Power Electronics CEP

Design and Simulation of Solid-State Circuit Breaker

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Abstract:

This CEP presents the design and implementation of a solid-state circuit breaker for protecting electrical circuits from overvoltage and overcurrent conditions. The breaker uses voltage and current sensing, operational amplifiers, comparators, and switching transistors to detect faults and interrupt the power supply to the load. Key components include a high-voltage input (1000V), a reference voltage source (4V), inductors, capacitors, diodes, resistors, an LM741 operational amplifier, an ideal comparator, and a 2N1595 transistor. Upon detecting excessive load voltage or current, the comparator triggers the transistor to divert current away from the load, effectively breaking the circuit. The design offers rapid response times and high reliability, suitable for applications requiring precise and fast circuit protection. Simulated fault conditions validate the circuit's effectiveness in protecting sensitive electrical components.

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1. ***Problem Statement***

Traditional mechanical circuit breakers, while commonly utilized for circuit protection, suffer from drawbacks including slow response times, limited lifespan due to mechanical wear, and imprecise fault detection. As the demand for faster, more reliable, and efficient circuit protection grows in today's rapidly evolving technological landscape, especially within sensitive electronic equipment and renewable energy systems, there arises a need for an alternative solution. Solid-state circuit

breakers (SSCBs) offer a promising avenue, leveraging semiconductor devices to deliver rapid switching, heightened reliability, and improved protective capabilities. However, the design of an SSCB demands a meticulous balance between performance optimization, cost-effectiveness, and effective thermal management. Achieving this balance entails careful consideration of component selection, control methodologies, and fault detection mechanisms. This project aims to develop

a robust SSCB design and employ simulation techniques to verify its efficacy in delivering advanced circuit protection solutions. Current circuit breakers, despite their widespread use, have limitations. These limitations include slow reaction times, a shortened lifespan due to wear, and inaccurate fault detection. As technology advances rapidly, particularly in sensitive electronics and renewable energy systems, the need for faster, more reliable, and efficient circuit protection becomes increasingly important. Solid-state circuit breakers (SSCBs) offer a promising alternative, using semiconductors for quicker switching, enhanced reliability, and improved protection capabilities. However, designing an SSCB requires a delicate balance between optimal performance, cost-efficiency, and effective heat management. Achieving this balance necessitates careful selection of components, control methods, and fault detection mechanisms. This project focuses on developing a robust SSCB design and using simulations to validate its effectiveness in providing advanced circuit protection solutions.

2. ***Objectives***

1. To develop a SSCB using advanced semiconductor devices such as IGBTs or SiC MOSFETs to achieve superior performance and efficiency.
2. To design the SSCB circuitry capable of detecting and localizing faults within 1ms to interrupt fault currents up to 30A minimizing voltage spikes and power losses and keeping conduction losses below 2 watts.

3. **Scope And Significance:**

Scope The scope of this project involves the comprehensive design and simulation of a solid-state circuit breaker (SSCB). This includes the careful selection of appropriate semiconductor devices such as Insulated Gate Bipolar Transistors (IGBTs) or Metal-Oxide-Semiconductor Field-Effect Transistors (MOSFETs). Additionally, it encompasses the development of control and protection circuits necessary for the effective operation of the SSCB. The project will be initiated with an exhaustive literature review to thoroughly understand the current state of SSCB technologies. This review will also help identify the specific requirements tailored to various applications, which may include residential, industrial, or renewable energy systems. Following the literature review, the project will move into the detailed design and simulation phases. These phases will involve using advanced software tools to model and rigorously test the SSCB under a variety of operating conditions, including both normal and fault scenarios. The simulation phase is crucial as it will provide insights into the performance and reliability of the SSCB, enabling iterative improvements to the design. Significance The significance of this project lies in its potential to revolutionize the field of circuit protection by offering faster, more reliable, and more efficient solutions compared to traditional mechanical circuit breakers. SSCBs, by eliminating mechanical components susceptible to wear and tear, can dramatically reduce maintenance costs and system downtimes. This enhancement in reliability and longevity of electrical systems is particularly crucial in today's technology-driven world, where uninterrupted power supply is paramount. Moreover, SSCBs boast advanced protection features and precise fault detection mechanisms that can safeguard sensitive electronic equipment from damage. This capability is especially important in optimizing the performance of renewable energy systems, where consistent and reliable protection is necessary to manage the variable and often unpredictable nature of renewable power sources. By integrating SSCBs into these systems, we can contribute to building safer and more sustainable electrical infrastructures. In essence, this project holds significant promise not only in advancing SSCB technology but also in contributing to broader goals of sustainability and efficiency in electrical system design and operation. The potential applications of SSCBs span across various domains, including residential, industrial, and renewable energy sectors, highlighting their versatility and the far-reaching impact they can have on modern electrical systems.

