Design and Experimental Investigation of Three-Phase Inductive Type Superconducting Fault Current Limiter based on Current Injection Method

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Abstract- This paper presents the experiment investigation of using the superconducting fault current limiter (SFCL) in combination with a circuit breaker (CB) to mitigate the consequences of various fault types in electrical power systems. From the experimental results the SFCL-CB system can provide fast and reliable fault protection, reduce the fault current, prevent damage to the system, prevent the fault from spreading to other parts of the system, and reduce the stress on other components in the system. The proposed system also demonstrates that the SFCL has a simple and reliable structure and a flexible control strategy. The objective was to establish an interdisciplinary application using superconductor-semiconductor coupling from the perspective of applied superconductivity and AC load. The experimental setup included a 380V/2.9A magnetic-controlled switcher-type fault current limiter, which was built to verify its characteristic. The real-time response of the SFCL system during a fault event was found to be critical in preventing damage to the system, and the SFCL's ability to limit the fault current and interrupt it safely made it an effective solution for protecting electrical power systems.

Keywords- SFCL; power semiconductor; commutation circuit and experimental investigation.

1. Introduction

Short-circuits may result in irreparable system damage if the overcurrent exceeds the installed equipment's capacity, so it's critical to keep the fault current within safe bounds.

To address this issue, possible solutions include replacing equipment in overstressed substations, constructing additional ones concurrently or adding a fault current limiter (FCL) device [1]. The restructuring of electric systems in many countries has led to increased fault current levels due to the connection of new energy suppliers. This can overstress installed protection equipment, necessitating changes in the system. However, replacing overstressed equipment can be time-consuming and limiting the fault current to safe levels for circuit breaker (CB) functioning can be difficult and expensive. FCL devices have been sought after since the 1970s to provide reliable fault current limiting. While still preserving redundancy and reliability, installing FCL devices is less expensive than replacing all of the equipment at a substation. [1-3]. In recent years, a number of current-limiting equipment and strategies have been presented to lessen the effects of short circuits. [3-10]. A device commonly used for limiting short-circuit current is the current-limiting reactor. It is designed to limit the current during abnormal conditions. Fuse can also provide protection by interrupting the fault current before it reaches to highest in the circuit [4]. Fault current limiters (FCLs) offer several advantages such as allowing the use of old or using less effective security measures, avoiding exorbitant device replacements, and protecting devices from the first peak during short circuits [4-6]. FCLs not only limit fault currents but also improve voltage characteristics during fault conditions. They also have a quick recovery time after the short circuit is extinguished and can be effectively coordinated with the available protection system.

The use of SFCL has emerged as a promising solution in comparison to conventional protection methods. This is owing to the fact that SFCLs are lossless during normal current operation since superconductors have zero resistance, and they provide a self-acting high impedance during over-current faults without the need for additional fault discovery and working circuits [10 -12]. Over the past few decades, for use in power transmission and distribution system applications, a number of SFCL concepts and schemes have been presented, each with a particular operating philosophy. There are many different classifications for FCLs, including saturated core type, superconducting (SC) type, electromechanical type, transformer type [13], reactor type [14] and resistive type [15], etc. recently, several high-voltage and high-capacity SFCL patterns have been successfully established and implemented in real power grid operations. For instance, in China, there is an ongoing 220-kV AC grid experimentally project involving SFCL technology [16].

To investigate the performance of a three-phase SFCL through both experimental and numerical approaches, and to verify. The ability of the SFCL to limit fault currents and to provide protection for power systems, also aimed to compare the results obtained from the experimental and numerical analyses to validate the effectiveness of the SFCL.

The experimentally investigate a three-phase high SFCL with two different trigger modes, namely resistive and inductive trigger modes, and to compare their performances. The validation of the FCL in reducing the fault current during a power system fault and to provide insight into the optimal trigger mode for achieving the best performance. The study also aimed to contribute to the development and optimization of high temperature SFCL for use in power systems [18].
Inspect the performance of a 3-phase resistive SFCL through experimental study. The limiter's efficiency in reducing fault currents and to analyze its thermal behavior under fault conditions, a limiter control strategy based on the creation of practical SFCL for power systems to enhance its fault current limiting performance [19].

The study [20] aimed to explore the performance of the proposed FCL in terms of current limiting capability, voltage drop, and stability during normal operation and fault conditions. The researchers also aimed to optimize the design of the FCL to enhance its performance and evaluate its practical feasibility for application in power systems [20].

The hybrid limiter of three-phase AC systems [21] was effective at reducing the fault current, reducing the temperature rise and power losses, and improving the power quality.

The three-phase FCL based on high-temperature SC cables. The FCL was designed to be compact and efficient, with high current limiting ratio and low insertion loss. Additionally, it sought to assess how the FCL performed in various fault scenarios, and compare its performance with that of conventional FCLs [22].

Hamada et al. [23] is to analyze the performance of a three-phase SFCL with one commutation circuit. The study aims look into the impact of the proposed limiter on the SFCL and the transient stability of the power system. Also carried out simulations and experiments to evaluate the limiter's performance and analyze the obtained results to verify the proposed limiter's efficiency [23].

The study [24] considers three operational modes of microgrids, including grid connected mode, islanded mode, and transition mode. In each mode, the authors proposed a specific objective function to optimize the sizing of the FCLs. Moreover, the optimal sizing of FCLs varied for different operational modes, highlighting the importance of considering different operational modes when sizing FCLs in microgrids [24].

In [25], the presents the basic working principle of SFCLs and their impact on power system fault current levels and dynamics. Furthermore, the discusses the benefits of SFCLs, such as reduced equipment damage, increased system stability, and improved power quality, and provides a comprehensive review of recent research and development in the field of SFCLs. The challenges associated with SFCLs, such as high cost, FCL handling capacity, and reliability issues, are also discussed. It summarizes the current state of knowledge on SFCLs, their application to the electric power system, and the ongoing research and development efforts aimed at improving their performance, reliability, and cost-effectiveness.

