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Inexpensive short-circuit current limiter and switching device based on one commutation circuit for a three-phase system

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Abstract

The escalating levels of fault currents resulting from short circuits, particularly in the context of distribution generators, have presented a critical need for the widespread implementation of fault current limiters (FCLs) in power systems. Despite their evident advantages, the extensive adoption of FCLs has been hindered by the high production costs associated with these devices. To address this challenge, a comprehensive study was conducted to develop a cost-effective FCL tailored specifically for three-phase power systems. This paper proposes a novel approach based on a single commutation circuit for the FCL and offers detailed insights into the construction of the FCL circuit, with a particular focus on efficient current interruption. Additionally, the study comprehensively discusses the logic controller and measurement system employed in conjunction with the proposed FCL, ensuring precise fault detection and rapid response to disturbances within the power grid. The integration of an artificial zero-crossing circuit within the FCL design further enhances its capability to limit short-circuit currents proactively, even before the occurrence of the first peak, thereby bolstering overall system reliability and stability. The study's significant contribution lies in achieving cost-effectiveness through the simplicity of the FCL's design, eliminating the need for extensive upgrades to various network components.

Keywords: Fault current protection, Fault current limiters, Low-cost FCL, Three phase system with single commutation circuit, Power system protection, Hybrid circuit breaker

Introduction

The continuous expansion of the electrical industry and the growing demand for electricity present significant challenges for the power grid, particularly concerning the management of increased short-circuit currents during fault conditions [1, 2]. Enlarging the entire system to accommodate higher fault currents is a feasible solution, but it entails substantial costs [3–5]. An alternative and practical approach lies in the implementation of FCLs, offering a cost-effective solution [6]. FCLs provide the advantage of mitigating the need for costly replacements or upgrades of existing devices as fault current levels rise, making them especially valuable for safeguarding older or less advanced equipment

[7]. Furthermore, FCLs protect devices from the initial surge during fault conditions and enhance the voltage profile [8].

Despite the benefits of FCLs, their widespread adoption is hindered by the associated production costs [9, 10]. Researchers have explored various models and techniques for FCL development [11, 12], leading to a deeper understanding of FCL operation and valuable insights into different cost-effective implementation approaches [13, 14]. Among the extensively studied methods is the use of superconducting materials in FCL designs [15, 16]. Superconducting fault current limiters (SFCLs) capitalize on the exceptional properties of superconductors to achieve high-performance fault current limitation [17, 18]. These materials exhibit zero electrical resistance below their critical temperature [19, 20], effectively impeding the flow of fault current. Extensive research has been conducted on SFCLs, analyzing their advantages and limitations in various power system scenarios [21, 22].

In addition to superconducting materials, non-conducting materials have also been a focus of research for developing FCLs [23, 24]. Non-conducting fault current limiters (NCFCLs) employ materials with high resistivity to restrict the fault current [25]. These materials, such as metal oxide varistors (MOVs) and composite materials, possess advantageous features like self-healing characteristics and rapid response times [26, 27]. Numerous studies have explored the application of NCFCLs in power systems, evaluating their cost-effectiveness and performance [28, 29].

Furthermore, various other FCL models and techniques have been investigated [3], including active current limiters [30], solid-state FCLs [31], and hybrid FCLs [32–34]. These approaches utilize advanced control algorithms [35], power electronics devices [36], and novel materials to achieve efficient fault current limitation while considering cost and system compatibility [37]. By thoroughly reviewing the existing literature, a comprehensive understanding of the different FCL models and techniques employed in various power system scenarios can be acquired. This knowledge serves as the foundation for developing a low-cost FCL based on a single circuit for three-phase networks, as presented in this study. The proposed FCL offers a simple structure, high reliability, and a cost-effective solution to address the challenges associated with escalating fault currents in power systems.

This paper examines the advantages of using a single commutation circuit in FCLs compared to employing three commutation circuits [38]. The investigation focuses on assessing the benefits of the single circuit approach in terms of simplicity, cost-effectiveness, reduced complexity, improved efficiency, space-saving characteristics, enhanced performance, higher power density, and ease of integration. The results highlight the significance of the single commutation circuit method, providing valuable insights for optimizing FCL technology and its application in various electrical systems. Understanding these advantages can lead to more efficient and reliable FCLs.

Proposed FCL (fundamental)

Figure 1 depicts a three-phase power system employing a single commutation circuit, with key components and their functions as follows:

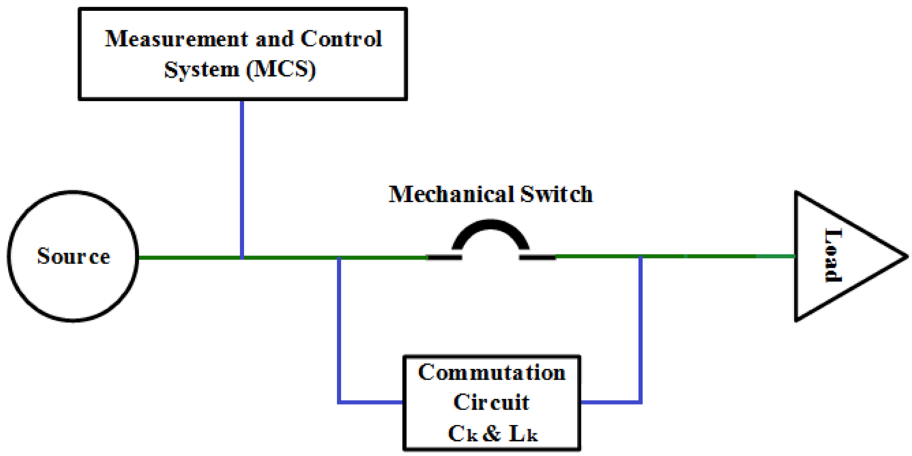

Fig. 1 The simple circuit structure for the economical FCL

- **Circuit breaker (CB)** Also known as the main switch, the CB functions as a rapid interrupter CB. In the event of a short circuit in the system, the measurement and control system come into action, activating the commutation circuit to limit the short-circuit current before disconnecting it. Once the short-circuit current is effectively limited, the CB trips, completely interrupting the current flow.
- **Current limiter (commutation circuit)** The current limiter consists of two elements, the pre-charged capacitor (C_k) and the inductive element (L_k), which are responsible for controlling and restricting the current flow within the circuit. During regular operation of the power system, the switch is closed, effectively short-circuiting the FCL and resulting in minimal power loss.
- **Measurement and control system (MCS)** The MCS plays a vital role in collecting and controlling data related to the circuit's operation. It constantly monitors the system for any anomalies or short circuits. Upon detecting a short circuit, it triggers the current limiting circuit and oversees its operation until the current is adequately reduced.

This circuit configuration ensures the efficient and safe operation of the power system, minimizing power loss during normal conditions and effectively restricting the short-circuit current to safeguard the system from potential damage.

Operation strategy and logic control

The reliability and stability of the FCL play a critical role in its effectiveness within the power system [39]. To achieve these essential aspects, the FCL must seamlessly operate during normal conditions while demonstrating swift and precise responsiveness in case of a fault. The key considerations for ensuring stability and reliability are as follows:

- **Normal operation** The FCL should exhibit uninterrupted performance during regular power system operation, allowing continuous power flow with minimal power loss.

- **Fault detection and prediction** In the event of a fault, the FCL must possess the capability to rapidly detect the fault and accurately predict the short-circuit current. Achieving this necessitates a highly sensitive measurement and control system capable of identifying abnormalities in the current flow.
- **Current limiting** Once a fault is detected, the FCL should effectively restrict the fault current to a safe level. This is accomplished through the parameters of the commutation circuit, which control the current flow and prevent it from surpassing the breaking capacity of existing CBs.
- **Interruption** The final stage of FCL operation involves the interruption of the fault current. To achieve this, a fast CB is essential, capable of interrupting the current at the zero-crossing point. This ensures a safe and efficient interruption of the fault current.

Figure 2 offers a visual representation of the FCL's operation, elucidating its functioning and the sequence of steps involved in fault detection, current limitation, and interruption. It is essential to recognize that the specific design and implementation of the FCL may vary depending on the power system's requirements and the type of fault current limiting technology employed.

The main component of the proposed FCL

Fast mechanical CB

Fast mechanical CB, main switch (MS), fast breaker (FB), or mechanical switch (MS) are different names for the same component, and it represents a critical component in the FCL circuit, and its operation is supported by a fast electro-dynamic drive. The main switch is a fast mechanical switch that can be visually represented as shown in Fig. 3. The key characteristics and functions of the main switch are as follows:

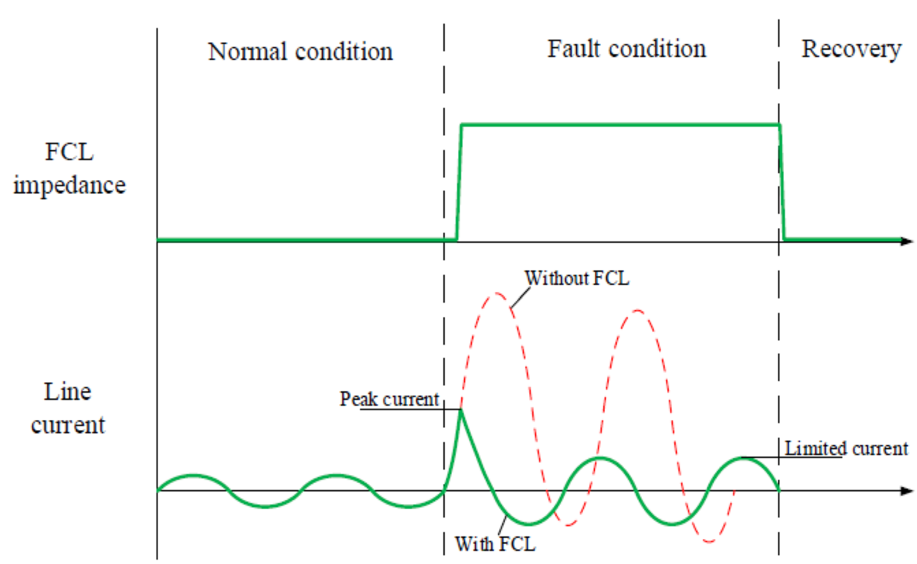

Fig. 2 The principle of operation of FCL and the effect on the FCL

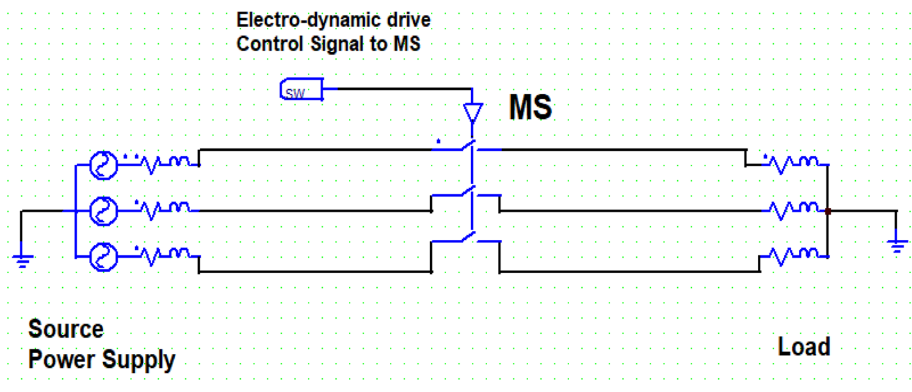

Fig. 3 The electro-dynamic drive circuit

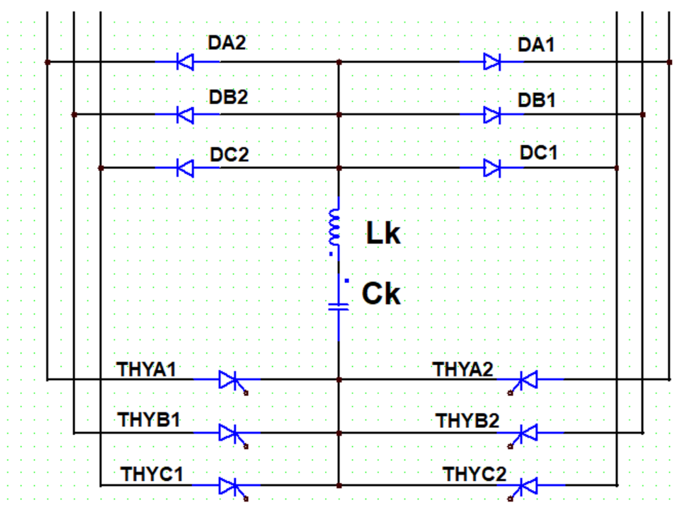

Fig. 4 Commutation circuit of the proposed FCL

- **Closed state** In the closed state, the contact of the main switch allows the flow of current through the circuit. This enables the normal operation of the power system, ensuring a continuous power flow.
- **Fast electro-dynamic drive** To open the main switch quickly in the event of a fault or abnormal condition, a fast electro-dynamic drive is employed. This drive mechanism applies a rapid electromagnetic force to separate the contact points of the switch, interrupting the current flow swiftly.
- **Low power losses** A notable feature of the MS is its ability to provide very low power losses during normal operation. This ensures efficient power transmission without unnecessary energy dissipation or heat generation.

By combining the fast mechanical switch with the electro-dynamic drive, the circuit can respond promptly to fault conditions, minimizing the duration of fault currents and improving the overall stability and reliability of the system. It must be considered that the specific design and implementation of the main switch may vary depending on the system requirements and the desired level of performance.

Commutation circuit

The commutation circuit, depicted in Fig. 4, consists of several key components, including the pre-charged capacitor, inductive element, and semiconductor switch. The selection of these parameters plays a crucial role in achieving a successful design for the FCL. The main challenge lies in choosing the right sizes for the capacitor and inductor, as well as determining the appropriate pre-charged voltage on the capacitor. These considerations are essential to ensure that the FCL can effectively detect and distinguish fault currents, regardless of the type of fault.

- **Pre-charged capacitor** The capacitor is responsible for storing electrical energy. It needs to be properly sized to provide sufficient energy for fault current detection. The capacitance value is determined based on factors such as the desired response time, fault current magnitude, and system requirements. A higher capacitance value can allow for greater energy storage, improving the FCL's ability to detect and respond to fault currents.
- **Inductive element** The inductor in the commutation circuit helps control the current flow and assists in limiting the fault current. The inductance value is selected to ensure smooth current transition and effective current limitation during fault conditions. The right inductance value depends on factors such as fault current magnitude, desired current limiting characteristics, and system specifications.
- **Semiconductor switch** The semiconductor switch, typically a solid-state device, is used to control the switching operation in the commutation circuit. It enables the activation and deactivation of the FCL based on fault conditions. The choice of the appropriate semiconductor switch depends on factors such as voltage and current ratings, switching speed, and power handling capabilities.

Selecting the correct parameters, including capacitor and inductor sizes, and determining the pre-charged voltage, require careful consideration and analysis. Factors such as fault current levels, system characteristics, and desired performance objectives must be taken into account during the design process. Ensuring sufficient energy storage and effective fault current detection are crucial for the reliable and efficient operation of the FCL. It is important to note that the specific parameter values and design considerations may vary depending on the specific requirements and constraints of the FCL application.

Indeed, sine waves oscillate around zero and have a frequency of approximately 50 cycles per second (50 Hz) in many power systems. In an ideal scenario, switching operations in the circuit should ideally occur at the zero-crossing point of the sine wave. This is because switching at zero current minimizes the occurrence of arcing, ensuring a more efficient and reliable operation of the mechanical CB [40, 41].

With the implementation of the commutation circuit, the mechanical CB sine wave. Instead, the primary role of the commutation circuit is to actively force the fault current to approach zero in a very short period of time, as illustrated in Fig. 5. By utilizing the commutation circuit, the fault current can be rapidly reduced and brought close to zero, enabling a smoother and faster interruption by the mechanical CB. This helps to minimize the arc and the associated problems caused by interrupting high