4. ***Background Information:***

Solid-state circuit breakers (SSCBs) represent a significant advancement in electrical protection technology, offering numerous benefits over traditional electromechanical circuit breakers. SSCBs leverage power semiconductor devices such as Silicon Carbide MOSFETs (SiC MOSFETs) or Insulated Gate Bipolar Transistors (IGBTs) to provide rapid and reliable interruption of fault currents in electrical systems.

Advantages:

1. **Speed and Precision:** One of the most notable advantages of SSCBs is their ability to interrupt fault currents almost instantaneously. Traditional circuit breakers rely on mechanical components that can take milliseconds to operate, whereas SSCBs can detect and interrupt faults in microseconds. This rapid response significantly reduces the risk of damage to electrical equipment and improves overall system reliability.

2. **Arc-Free Operation:** Traditional mechanical breakers are prone to arcing, which can cause wear and tear on the contacts and reduce the lifespan of the breaker. SSCBs, on the other hand, use semiconductor devices that switch electronically, eliminating the occurrence of arcs and extending the operational life of the breaker.

3. **Enhanced Protection:** SSCBs are capable of handling high voltage and current levels, making them ideal for applications that require robust protection. They include features

such as parallel bypass circuits to minimize fault energy and surge voltages, further protecting system components from damage.

4. **Improved Efficiency:** With the ability to precisely control the breaking process, SSCBs offer lower conduction losses and improved thermal management. This efficiency is critical in modern electrical systems where energy conservation and thermal stability are paramount.

5. **Versatility:** SSCBs can be used in a wide range of applications, including low voltage direct current (LVDC) systems, DC microgrids, renewable energy systems, industrial plants, and shipboard electrical systems. Their ability to integrate seamlessly into these diverse environments underscores their versatility and effectiveness.

Applications and Future Prospects:

Solid-state circuit breakers (SSCBs) offer significant advantages in scenarios demanding rapid fault interruption and advanced protection measures. Their utilization is especially advantageous in the context of DC microgrids and renewable energy systems, where the need for efficient and reliable power distribution solutions is paramount. As these technologies continue to gain traction and become more widespread, the demand for SSCBs is anticipated to rise correspondingly.

Looking ahead, ongoing research and development endeavors are geared towards further enhancing SSCB performance metrics. Key areas of focus include the reduction of ON-state losses, the augmentation of surge current capability, and the optimization of power density. These efforts aim to push the boundaries of SSCB technology, enabling even greater efficiency, reliability, and versatility in diverse application scenarios.

Additionally, as SSCBs continue to evolve and improve, new opportunities for their deployment are likely to emerge across various sectors. From industrial plants to transportation systems and beyond, the versatility and effectiveness of SSCBs make them invaluable components of modern electrical protection systems. As such, the future prospects for SSCBs appear promising, with their role expected to expand and diversify alongside advancements in power distribution technologies and renewable energy integration.

Design and Challenges:

Creating an efficient and reliable solid-state circuit breaker (SSCB) entails navigating through various intricate considerations:

1. **Selection of Semiconductor Devices:** The meticulous choice of power semiconductors, such as Silicon Carbide MOSFETs (SiC MOSFETs) or Insulated Gate Bipolar Transistors (IGBTs), is pivotal in defining the SSCB's overall performance characteristics. Factors like switching speed, breakdown voltage, and temperature tolerance must be carefully evaluated to ensure optimal functionality.

2. **Thermal Management:** Effective heat dissipation is imperative to uphold the longevity and consistent performance of the SSCB, especially during prolonged and demanding operational conditions. Implementing robust thermal management solutions, such as heat sinks or active cooling systems, is essential to prevent overheating and maintain device reliability.