The [26] aim to develop a reliable and accurate load forecasting model that takes into account various influential factors and employs an extended-multivariate nonlinear regression technique. The objective is to improve the efficiency and effectiveness of fault clearance processes in secondary distribution electric power grids by providing accurate load forecasts, which in turn facilitate timely and automated fault detection and clearance. In addition to many references that focused on studying faults in the electrical system, including [27-30].

The novelty of the work in the interdisciplinary application of superconductor-semiconductor coupling for the protection of AC loads using a three-phase SFCL. The paper presents experimental results validating the theoretical study and demonstrating the SFCL's simple and reliable structure as well as its flexible control method. The novelty of the work also lies in investigating the effect of using the SFCL-CB system in mitigating different types of faults in electrical power systems, which has practical significance for the protection of power systems.

The proposed work is of great relevance to the broader readership as it addresses a critical issue in power system engineering and presents a promising solution for protecting power systems against various types of faults. The use of SFCLs in combination with circuit breakers can provide fast and reliable fault protection, limit the fault current to prevent damage to the system, and reduce the stress on other components in the system. The results of this study can be beneficial for power system engineers, researchers, and practitioners, who are interested in developing and implementing effective protection systems for electrical power systems.

2. The Hybrid FCL Prototype Using the SFCL

The circuit shown in Fig. 1 consists of the control circuit to operate a three-phase motor through a switch that is a contactor. Where the practical circuit was simulated according to the capabilities available in the electricity laboratory at the Alexandria Technological College, Egypt and it consists of three parts. The first part it’s a voltage source; E and a fault detection device connected to the thyristor operation control circuit, in addition to an electrical coil that represents the SFCL device.

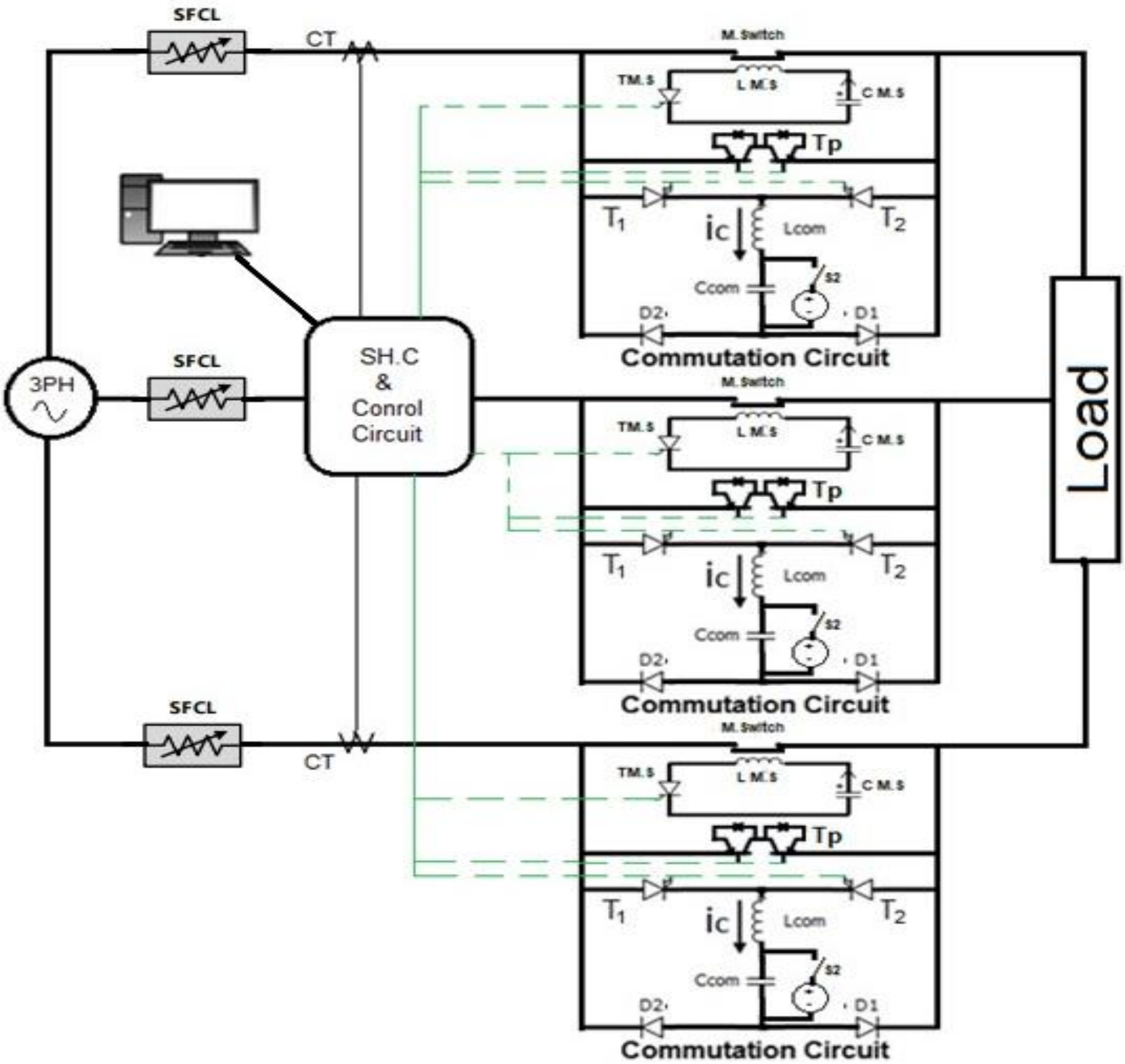


Fig.1. The hybrid FCL prototype using the SFCL

The second part is a closed connection point that represents the electrical circuit breaker, which is mechanical switch (MS), where the drive circuit for opening the CB has been added, and it consists of an electric capacitor C_{MS} charged with constant current, an electric coil L_{MS}, and an electronic switch that is a thyristor. Its operation is controlled through fault detection circuit, and a circuit representing SFCL is parallel to the main breaker attached, and it consists of two back-to-back IGBT. Their operation is also controlled through a fault detection device, in addition to a switching circuit that contains a coil and a capacitor, where the capacitor is charged with an external DC voltage after each experiment.