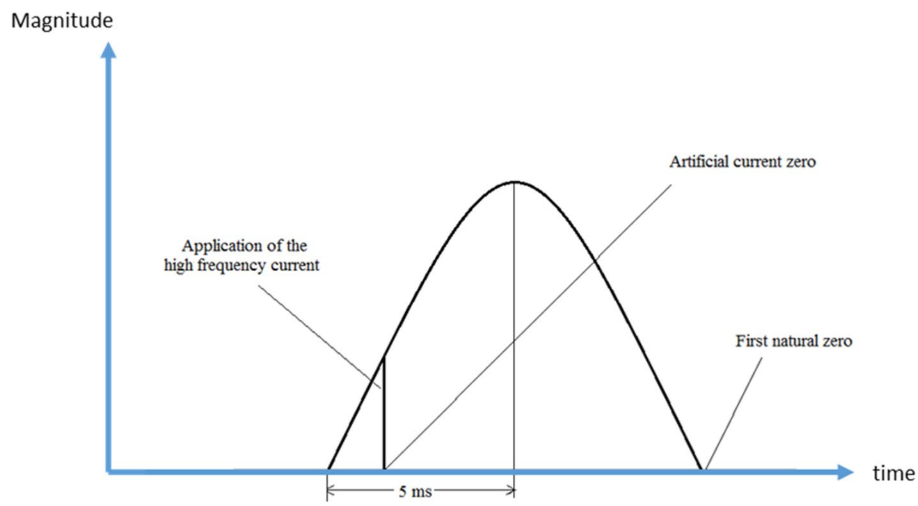

Fig. 5 Fault current limited using commutation technique

fault currents. The synchronized switching between the commutation circuit and the mechanical CB at or near the zero-crossing point of the sine wave enhances the effectiveness of the fault current interruption, improving the overall reliability and performance of the system.

Measurement and control system

There are generally two methods used for error detection in FCLs. The first method involves continuously monitoring the magnitude of the line current to check for a short-circuit condition. The second method is to examine the rate of change of current (dt/di). While both approaches can be used, each method has its limitations [42, 43].

When using magnitude as the sensing technique, there is a risk of false triggering of the FCL due to inrush currents caused by heavy loads connected to the system, which are not actual faults. Therefore, relying solely on current magnitude may result in incorrect fault detection. On the other hand, when considering only the rate of change of current, it does not necessarily indicate an error condition. Current can change rapidly for various reasons other than faults, such as switching operations or load fluctuations. Therefore, relying solely on the current rate of change may lead to false alarms or missed fault detection.

To address these limitations, a comprehensive approach can be adopted, as depicted in Fig. 6. The algorithm combines both the current rate of change (di/dt) and the short-circuit current magnitude (I_{rms}) to make a more accurate decision regarding fault conditions. The algorithm's general framework considers the trend of current rate of change over time and compares it with a threshold value. Additionally, it takes into account the magnitude of the line current and compares it with a predetermined threshold. By combining these two parameters, the algorithm can make a more informed determination of whether an error condition exists.

It is important to note that the specific thresholds and criteria used in the algorithm may vary depending on the specific application and system requirements. Fine-tuning

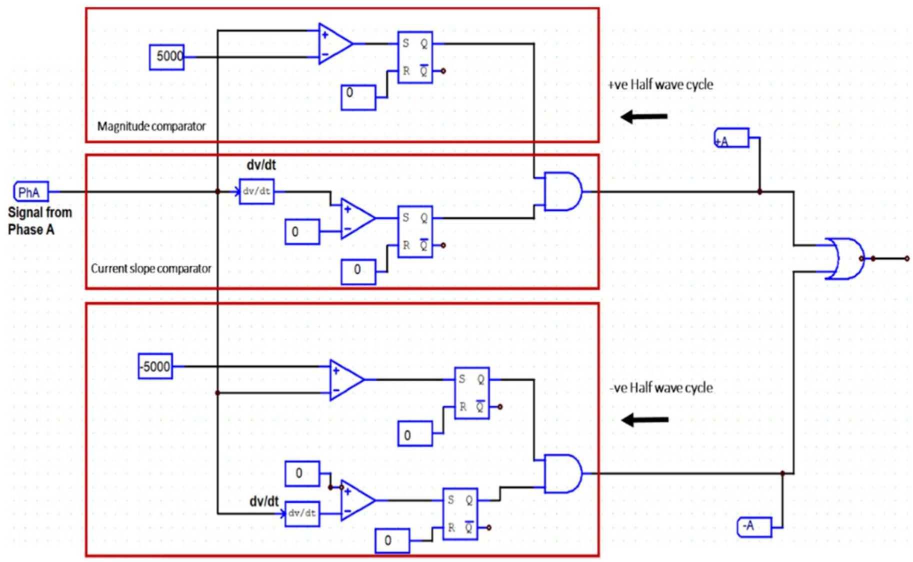

Fig. 6 Short-circuit detection on +ve half cycle and −ve half cycle for phase A

and customization of the algorithm are essential to ensure reliable and accurate fault detection while minimizing false alarms. Figure 6 illustrates the short-circuit detection on + ve half cycle and -ve half cycle for phase A based on the current rate of change (di/dt) and the short-circuit current magnitude (I_{rms}), highlighting the integration of these parameters for effective fault detection in FCL systems.

The current limiting and interruption operation sequence

The control operation of the proposed FCL begins during normal operation, where the main switch is closed, allowing the line current to flow. However, in the event of a fault, a specific control mechanism is activated. The following steps outline the control operation sequence:

1. **Measurement of load current** The load current is measured, and its absolute value is determined.
2. **Comparison with threshold values** The absolute value of the load current is compared with two preset threshold values (I_{th}). One threshold value is positive, while the other is negative. This step helps determine whether the fault current is in the positive or negative cycle of the current waveform.
3. **Fault detection** The fault is detected if two conditions are met:

    a. The magnitude of the fault current exceeds the threshold value (I_{th}).
    b. The slope of the current waveform is increasing or has a positive value.

4. **Instant t_1** Once the fault current is detected at instant t_1, two signals are simultaneously conveyed from the control circuit:

    a. Signal to activate the commutation circuit.

