shape is in scenario ‘with DG&SCSFCL/0.0023H’ after checking the performance of that FCL by carrying out various simulations.

Six case studies are considered cases as follow sequence:

1) Check current waveforms in the distribution system with and without an SCSFCL cases, then check efficiency of the SCSFCL to regains the fault current levels in the distribution system to that levels before inserting the DG in the grid, which is the theoretical SCSFCL behavior.

2) A comparative study between “no DG, with DG and (with DG and SCSFCL)” fault cases.

• The bolted three phase-to-ground faults are not the only faults used in all thesis simulations, despite it is the highest value and the worst case scenario for any distribution system fault current. But in this thesis it was simulated different fault types and locations to assure that the SCSFCL mitigates the fault current during any type of fault at any point in the system, such as:

- If fault was inserted at location (3), then the two circuit breakers (CB1, and CB2) in the test system will observe the same amount of currents. So the SCSFCL mitigates the fault currents of CB1, and CB2 in the same range (from 8.75kA to 6.25 kA).

  Also, harmonics will be observed during the fault only.

- if fault was inserted at location (4)The SCSFCL limited the fault current through CB2 from 30 kA to 10kA with 33% reduction rate , while the three-phase fault current in CB1 does not mitigated at all because this fault current through CB1 does not change by inserting DG in the test system.

The obtained results ensure that the model is easily used in other distribution systems. The results show also that the model performances can meet utility's needs in mitigating fault current at all types of fault and different fault positions. SCSFCL does not affect the steady state currents, because it has a low steady state impedance

.

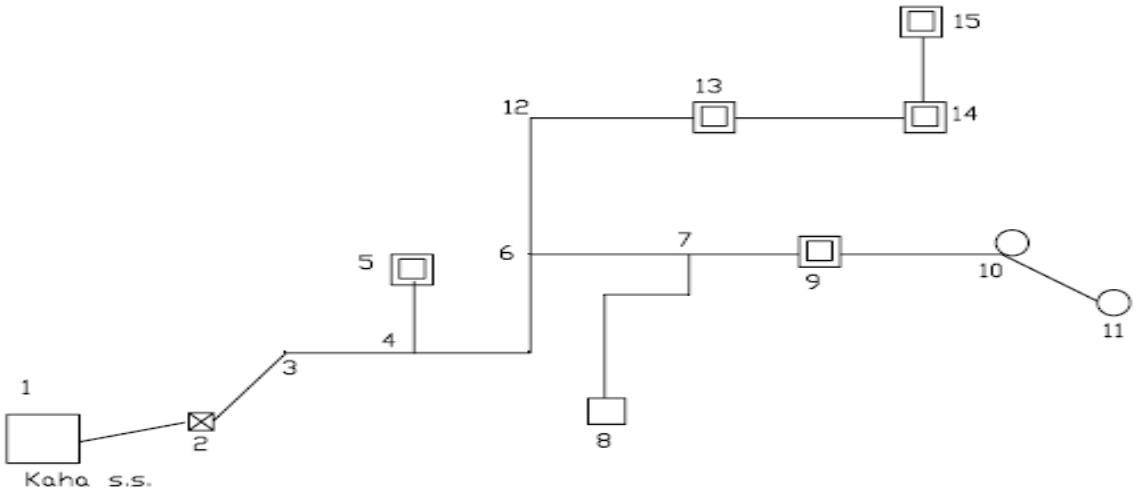
Future Work

In modern grid, when short circuit connection happens at a presence of DG, the coordination between fuse and re-closer is mismatched and so decreases the network reliability. FCL is used to solve this problem and generally to improve the reliability of the modern distribution networks

The future work is for designing SCSFCLs prototype on ways of reducing the initial capital cost to be viable for power utilities consideration in fault level management.

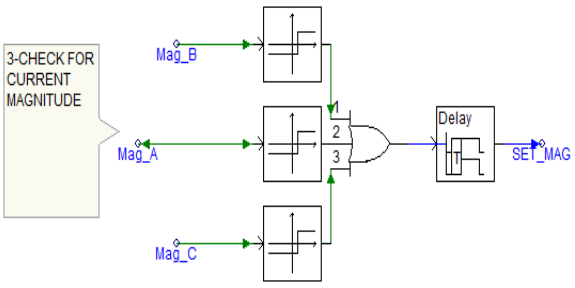
Then to investigate the SCSFCL prototype operation in the actual protection devices.