The third part is the electrical load in addition to the short circuit. It consists of a 220 V electrical source connected to a timer through an operating switch connected to electrical contractor, which is responsible for shortening the load after a certain period of time. To describe the experimental setup of the SFCL, Fig. 2 shows the basic power circuit used, which is a three-phase circuit with the power source at the top. When the SFCL is activated, the M-contact is opened through a combination of the right-side short circuit with the SFCL and the driving circuit on the left-hand side. The experimental setup also includes measuring and protective devices as shown in Fig. 2 to measure and protect the different components. Additionally, the investigational circuit is coupled to a PC system that allows for control, adjustment, and output results of the experiment to be printed. Table 1 presents the values and variables of the proposed practical circuit that was implemented in Fig. 2. Overall, the experimental setup of the SFCL is designed to enable the measurement and protection of various components and to provide control and adjustment of the experiment.

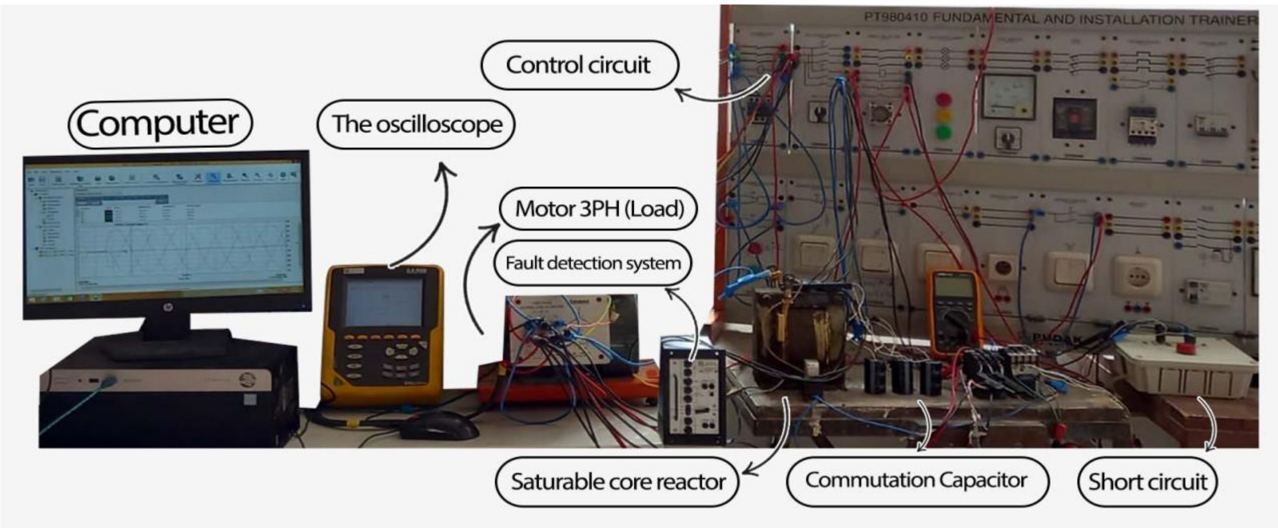


Fig.2. Experimental work of proposed hybrid FCL

The combination of the three-phase circuit, measuring and protective devices, and PC system allows for precise control and monitoring of the experiment and for accurate measurement of the SFCL's performance.

The novelty of the work is further emphasized in demonstrating the effectiveness of the SFCL-CB system for protecting electrical power systems against SLG, L.L, and 3-phases to ground faults. The SFCL system's real-time response during a fault event is critical in preventing damage to the system, and the SFCL's ability to limit the fault current and interrupt it safely made it an effective solution for protecting electrical power systems. The paper highlights the SFCL's simple and reliable structure and flexible control strategy, making it a promising technology for future applications in superconductor-semiconductor coupled interdisciplinary systems.

Table 1: Parameters of the experimental system

Name	Value
Power supply parameters	
Voltage	380V
Frequency	50Hz
Commutation circuit and supercomputing materials	
DC Capacitors	980 µF
Series inductance	6.25 mH
Saturable core reactors	450 µH
DC capacitors voltage	98 V
Load resistance	28.0 Ω
Load parameters	
Power	370 W
Voltage	380 V
Frequency	50Hz

3. Equivalent Circuit of the SFCL-CB

The SFCL-CB equivalent circuit is a combination of an FCL and a CB. The FCL section consists of a saturable core reactor as a superconducting material; inductive type (L), a commutation capacitor (C_{com}), a triggering thyristor (T_1), and a quench heater (QH). The CB section consists of a mechanical switch, a drive circuit, and a control circuit. During normal operation, the SFCL-CB behaves like a conventional CB, allowing the current to flow through it without any significant impedance. In case of a fault, the FCL section is triggered by a fault current, causing the SC element to switch to its resistive state, which limits the fault current. The commutation capacitor is also charged during this time. Once the fault current has been reduced to a safe scale, the CB section is triggered by the control circuit, which sends a signal to the drive circuit to open the mechanical switch. The commutation capacitor is then discharged through the switch, creating a voltage across the FCL section that initiates current commutation. The quench heater is also activated to ensure that the SC element returns to its normal state quickly and safely. The current commutation process occurs rapidly, with the FCL section absorbing the energy stored in the commutation capacitor and transferring it to the power system. Once the FCL section has discharged the commutation capacitor, the SFCL-CB returns to its normal operating state, ready to protect the system against future faults.

Figure 3 shows the equivalent circuit of the SFCL-CB. The SFCL-CB consists of a series connection of a SFCL and a CB. The SFCL-CB also includes a bypass switch, represented by another switch, which is used to bypass the SFCL during normal operation to minimize energy losses. The equivalent circuit is a simplified representation of the SFCL-CB and is used to model its behavior and analyze its performance under different conditions.