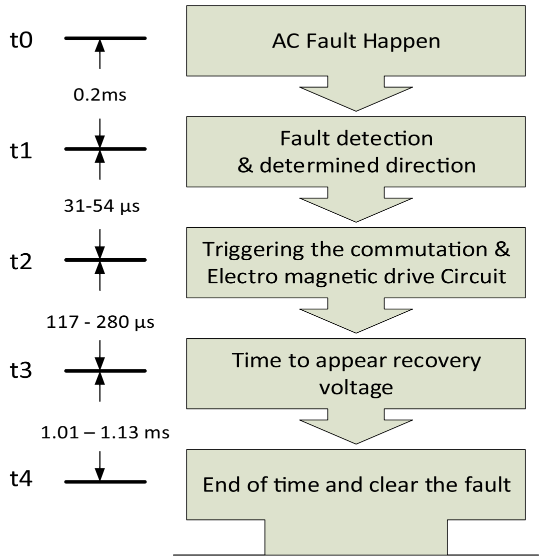

Fig. 7 The current limiting and interruption operation sequence for the proposed FCL

Table 1 Show circuit parameters of the proposed FCL

Source parameters	
Voltage source	400 V_{RMS}
Frequency	50 HZ
Impedance source	$L = 3*10^{-6}$ F & $R = 1*10^{-2}$ Ω
Load parameters	
Load impedance	$L = 3*10^{-3}$ H & $R = 0.15$ Ω
Load current	60 A
Commutation circuit parameters	
Commutation capacitance	4 mF
Commutation inductance	$3*10^{-3}$ H

b. Signal to trigger the thyristors (THYx) and initiate the opening of the MS using the electro-dynamic drive.

The sequence of current limiting and interruption operations is then initiated. Figure 7 depicts the current limiting and interruption operation sequence for the proposed FCL. During this sequence, the commutation circuit actively limits the fault current, and the MS opens to interrupt the current flow. The coordination of these actions ensures the efficient and effective limitation and interruption of the fault current. The control operation sequence presented here provides a general overview of the steps involved in fault detection, current limiting, and interruption for the proposed FCL.

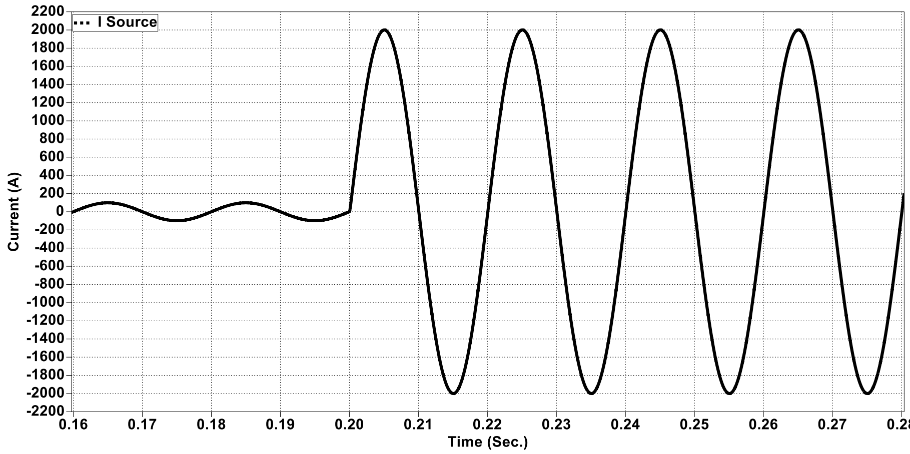

Fig. 8 Prospected short-circuit current

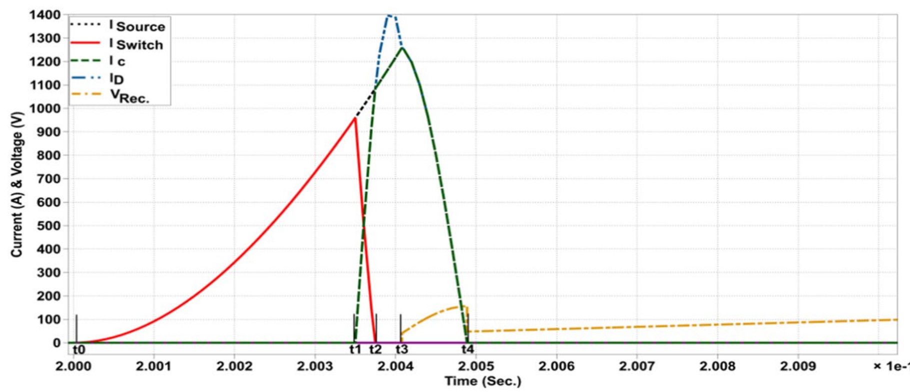

Fig. 9 Current and voltage waveforms using FCL

Simulation results

Simulation results with the parameters provided in Table 1**,** and a fault occurring at t = 0.2 s, shown in Figs. 8 and 9, yield the following observations regarding the normal current before short circuit, the prospective fault current, peak let-through current, fault clearance time, and peak recovery voltage:

- **Normally Load Current:** The simulation result in Fig. 8 indicates that the normal load current according to circuit parameters is 100 A.
- **Prospected short-circuit current** The simulation indicates that the prospected short-circuit current, as shown in Fig. 8, is 2000 A due to the inductive load and the fast transient in the system.
- **Peak Let-Through Current of Phase A** The simulation indicates that the peak let-through current, as shown in Fig. 9, is 1.2kA. This value represents only 60% of the prospective current amplitude. This indicates that the short-circuit current is effectively limited to a small percentage of its maximum potential, demonstrating the successful current limitation capability of the system.