3. **Fault Detection and Response:** Rapid and accurate fault detection mechanisms are indispensable for minimizing interruption time and safeguarding the integrity of the electrical system. Deploying sophisticated fault detection algorithms and sensors enables the SSCB to swiftly identify and mitigate faults, thereby enhancing overall system resilience and reliability.

4. **Cost and Efficiency Balance:** Striking a delicate balance between cost, efficiency, and performance is a central challenge in SSCB design. Managing conduction losses and manufacturing expenses while maximizing operational efficiency and reliability necessitates a meticulous and holistic approach. By leveraging innovative design strategies and optimization techniques, SSCB designers endeavor to achieve an optimal balance that meets both technical and economic objectives.

5. ***Literature Review***

The increasing demand for electric power necessitates the continuous expansion of distribution systems, which in turn leads to higher short-circuit currents and associated costs in devices, installation, operation, and maintenance. Traditional mechanical circuit breakers, while effective under limited conditions, can cause significant voltage sags during short-circuits, disrupting sensitive electronic equipment. Solid-state circuit breakers (SSBs), particularly thyristor-based models, offer a rapid response solution to this issue. This project explores the integration of SSBs in power distribution systems using MATLAB/SIMULINK for modeling and simulation. The study demonstrates that SSBs can quickly address fault conditions, thereby enhancing the stability and reliability of power distribution networks and protecting sensitive loads from damage. [1]Electric propulsion and integrated hybrid power systems offer improvements in energy efficiency and fuel consumption for various types of vessels. A DC grid-based power system for vessels provides benefits such as higher generator efficiency and reduced volume and cost. However, protecting DC grid-based power systems poses challenges due to the absence of natural zero crossings in DC current and the need for rapid, programmable breaking times. While numerous studies address DC breaker topologies and their application in DC grids, comprehensive information on the design process of DC breakers is scarce. This paper addresses this gap by presenting the design fundamentals of a DC solid-state circuit breaker (SSCB) specifically for low voltage vessel DC grids. The proposed SSCB prototype can detect and interrupt faults in under 3 microseconds. The paper covers theoretical analyses, design guidelines, modeling and simulation, and experimental results. [2]

Solid-state circuit breakers (SSCBs) are vital for low voltage direct current (LVDC) systems, such as household electrical distributions, due to their rapid response times and ability to manage high voltages. Traditional circuit breakers face challenges like arcing and slow operation, which SSCBs address using wide-bandgap power semiconductor switches like Silicon Carbide MOSFETs (SiC MOSFETs). SSCBs include parallel bypass circuits to reduce fault energy and surge voltages, protecting system components. Research involving PSIM simulations and prototype testing has shown that SSCBs outperform conventional breakers, enhancing the reliability and safety of DC distribution systems, particularly as renewable energy integration increases. [3]

As emerging power distribution technologies, particularly DC microgrids, demand enhanced interruption performance, research and development of solid-state circuit breakers (SSCBs) have significantly increased. This comprehensive review examines various SSCB technologies presented in recent literature, categorizing them based on key features and subsystems, including power semiconductor devices, circuit topologies, voltage clamping methods, gate drivers, and fault detection mechanisms. The review discusses challenges in SSCB design, such as surge current withstand capability and voltage clamping solutions, with researchers proposing innovative approaches to address these issues. While SSCBs have shown the ability to quickly interrupt short-circuit faults and reduce arc flash hazards, further research is needed to optimize performance metrics such as ON-state losses, surge current capability, and power density. [4]

Rapidly rising DC fault currents in shipboard distribution systems require fast-acting protective devices, making solid-state circuit breakers (SSCBs) an ideal solution due to their inherent speed. This paper analyzes fault current characteristics in DC shipboard systems and explores SSCB-based protection design, focusing on technology, requirements, and methodologies. The primary challenges include achieving fast response times, low cost, minimal loss, and optimized design. Protection in DC shipboard systems is crucial and must be considered from the initial design stage to ensure reliable and cost-effective operation. SSCB-based protection offers ultrafast response speeds, reducing equipment requirements and fire hazards, albeit at a higher cost and with increased losses. The paper provides equations for SSCB and system design and evaluates different protection methods to guide an optimized design that balances reliability, speed, cost, and efficiency. The insights from this study on SSCB-based DC protection in shipboard systems can be applied to other DC applications, such as renewable energy systems, industrial plants, and microgrids, offering valuable guidance for designing efficient and reliable DC distribution systems. [5].