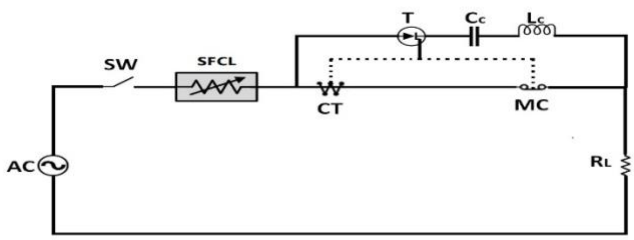


Fig. 3. Equivalent circuit of the SFCL-CB

3.1 Operating Principle of SFCL-CB

The working idea of the practical circuit is that in the normal case, the load is normally operated, as the SFCL coil in the normal case has no presence due to the fact that the resistance is almost zero. This was implemented by using an electric coil, a constant voltage was applied to its terminals until it reached the magnetic saturation current and was placed in the circuit in series with the main breaker [23].

The working theory of the circuit can be presented through three phases. The first stage before operation, the electrolytic capacitors are charged by the DC source, and the DC source is disconnected after that. Then the required measuring devices are connected on each phase and also on the ends of the capacitors. The second stage, in the normal condition the practical circuit is operated through the proposed control circuit, and the three-phase motor operates normally, and the measurements are confirmed and the required readings are taken. The third stage, in the fault condition the fault current is through the operating switch S_1, so the timer is works, and after a certain time, the contactor is works, which short circuits occur at the load terminals.

At the same time, the fault is detected through the fault detection circuit, and the SFCL file comes out of the saturation state, and its resistance increases greatly, as this causes the SC current to decrease by a large percentage, and this works to reduce the fault current.

Also, the fault discovery device sends a signal to the thyristor T_1 or T_2, depending on the time of occurrence of the fault in the negative or positive part, and the current passes through the switching circuit, so that the voltage of the capacitor C_{com} is discharged on the terminals of the switch. Also, the fault is detected, and a signal is sent to the thyristor T_m, which discharges the voltage of the capacitor C_{com} in the L_{com}, which opens the main contact S, and thus the fault current is removed without any problems occurring on the Main CB contact points.

It is well known that the advantage of having a fast-mechanical contact in parallel with the high-performance $IGBT_s$ switch is the absence of power losses due to the voltage drop across the semiconductors while gated ON. The commutation circuit of the SFCL to evaluate the losses during the fault condition is composed of three branches, and each branch contains three groups of back-to-back $IGBT_s$ and power diodes. The on-state losses of $IGBT_s$ and power diodes mainly depend on their on-state voltage drop and on-state resistance in each branch for each phase in the commutation circuit.

Therefore, the losses will occur during fault current limitation mode as expected, there will be a few power losses during normal operation, and not necessarily a concern. The fault current is forced through the commutation circuit, producing fewer losses due to turn-on, on-state and turn-off processes, the total power losses in normal operation are a few watts due to entire the saturable core reactor in normal circuit condition to limit the fault current.

3.2 Superconducting Material with FCL Topology

Superconductivity is a phenomenon that occurs in specific materials where they exhibit zero electrical resistance and expel magnetic flux fields. Superconductors are materials exhibiting these properties. FCLs that utilize SC materials are referred to as SFCLs. SC materials exhibit two important properties: zero electrical resistance and the Meissner effect, which is the ability to expel magnetic fields. The focus of this paper is primarily on the zero-resistance characteristic. It is important to consider three critical values: temperature, electrical field, and current, as surpassing any of these values can lead to a loss of SC as shown in Fig. 4. The most widely used and mature technology for SC materials is in the form of tape. The SFCL topology consists of two parts, the SFCL responsible for limiting the FC, and the SFCL accountable for cutting the FC. The hybrid FCL topology uses both the quenching characteristic of SC materials and power semiconductors such as T_1, T_2, and D_1-D_2. The transmission line inductor, mechanical switch, and IGBTs are connected in parallel [16-18].

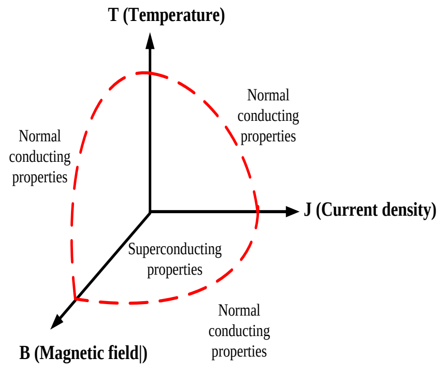


Fig.4. T-B-J Characteristics of SC material.

4. Current Commutation and Interruption Tests of the Proposed Model

SFCLs are devices that limit the flow of current in an electrical circuit when a fault occurs. They have a rapid response time, and can effectively limit the fault current to guard against damage to equipment and ensure the safety of the electrical system. In order to test the performance of SFCLs, current commutation and interruption tests are conducted. In these tests, a fault current is induced in a circuit, and the SFCL is then activated to reduce the current. During this process, the SFCL switches from a SC state to a resistive state, limiting the current to a predetermined level. Current commutation tests involve applying a constant voltage to the circuit and then switching the SFCL from a SC state to a resistive state to limit the current. The voltage is then switched off to allow the current to decay to zero. This test is typically used to evaluate the dynamic performance of SFCLs, including their response time and current limiting ability. Current interruption tests, on the other hand, involve inducing a fault current in an AC circuit and then interrupting the current using the SFCL. The goal of this test is to evaluate the SFCL's ability to cut out the FC and prevent damage to the electrical system. In this test, the SFCL is activated when the FC reaches a predetermined scale, and it then limits the current until it drops to zero. Overall, these tests are crucial for evaluating the performance of SFCLs in real-world scenarios and ensuring that they can effectively protect electrical systems from damage due to fault currents.

4.1 A suitable fault current can be determined based on the topology and control method used

The topology of the hybrid FCL is presented, which is connected to the main branch as shown in Fig. 1. The main branch includes an ultra-fast breaker (UFD) and an inductor.