Appendix (A) single line diagram of the test bed system [8]

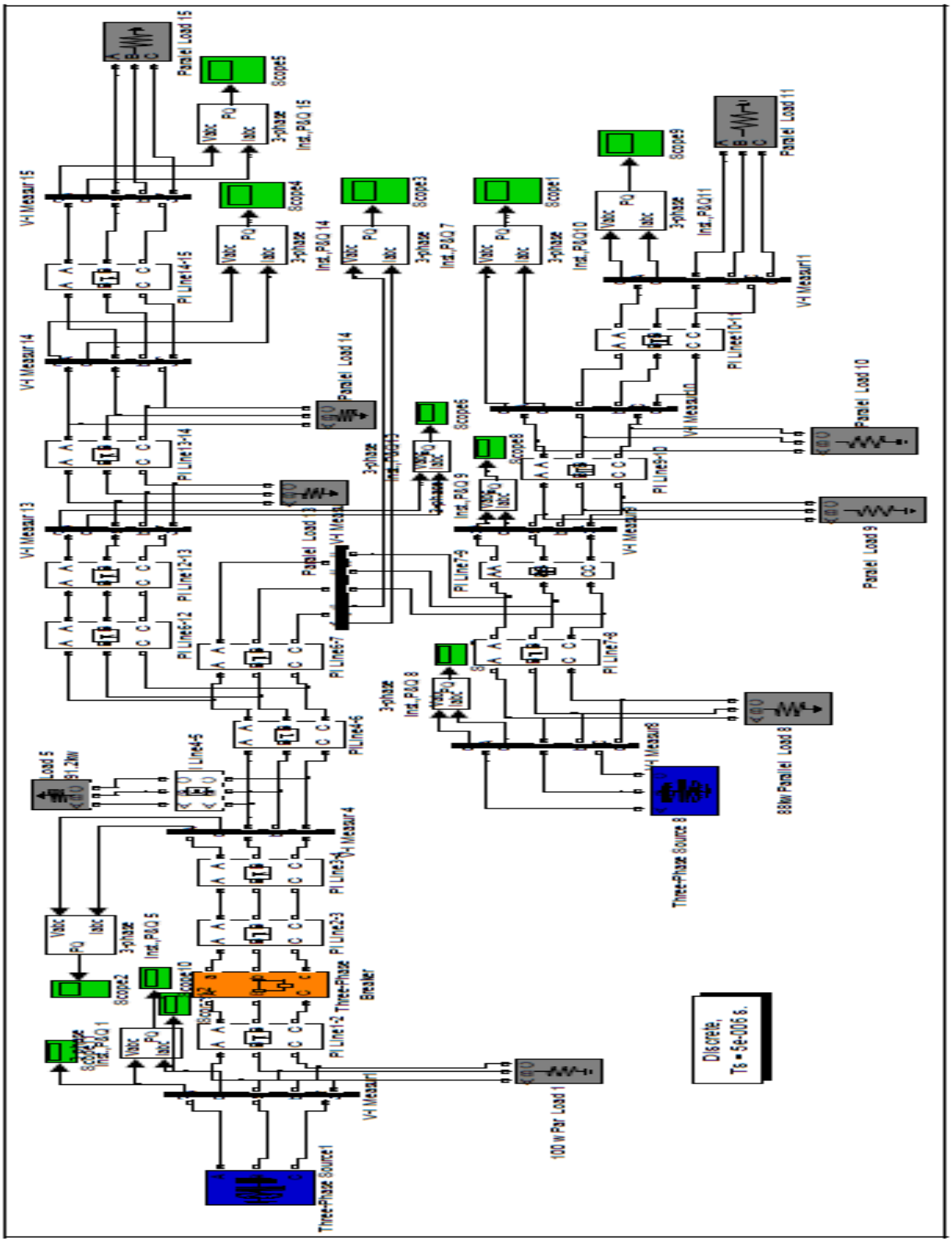


Appendix (B) part of proposed PSCAD/EMTDC model