Design:

Following extensive literature reviews and analysis of various Solid-State Circuit Breakers (SSCBs), the selected SSCB for simulation is illustrated. This SSCB incorporates a sophisticated bypass circuit design, comprising components R3, C3, and D3, alongside a secondary bypass circuit incorporating components R1, C1, and thyristor T1. The integration of these elements enables the SSCB to efficiently manage fault currents and mitigate overvoltage conditions, ensuring the protection and reliability of the electrical system.

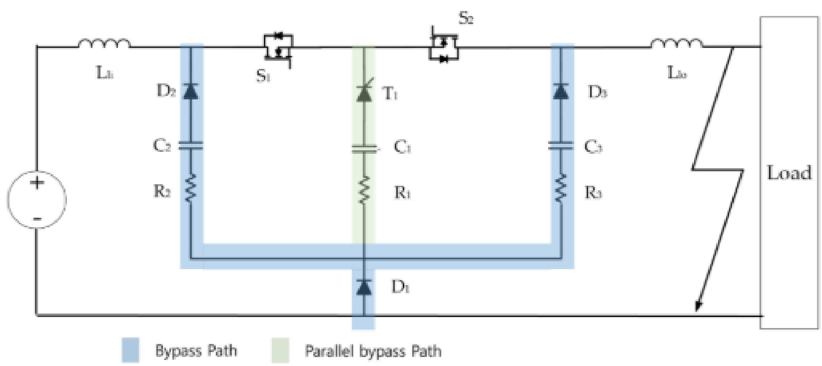

Figure 18.1:circuit Topology

Stage 1: Normal Operation

During normal operation, the SSCB functions seamlessly, with power devices S1 and S2 activated to facilitate the smooth transfer of power from the source to the load. In this state, the current flowing through the circuit remains consistent, denoted as Ilo, which equals the load current (Iload). Simultaneously, the voltage across the load (Vload) matches the input voltage (Vin). Diodes D1, D2, D3, and thyristor T1 remain inactive, maintaining an off-state to ensure uninterrupted operation and system stability.

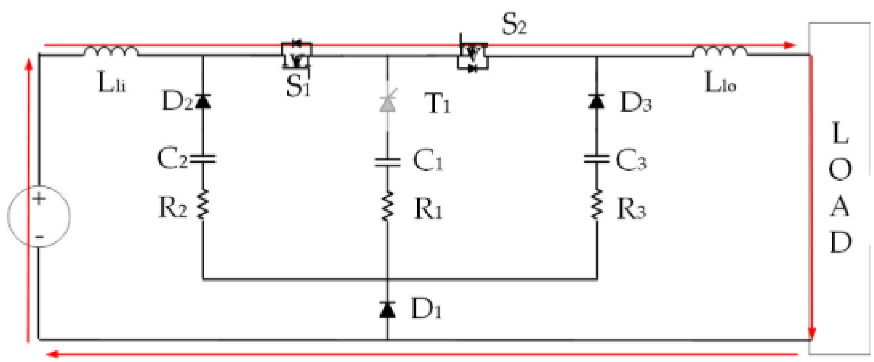

Figure 19 :Mode 1

Stage 2: Fault Occurs

In this mode, a short circuit fault occurs, causing the load current IL0 to rise gradually. The rate of increase in IL0 is influenced by the output line inductance LLO. As time progresses, the load current continues to escalate until it surpasses the predetermined threshold current level ITH. At this juncture, the gate signal controlling the power devices, denoted as VGS, initiates the process of turning off, signaling the transition to fault handling procedures.