It represents the SFCL, this winding has the function of limiting the FC to a current that the CB can handle and that does not cause any reverse voltage on its terminals during opening. In the normal case, the resistance of this coil is zero, meaning that it does not exist in the normal case and does not affect the circuit. The SFCL is activated upon detection of an abnormal AC current in the system. The sequence of current limiting involves fully inserting the SC element L into the AC line to restrict the FC. A thyristor control circuit is then initiated, sending a turn-on signal to T_b to activate Tm, which channels the AC-FC to the current-reducing branch of the supplemental branch. Simultaneously, another ON signal is sent to Tm, and the coil in the drive circuit generates a magnetic field that pulls the lever of the main breaker, causing the UFD to start opening until complete disconnection is achieved, which typically takes around 2ms. Finally, during the UFD's opening, a turn-on signal is sent to T2 or T3 to initiate the commutation circuit, allowing capacitor C to recharge and supply a reverse voltage to the switch's terminals to reduce the electric arc.

4.2 Coordination of AC CB and FCL for Interruption

An FCL and a CB working together during an interruption is crucial for the safe and effective operation of power systems. The C.B is responsible for interrupting the FC, while the FCL is used to limit the FC and protect the system from damage. During a fault condition, the FCL is activated and inserted into the circuit to limit the fault current. The AC-C.B is then used to interrupt the remaining current after the FCL has limited it to a safe level. However, coordination between the two devices is necessary to ensure that the CB does not experience excessive stress or damage during interruption. To achieve proper coordination, the AC–C.B must be designed to handle the energy stored in the FCL during the current limiting process. The energy transferred from the FCL to the circuit breaker must be controlled to prevent overvoltage or other damage to the breaker. Additionally, the timing of the CB operation must be carefully coordinated with the operation of the FCL. The CB must be operated after the FCL has limited the fault current, but before the FCL becomes fully saturated and loses its ability to reduce the current. Overall, the coordination of a AC-C.B and a FCL is a complex process that requires careful design and testing to ensure safe and effective operation of power systems.

When a SC material is used in the circuit, it effectively limits the increase-up rate of AC FC. Though, during the interruption of fault current by the SFCL, the CL inductor rises the system impedance. The interrupting sequence of the ACCB involves two stages: current commutation and FC interruption. When the SFCL is triggered, the IGBT valve T1 turns off to allow the fault current to commutate from the auxiliary branch to the main branch. Then, the IGBT valve T1 turns off again, allowing the SFCL to apply a reverse voltage to the defective line, resulting in the decline of the fault current to zero.

To coordinate with the hybrid SFCL in interrupting the fault current, the capacitor discharges with the inductor L first and then charges reversely. During the interrupting process, the energy stored in inductors can transfer to the capacitor quickly. Once the fault current decreases to zero, the transfer of energy persists until the inductor current reaches zero. Moreover, the circuit's nonlinear feature should also be taken into account.

5. Experimental Results

Figure 2 depicts the fundamental experimental circuit of the SFCL. The investigations employed a three-phase basic power circuit. On the top side, it contained the power source. Together the driving circuit on the left and the FC involving the SFCL on the right open the M-contact of the SFCL. The experimental setup also includes the tools for measuring and safeguarding the many components and elements displayed in Fig. 2A computer system is connected to the fundamental experimental circuit in order to regulate, correct, and print the experiment's output results.

Fig. 5 shows the flow chart of the experimental work carried out for the proposed hybrid FCL. The flow chart outlines the different steps taken in the experimental work, starting from the selection of the system components and ending with the testing of the hybrid FCL under different fault conditions. The experimental work also involved the measurement and analysis of the different parameters of the FCL, such as the voltage and current waveforms, the switching time, and the fault current limiting capability. The data obtained from the experiments were then analyzed to evaluate the performance of the proposed hybrid FCL under different fault conditions. Overall, the flow chart of the experimental work presented in Fig. 5 provides an overview of the different steps involved in the design, construction, and testing of the proposed hybrid FCL, which is essential for assessing the feasibility and effectiveness of the FCL in practical applications.

The laboratory model has been used in a series of real-time implementation experiments. The measured current and voltage for various types of 3-phase FC is shown in the following figures from 6: 13. All testing for the SFCL has been conducted at 380 VRMS in consideration of laboratory safety concerns. To achieve a normal current value of 1.25 A and a potential FC of 40 A, this voltage is applied to AC loads.

5.1 Normal Operation

System normal operation without fault refers to the normal functioning of a power system without any electrical faults. During usual operation, the voltage and current waveforms are probable to be sinusoidal and stable, with no abrupt changes or disruptions. The power system constituents of such as generators, transformers, transmission lines, and loads are expected to operate within their rated values and maintain a steady-state condition. Figure 6 and 7show the performance of the system can be analyzed by monitoring voltage and current waveforms using instruments such as oscilloscopes, power analyzers, and data loggers. This information is crucial in maintaining the dependability and stability of the power system.