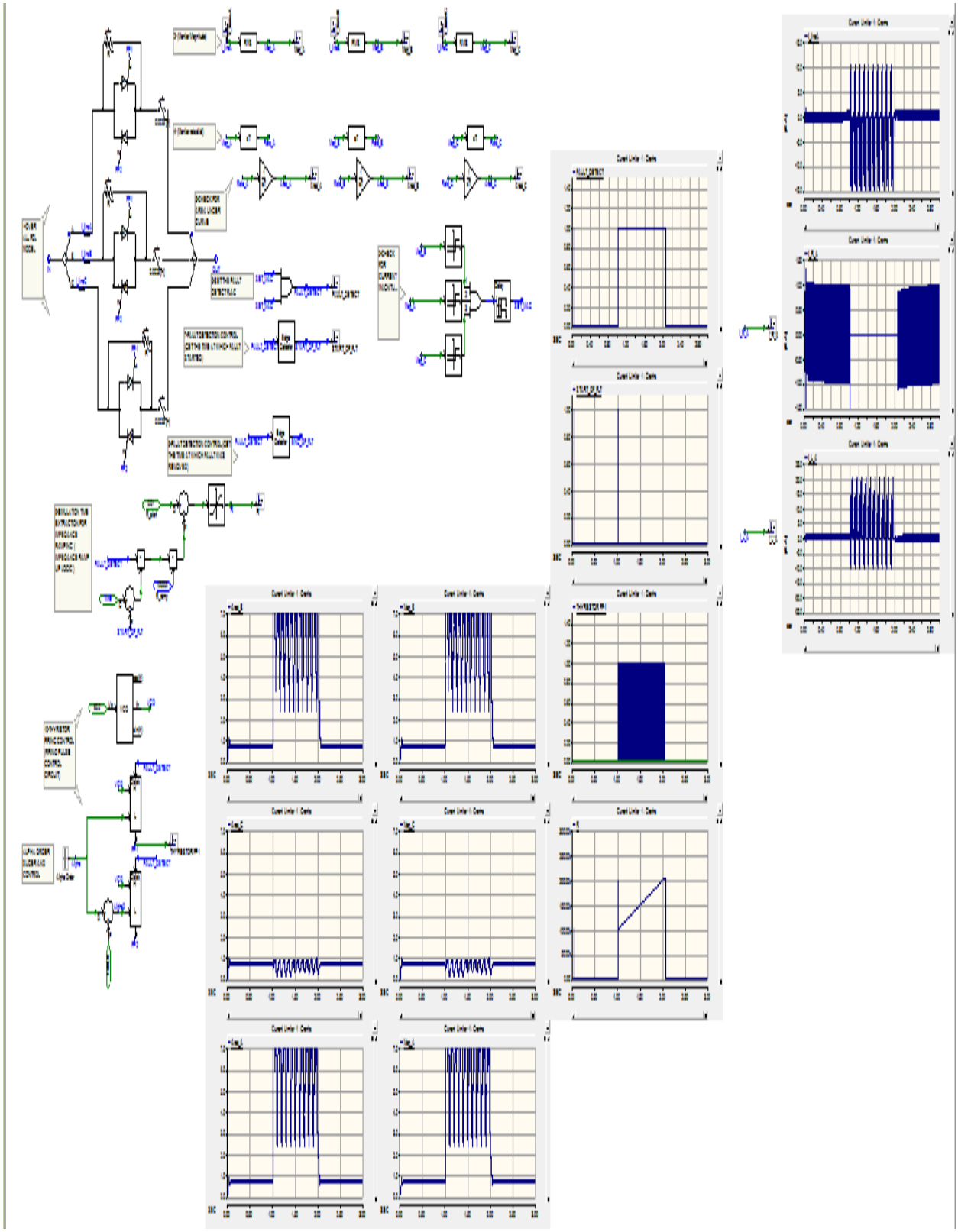
L (H)	Corresponding comparator
0.23	0.04
0.023	0.4
0.0023	1
0.00023	2