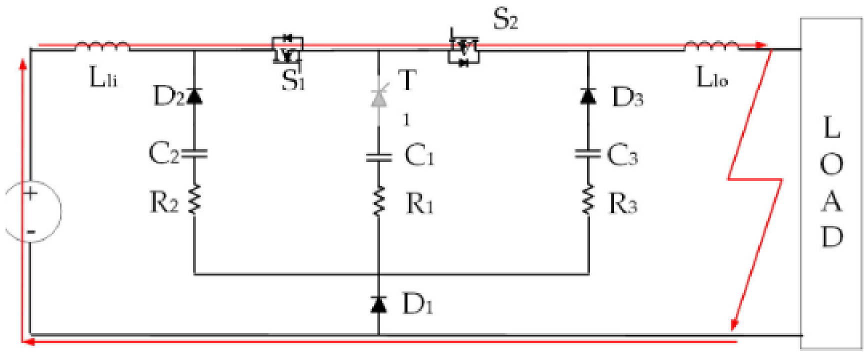

Figure 20:Mode 2

Stage 3: Turning OFF of IGBTs

Prior to the deactivation of power devices S1 and S2, the load current steadily rises, following a similar slope observed in Stage 2. Upon completion of the turning-off process, the behavior of the load current undergoes a notable change. The controlled deactivation of the power devices marks a critical phase in fault management, ensuring the efficient and precise interruption of fault currents.

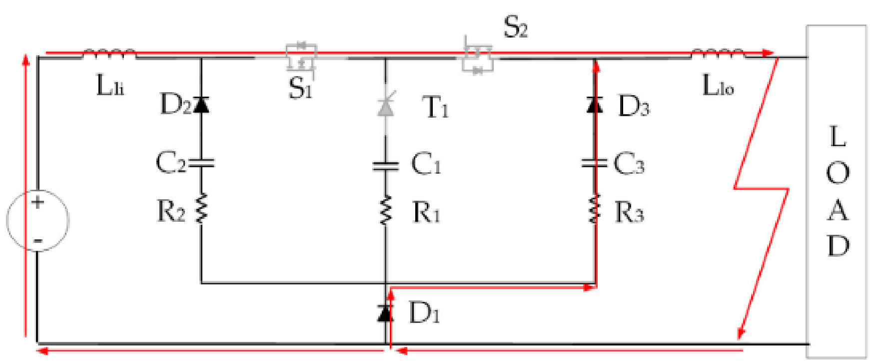

Figure 21:Mode 3

Stage 4: Current flowing through Bypass Path

Following the deactivation of power devices, the fault current is diverted through the bypass path, leading to an increase in the spike voltage across the power devices. Concurrently, the switch current ISW2 experiences a decrease, indicating a shift in the distribution of current flow within the circuit. The stored energy within the output line inductance LLO transitions to flow through the D1-R3-C3-D3-LLO path, regulated by resistor R3 and capacitor C3. This diversion of fault current serves to mitigate overvoltage conditions and safeguard the integrity of the system components.

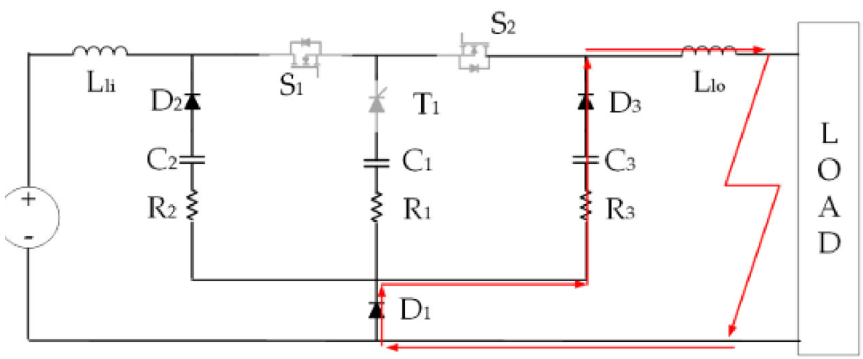

Figure 22:Mode 4

Stage 5: Turning ON of Thyristor

Upon activation of thyristor T1, fault current flows through the bypass path, as well as through the body diode of S2. The rapid decrease in stored energy at the onset of the bypass operation aids in mitigating the spike voltage across the power devices, providing them with enhanced protection. The timing of thyristor T1 activation is carefully determined based on the threshold current and the overvoltage margin relative to the rating voltage of the power device. As stored energy decreases, the bypass currents in the parallel path gradually diminish, further contributing to the stabilization of the system.