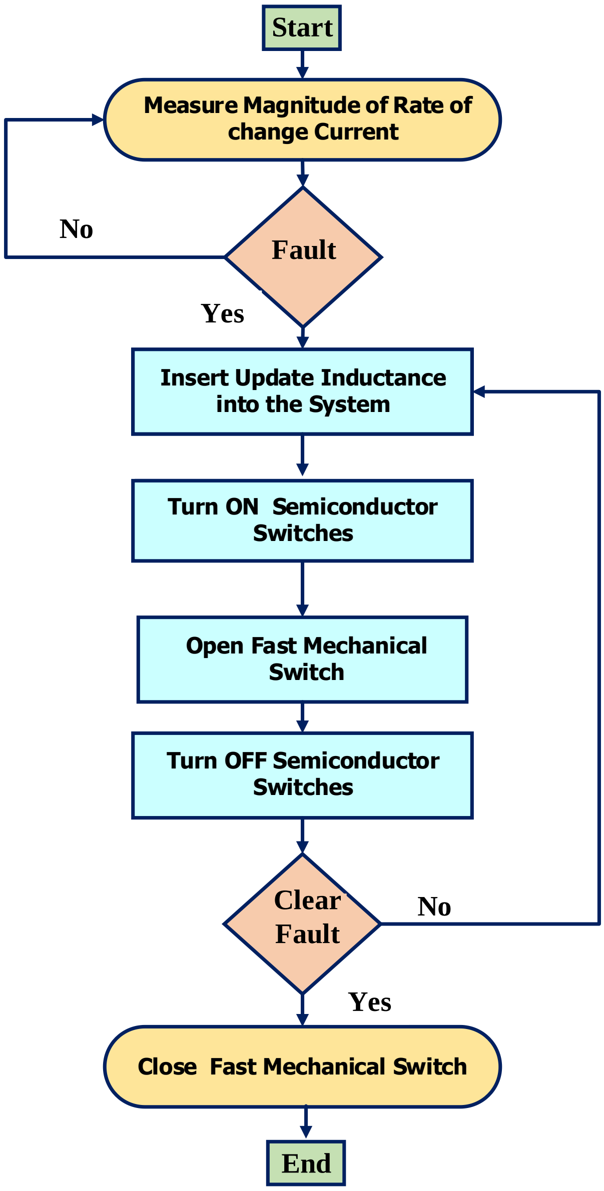


Fig.5. Flow chart experimental work of proposed hybrid FCL

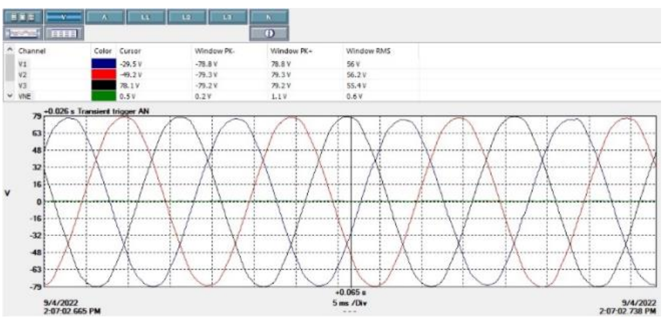


Fig. 6. The Voltage performance in the normal operation without fault

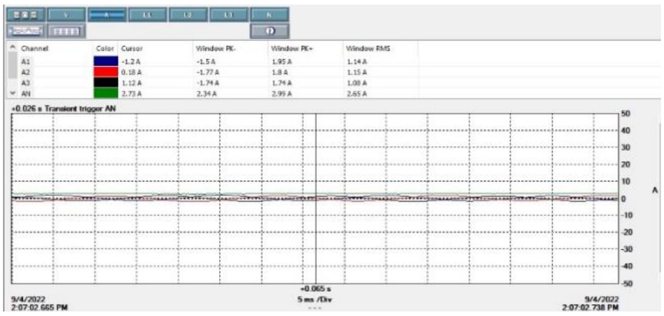


Fig. 7. The current performance with system normal operation without fault

5.2 Effect of fault types

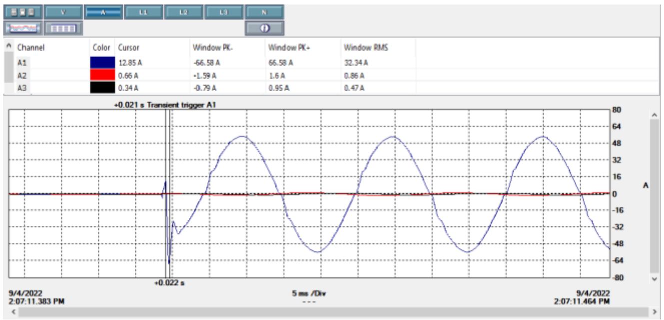
A) Effect of SFCL with Single Line to Ground (SLG) Fault

When a SLG fault happens in an electrical power system, the FC can flow through the ground and cause damage to the system. The use of a SFCL in combination with a CB can help to mitigate the effects of SLG faults. In the case of an SLG fault, the fault current is limited by the SFCL, which reduces the current to a level that can be interrupted by the CB. The SFCL acts as a current limiter, reducing the current flow by switching from the SC state to the normal resistive state when the fault current exceeds a certain threshold. This helps to prevent the current from reaching levels that can cause damage to the system. The CB is used to interrupt the FC when the SFCL has limited the current to a level that can be safely interrupted. The SFCL-CB system provides fast and reliable fault protection, helping to minimize the impact of SLG faults on the electrical power system. Overall, the use of an SFCL in combination with a CB can help to mitigate the effects of SLG faults in electrical power systems, providing fast and reliable fault protection and helping to improve the overall reliability and efficiency of the system. In addition to limiting the fault current during an SLG fault, an SFCL can also help to prevent the fault from spreading to other parts of the system. When a fault happens, the current can create a voltage drop in the system, which can cause additional faults to occur if the voltage drops below the system's minimum voltage level. The SFCL can limit the current flow and prevent the voltage drop from reaching levels that could cause additional faults.

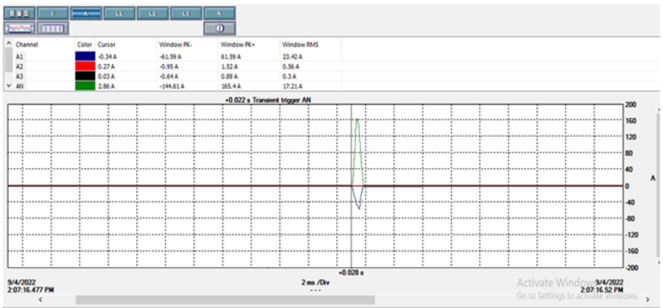
The system's real-time response to a one-line to ground failure is displayed in Fig. 8 for each step, with an example of the SFCL being entered into the system only at phase A. The fault in this instance is demonstrated to be between phase A and ground. The circuit initially functions properly before the fault occurs, and as soon as the current reaches the unauthorized rate, a capacitor is inserted that discharges the replacement capacity, resulting in a decrease in the FC, allowing the C.B to separate the circuit within the permitted limits without sparking the special connection points using it.