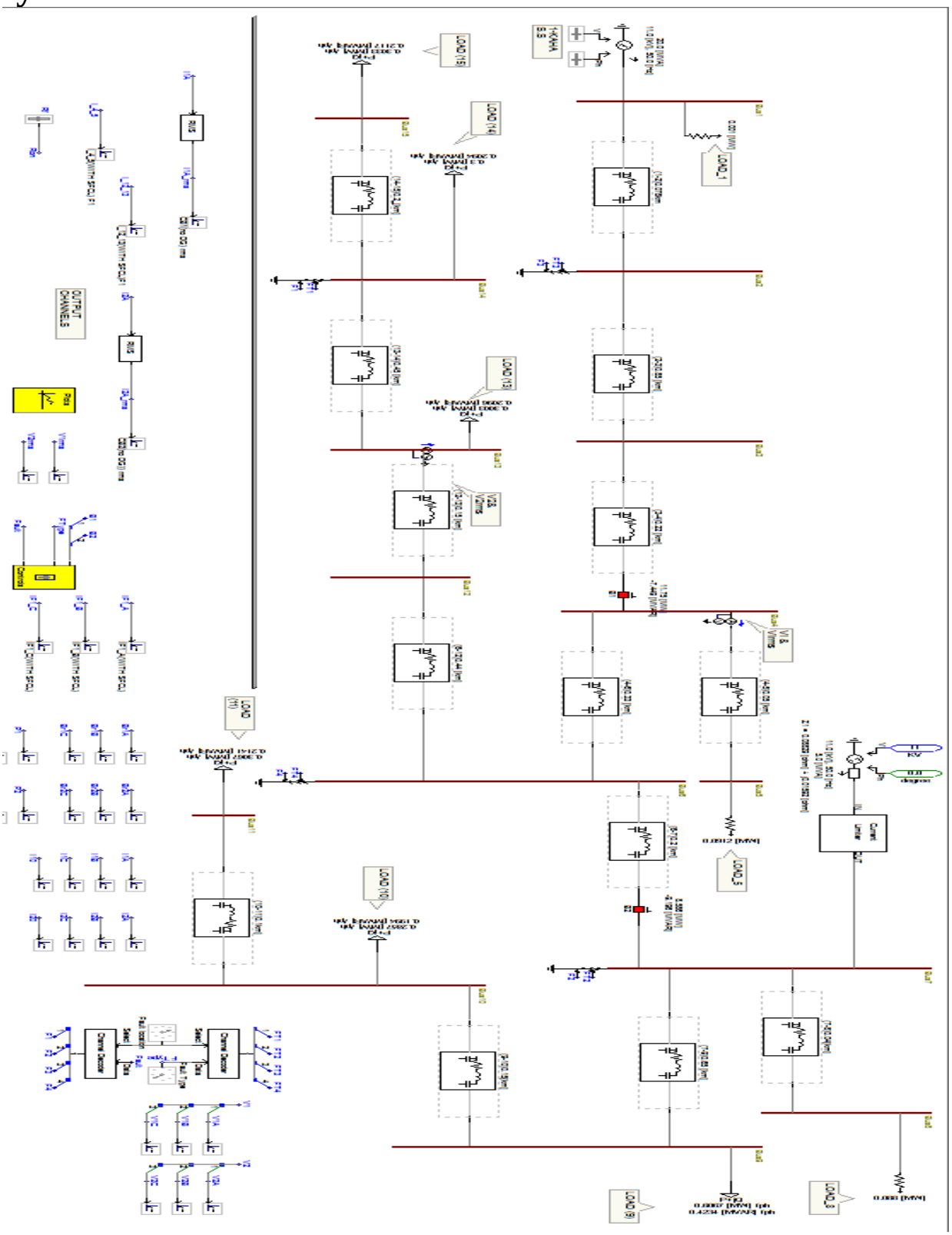
Appendix (C) MATLAB simulation of the test system [8]



Appendix (D) PSCAD/EMTDC simulation of the MODEL



Appendix (E) PSCAD/EMTDC simulation of the test system



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