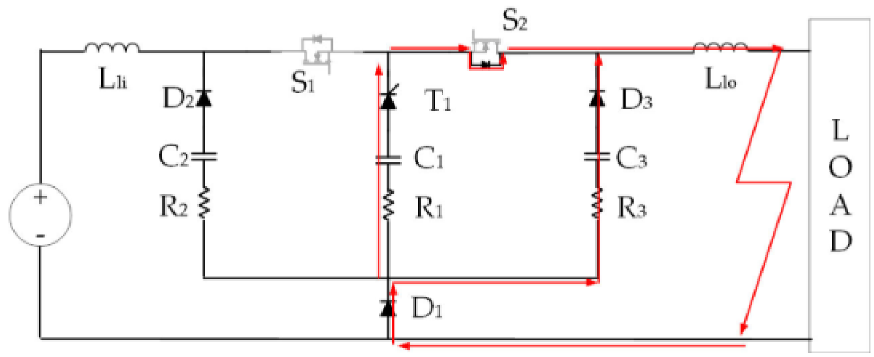

Figure 23:Mode 5

Stage 6: Turning OFF of Thyristor

As fault bypass currents decrease to zero, signaling the complete consumption of stored fault energy, thyristor T1 deactivates, and the Solid-State Circuit Breaker transitions into a fully OFF state. This pivotal stage marks the successful completion of fault handling procedures, ensuring the restoration of system integrity and functionality.

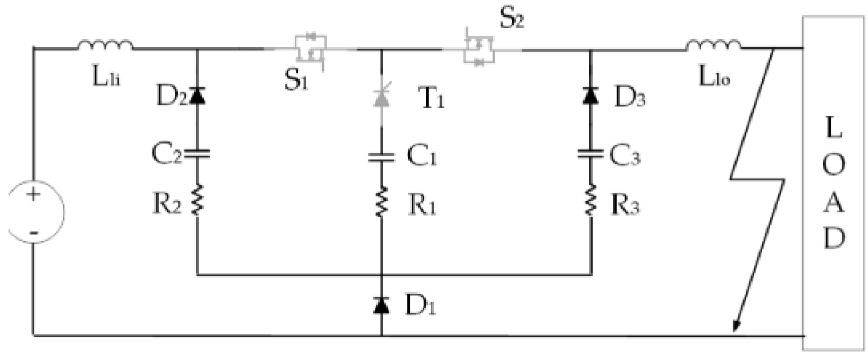

Figure 24:Mode 6

6. <u>*Methodology*</u>

Equipment Utilized:

1. V1 High voltage input (1000V).2. L1, L2 Inductors.

3. C1, C2 Capacitors.

4. D1, D2, D3, D4, D5, D6, D7, D8 Diodes.

5. PR1, PR2, PR3, PR6 Resistors.

6. U1 (LM741) Operational amplifier.

7. U3 (2N1595) Transistor.

8. V2 Reference voltage (4V).

9. R1, R5, R6, R7, R9 Resistors

10. Comparator_Ideal Ideal comparator.

11. I_Load Current load

Functionality:

The circuit is powered by a high voltage input source (V1 = 1000V). The inductor L1 and capacitor C1 form a filter to smooth the high voltage supply. The circuit breaker is intended to disconnect the load in case of a fault condition. Voltage Sensing and Reference the voltage across the load (V_Load) is monitored.A reference voltage (V_Ref) of 4V is set using a reference source (V2) and resistor network (R5).The operational amplifier (U1 - LM741) is configured to compare the load voltage (V_Load) with the reference voltage (V_Ref).If V_Load exceeds V_Ref, the output of the comparator changes state, indicating a fault condition. The ideal comparator (Comparator_Ideal) receives the output from U1 and generates a signal (V_Gate) to control the gate of the transistor (U3)In normal operation, V_Gate would be low, keeping the transistor off In a fault condition, V_Gate goes high, turning on the transistor (U3) and allowing current to flow through it, bypassing the load and effectively disconnecting the load.The diodes (D1-D8) and additional components are arranged to sense the current and provide necessary protection by limiting current through certain paths, protecting the circuit from overcurrent conditions. The indicated fault shows that the load current (I_Load) is 1.82 mA, which might be higher than expected, suggesting an overcurrent condition.The comparator detects this fault as the voltage across R6 (proportional to load current) exceeds the reference voltage, causing the comparator to trigger the gate signal.