- **Fault Clearance Time** The simulation results show that the fault clearance time is remarkably short, measuring only 26 µs. This swift fault clearance time ensures a rapid interruption of the fault current, minimizing the duration of the fault and reducing the potential for damage to the system.
- **Peak Recovery Voltage** The peak recovery voltage across the contact of phase A is reported to be within the acceptable limit of 200 V. This indicates that the voltage level is maintained within the specified range after the fault clearance, ensuring the safe and reliable operation of the system.

These simulation results as shown in Fig. 8 highlight the effectiveness of the proposed short-circuit current limiter in limiting the fault current, achieving fast fault clearance, and maintaining the recovery voltage within acceptable limits. The parameters and performance values provided demonstrate the capability of the system to provide efficient protection and reliable operation for power supply systems.

Experiment data and results

Experiment setup

Figure 10 shows the final photographic image of the proposed model that was built in the laboratory, where the upper part of the image indicates the three-phase power source, the right side of the image indicates the short circuit and commutation circuit, the load is represented by a three-phase electric motor in the middle of the image, and it feeds the power quality analyzer as an oscilloscope to given signals on the computer screen to the left of the image.

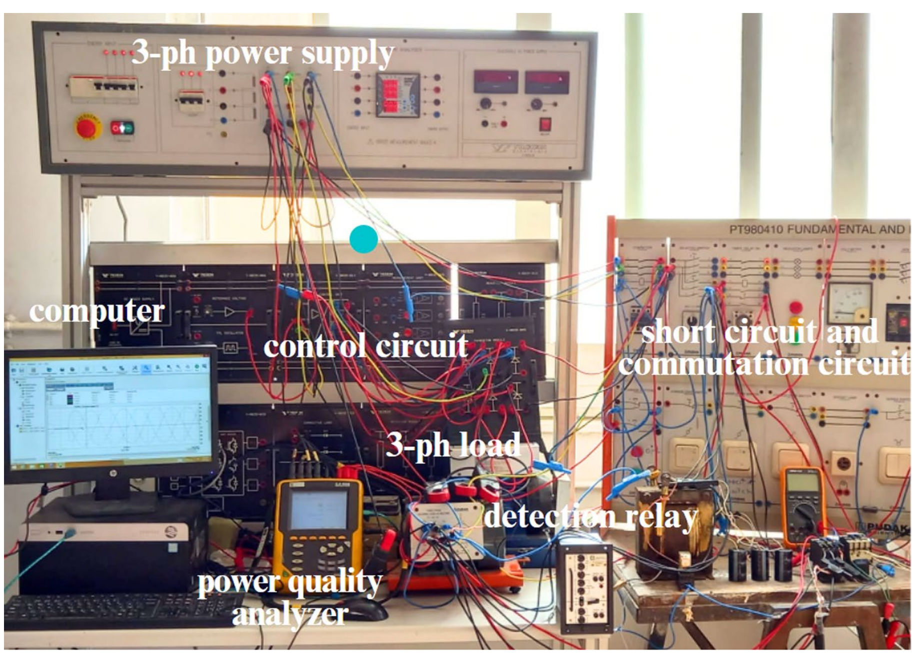

Fig. 10 Laboratory model for proposed FCL

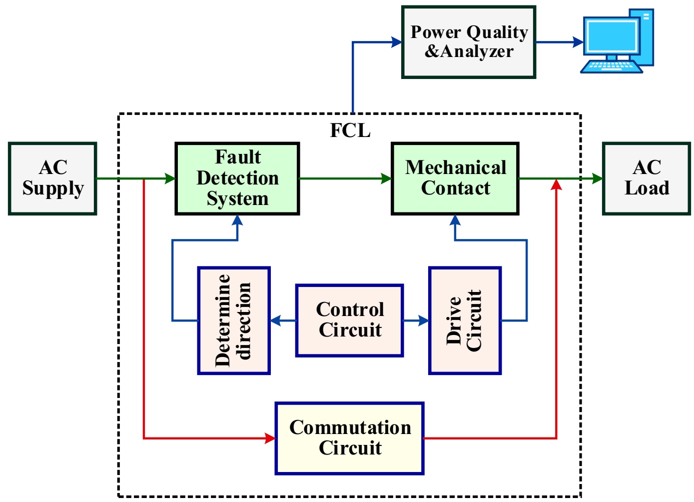

Fig. 11 The block diagram of the experimental FCL model

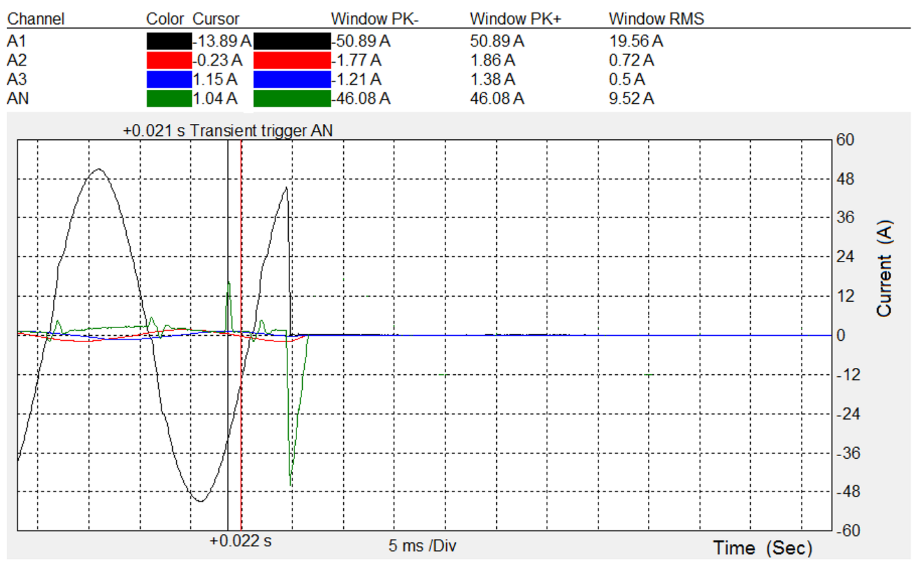

Fig. 12 The model response for current waveforms at line to ground fault (A1)