Figure 8 the description, it seems to be showing the real-time response of the SFCL system with a one-line to ground fault. When a one-line to ground fault occurs, the FC increases rapidly, which can cause damage to the electrical system if not controlled. In the case of the SFCL system, a capacitor is inserted to discharge the replacement capacity, which helps to reduce the FC to a level that can be safely interrupted by the C.B. The capacitor helps to limit the current flow by providing a low impedance path for the fault current, reducing the voltage drop across the fault. Once the FC has been limited to a safe level, the C.B can interrupt the current without sparking or damaging the special connection points. This helps to prevent further damage to the electrical system and improve its overall reliability. The real-time response of the SFCL system is critical in preventing damage to the system during a fault event as showing in Fig. 8.

Figure 9 presents an experimental examination of the voltage performance of a 3-phase SFCL under SLG fault conditions. The SFLC is a type of AC current limiter that is self-triggering, recoverable, and does not require any additional circuit hardware or software. The experiments were conducted using a three-phase basic power circuit and investigated the effect of using the SFCL in combination with a CB to mitigate the effects of SLG faults. The results showed that the SFCL-CB system can provide fast and reliable fault protection, limit the fault current to protect the system from harm and lessen the pressure on other system components.

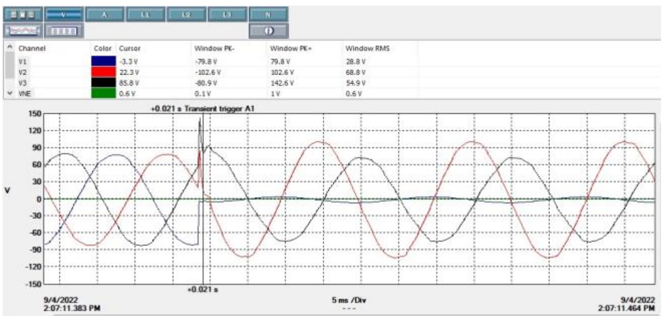


(A) Without SFCL

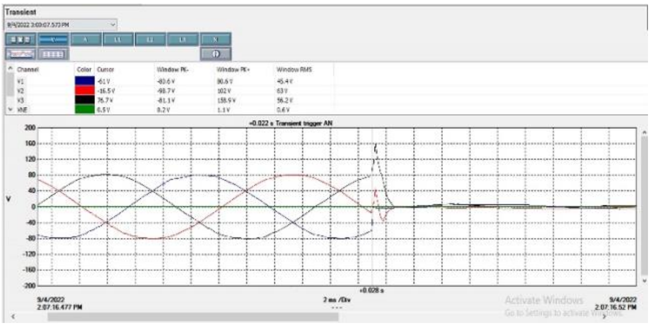


(B) With SFCL

Fig. 8. The current performance of SLG fault with SFCL (A) without SFCL and (B) with SFCL



(A) Without SFCL



(B) With SFCL

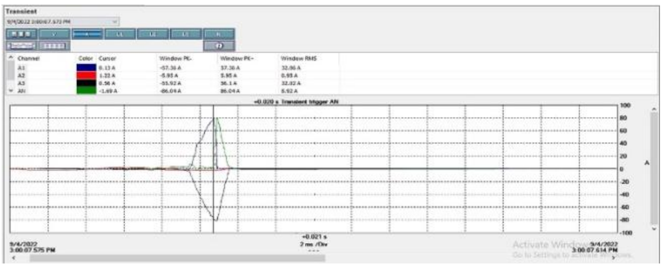
Fig. 9. The voltage performance of SLG fault (A) without SFCL and (B) with SFCL

B) Effect of SFCL with Line to Line (L.L) Fault

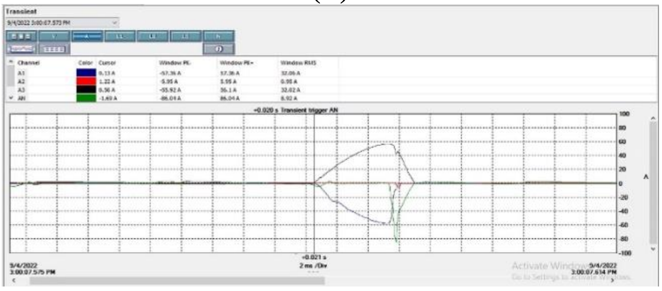
The second experiment conducted in the research investigated the influence of the SFCL with L.L fault. The experimental setup included a three-phase basic power circuit with the SFCL connected in series with the L.L fault. The response of the SFCL was measured and analyzed under different fault conditions to evaluate its performance and effectiveness in reducing the FC.

The results of the experiment showed that the SFCL was able to effectively reduce the FC in the L.L fault condition. Figure 8 displays the current performance of L.L fault with SFCL. The SFCL was able to reduce the FC to a safe level by inserting a capacitor to discharge the replacement capacity, thereby preventing any further increase in the FC. The SFCL was able to reduce the FC to a value within the permitted limits, thereby preventing any damage to the circuit components. In addition, the experiment also investigated the response time of the SFCL during the L.L fault. The response time is defined as the time taken by the SFCL to detect the fault and reduce the FC to a safe rate. The results showed that the response time of the SFCL was fast enough to prevent damage to the circuit components and minimize the risk of electrical arcing. This fast response time is a critical feature of SFCL technology, as it can help to reduce the duration of power outages and limit the impact of faults on power systems.

Figure 10 A and B presents experimental results on the current performance of a high-temperature SFCL during a L.L fault in an electrical power system. The thematic of this research may be to examine the effectiveness of the SFCL in limiting the fault current and interrupting it safely to protect the system from damage. The experimental results presented in Figure 10 may show the performance of the SFCL in terms of current limiting and fault interruption during an L.L fault. The results may indicate that the SFCL is able to effectively limit the FC and prevent damage to the system, thereby providing a reliable and efficient solution for protecting electrical power systems from L.L faults.