Figure 11 gives the block diagram that shows the principle operation of the proposed FCL technique, as it includes the three-phase power source 380 V that feeds the load through the mechanical contact under normal conditions. While under abnormal conditions, the control circuit determines the fault direction and at the same time sends a tripping signal to open the mechanical contact.

Experiment results

The practical circuit was built to give a fault current with a maximum value of 100 A. Through laboratory experiments, the proposed technique proved its effectiveness in commutating the fault current in three-phase circuits using one commutation circuit, and Fig. 12 shows the current waveforms at a single line to ground fault (A_1). The

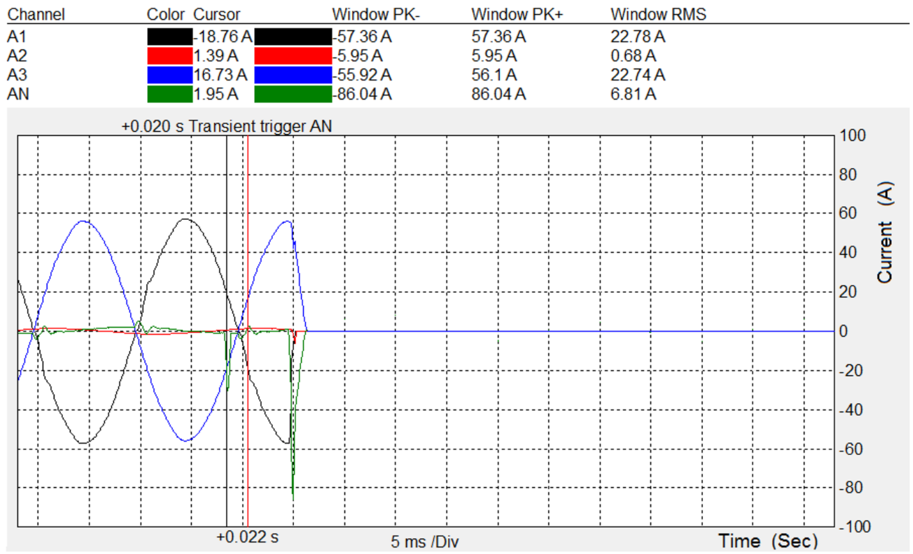

Fig. 13 The model response for current waveforms at line-to-line fault (A_1-A_3)

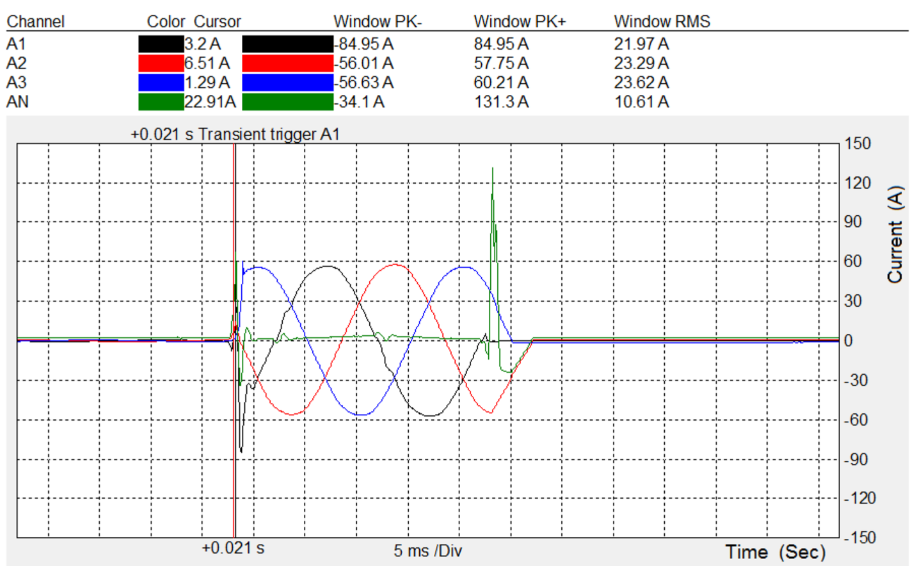

Fig. 14 The model response for current waveforms at symmetrical fault

commutation capacitor current (A_N) discharges the commutation current when the fault current reaches the preset value, and the fault current is successfully commutated at a time of 0.027 s.

The response of the proposed FCL for line to line and symmetrical faults are shown in Figs. 13 and 14, respectively. It is clear from this that when the fault current reaches the predetermined value, the control circuit activates the commutation circuit to inject the discharge current opposite to the fault current, and then the fault current has been successfully interrupted.

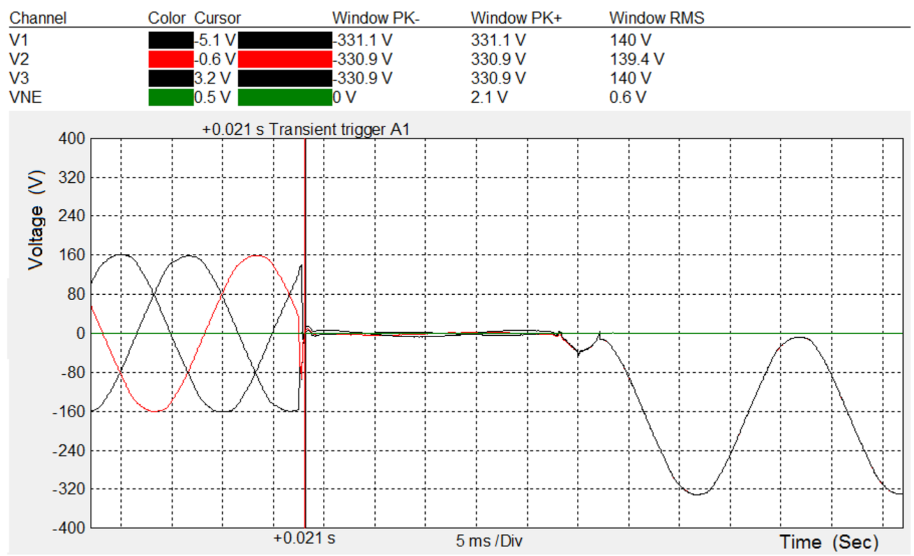

Fig. 15 The model response for voltage waveforms at symmetrical fault

Figure 15 presents the voltage waveforms in the case of a symmetrical fault. It is worth noting that when the fault current is successfully interrupted at the time of 0.05 s., the time to appear the recovery voltage is delayed, thus delaying the onset of the recovery voltage in this way reduces the possibility of an electric arc.

Verification for experiment results with simulation results

Based on the outcomes of the simulation, it is evident that effective current limitation can be achieved up to approximately 35–40% of the prospective fault current. In practical application, successful fault current limitation is achieved within the range of 55–60% of the prospective fault current. Simulation results indicate that the utilization of a super-capacitor with a substantial capacitance and high rated voltage could potentially extinguish fault currents up to 50 kA. Conversely, employing a capacitor with modest capacitance, around 400 μF, and a rated voltage of up to 400 V, has demonstrated the capability to discern fault currents up to 250A.

The fault commutation method is introduced in the present paper as a new current limiting technique. The elaboration of the associated circuits, treatment of certain aspects of the application, and the experimental investigation carried out lead to the conclusion that the proposed method can be effectively used as a current limiting link in AC power systems. The economic studies made are of necessity simple and brief but the cost estimation of a fault commutation circuit in the high voltage range shows that this can successfully compete with the method on economic grounds.

Conclusions

The article presents an innovative and cost-effective solution for limiting short-circuit currents using a single commutation circuit and a high-speed CB. The primary focus is on leveraging semiconductor devices, fast fault detection, and phase control technology to enhance the performance of existing power supply systems. By incorporating an artificial zero-crossing circuit, the proposed design aims to restrict the short-circuit current before the occurrence of the first peak. Notably, one of the key advantages highlighted in the article is the cost-effectiveness of this FCL compared to alternative solutions. Its simplicity in design contributes to lower costs, eliminating the need for upgrading various network components such as generators, transformers, switches, and transmission lines.

However, the proposed FCL scheme does have certain limitations that warrant consideration. Depending on the specific design and components utilized, there may be constraints in handling high fault currents that can be effectively limited by the FCL. Additionally, designing and implementing an effective control algorithm that ensures proper fault current limiting and coordination with the power system can pose challenges. Moreover, the physical capabilities and cost of implementing the FCL system could limit the practical comparison to simulation results, and laboratory safety concerns may need to be addressed.

To ensure the stability and reliability of the proposed FCL scheme in the network, future efforts should be directed toward comprehensive field trials and real-world deployment. Conducting these trials will validate the performance and effectiveness of the FCL system in diverse power system environments. Collaborations with power utilities or industry partners will facilitate deploying the FCL system in selected locations, allowing for an evaluation of its performance under actual operating conditions. Furthermore, comprehensive performance testing of the FCL prototype should be conducted under various fault conditions and load scenarios. This will enable measuring its effectiveness in limiting short-circuit currents, evaluating its response time, and verifying its reliability and stability. By addressing these aspects, the proposed FCL scheme can be refined and optimized to meet the demands of modern power systems, paving the way for more efficient and reliable electrical power engineering solutions in the future.

Abbreviations

C_k	Pre-charged capacitor
L_k	Inductive element
DA_1	Diode for phase A in the positive half cycle
DA_2	Diode for phase A in the negative half cycle
DG	Distributed generator
FCL	Fault current limiter
I_{th}	Threshold values which the value the FCL start operation
Lk	Symbol for inductive component in commutation circuit
MCS	Measurement and control system
MOV	Metal oxide varistors
MS	Main or mechanical switch
NCFCLs	Non-conducting fault current limiters
SFCL	Superconducting fault current limiters
$THYA_1$	Thyristor for phase A in the positive half cycle
$THYA_2$	Thyristor for phase A in the negative half cycle

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Author contributions

AR conceptualized and designed the study, conducted experiments, analyzed data, and wrote the manuscript. AMH contributed to data analysis, interpretation, and provided critical revisions to the manuscript. SH provided expertise in FCL, contributed to data interpretation, and assisted in manuscript preparation. KMA contributed to data analysis, interpretation, and provided critical revisions to the manuscript. All authors have read and approved the final version of the manuscript.

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Availability of data and materials
The datasets or materials used in this research are available upon reasonable request to the corresponding author. We are committed to promoting transparency and facilitating the replication of our study.

Declarations

Competing interests
The authors declare no competing interests that could influence the objectivity or impartiality of this research. There are no financial, personal, or professional relationships that could be perceived as potential conflicts of interest.

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