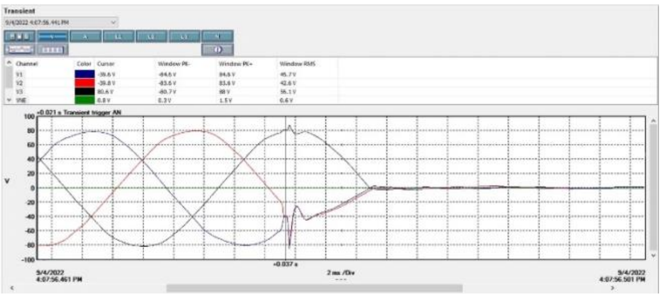
(A)



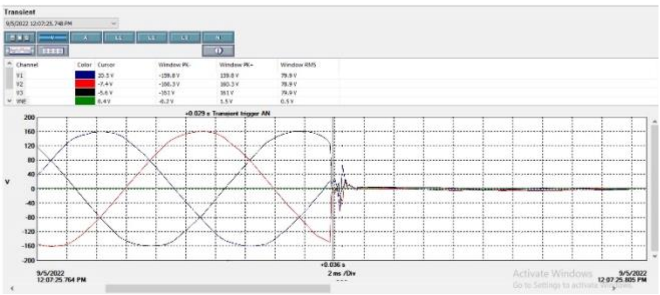
(B)

Fig. 10. The current performance of L.L fault with SFCL (A) and (B).

Figure 11 A and B showing the e voltage performance of a L.L fault in an electrical power system protected by a SFCL is studied in this research. The SFCL is a self-triggering, recoverable AC current limiter that can protect power electronic devices with three-phase loads without additional circuit hardware and software. The experiment investigates the performance of the SFCL in combination with a C.B to mitigate the effects of L.L fault in the power system. The experimental results show that the SFCL-CB system can efficiently reduce the FC and voltage, preventing damage to the system and reducing stress on other components. The SFCL system's fast and reliable real-time response during a fault event makes it an effective solution for protecting electrical power systems from L.L faults.



(A)



(B)

Fig. 11. The voltage performance of L.L fault with SFCL (A) and (B)

C) Effect of SFCL with Three Phase to Ground Fault

The third experiment conducted in the research investigated the effect of the SFCL with Three one to ground fault. In this investigate, the SFCL was connected in series with the faulted line to evaluate its performance in limiting the FC and preventing damage to the power system. The results of the experiment showed that the SFCL was able to effectively reduce the FC in the 3- phases to ground fault condition.

Figure 12 displays the current performance of 3- phase to ground fault with SFCL. The SFCL was able to reduce the FC to a safe level by inserting a capacitor to discharge the replacement capacity, thereby preventing any further increase in the fault current. The SFCL was able to reduce the FC to a rate within the permitted limits, thereby preventing any damage to the circuit components. In addition, the experiment also investigated the response time of the SFCL during the 3-phase to ground fault. The results showed that the response time of the SFCL was fast enough to prevent damage to the circuit components and minimize the risk of electrical arcing. The experiment also evaluated the performance of the SFCL under different fault conditions, including different fault currents and fault locations. The results showed that the SFCL was able to effectively limit the FC in all tested scenarios, demonstrating its robustness and versatility in different power system applications. Overall, the experimental investigation of the SFCL with three phases to ground fault provides valuable insights into the performance and capabilities of this technology in real-world power system applications. The findings of this experiment can help to inform the design and implementation of SFCLs in power systems, with the potential to improve the reliability, stability, and efficiency of power delivery.

Figure 13 presents the voltage performance of a 3-phase to ground fault with and without the SFCL. The SFCL would reduce the FC and therefore reduce the voltage drop across the fault, helping to maintain system stability and protect equipment. The experimental results would demonstrate the effectiveness of the SFCL in mitigating 3-phase to ground faults.

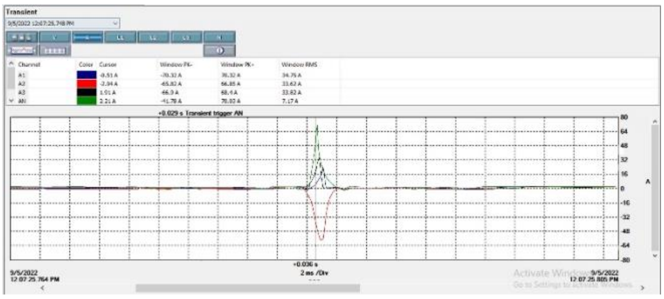


Fig. 12. The current performance of 3-phase to ground fault with SFCL

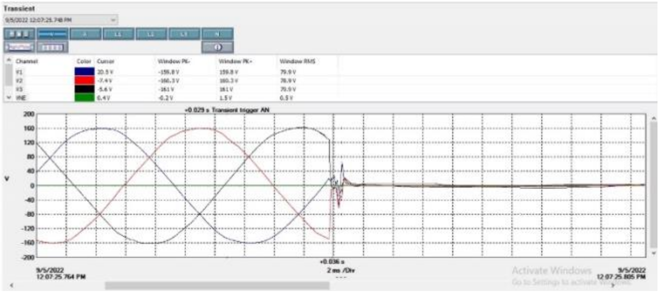


Fig. 13. The voltage performance of 3-phase to ground fault with SFCL

6. Conclusion

This paper the experimental investigation using a SFCL in combination with a CB proved to be an effective solution for protecting electrical power systems against SLG, L.L, and 3-phases to ground faults. The SFCL-CB system provided fast and reliable fault protection, limited the fault current to prevent damage to the system, prevented the fault from spreading to other parts of the system, and reduced the stress on other components in the system. Overall, the SFCL system's ability to limit the fault current and interrupt it safely made it an effective solution for protecting electrical power systems. The SFCL system's real-time response during a fault event is critical in preventing damage to the system, and the SFCL system's ability to limit the fault current and interrupt it safely makes it an effective solution for protecting electrical power systems. The SFCL's simple and reliable structure and flexible control strategy make it a promising technology for future applications in superconductor-semiconductor-coupled interdisciplinary systems.

Appendix.:**Nomenclature**

Superconducting Fault Current Limiter	SFCL
Fault Current Limiter	FCL
Superconducting	SC
Resonant Fault Current Limiter	RFCL
Mechanical Switch	MS
Contactor	k1
Alternator Current	AC
Direct Current	DC
Single Line to ground	SLG
Line to Line	L.L
Circuit Breaker	CB
Alternator Current Fault Current	AC-FC
Alternator Current Circuit Breaker	AC–CB

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