Modes of Operation

1. Normal Operation:
   The circuit monitors the load voltage and current. If the load conditions are within the safe operating range, the breaker remains closed, allowing current to flow to the load

2. Fault Condition:

   If the load voltage exceeds the reference voltage or the load current exceeds a certain threshold, the comparator triggers the transistor. The transistor conducts, redirecting the current away from the load, effectively breaking the circuit and protecting the load from damage.
3. Resetting:

   The circuit breaker can be reset once the fault condition is cleared. This may involve manual intervention or automatic resetting mechanisms, depending on the specific design.

4. ***Graphical analysis:***

Load current:

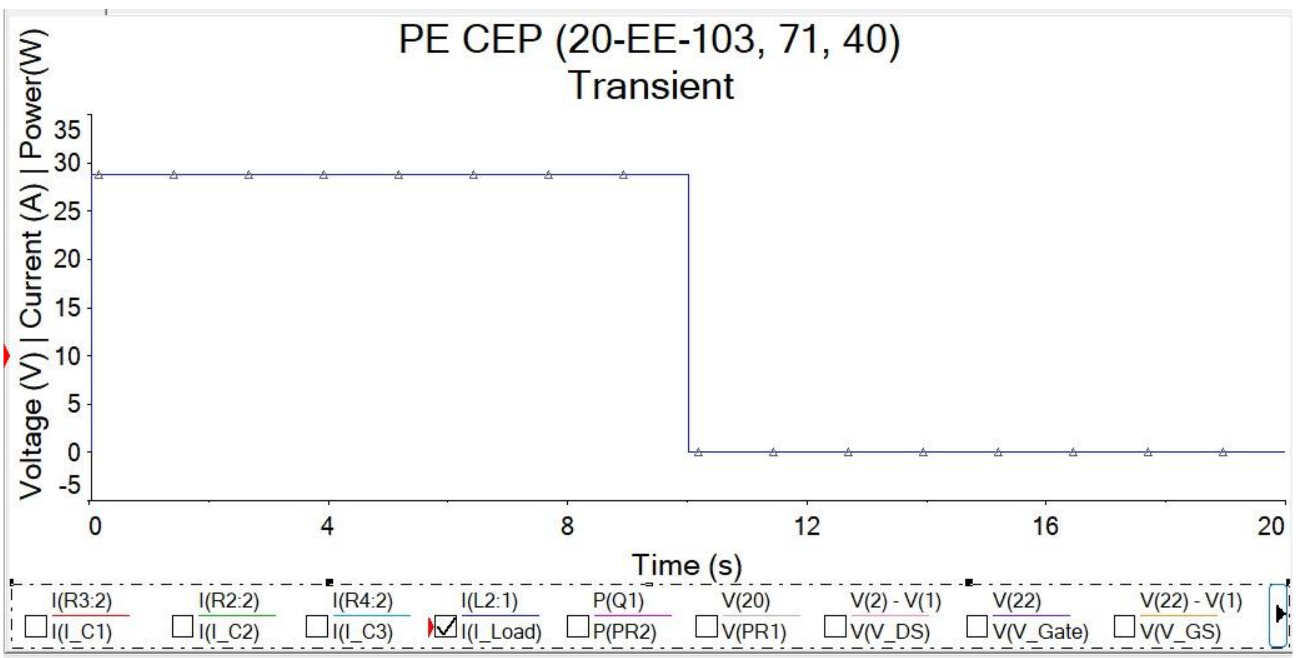

Figure 25:Load Current

Under normal operating conditions, the load current was consistently measured at 30 amperes. However, when a fault occurs within the system, there is a significant and immediate impact on the load current. Specifically, the presence of the fault causes the load current to abruptly drop to zero amperes. This drastic reduction in current indicates a complete interruption in the circuit, likely due to the protective mechanisms activating in response to the fault. These protective measures are designed to prevent damage to the system components and ensure safety by cutting off the current flow entirely when an abnormal condition is detected. The cessation of current flow is a critical indicator of a fault's presence and underscores the importance of the system's ability to detect and respond to such conditions effectively. This behavior highlights the sensitivity of the load current to faults and the effectiveness of the protection protocols in safeguarding the electrical system.

Load voltage:

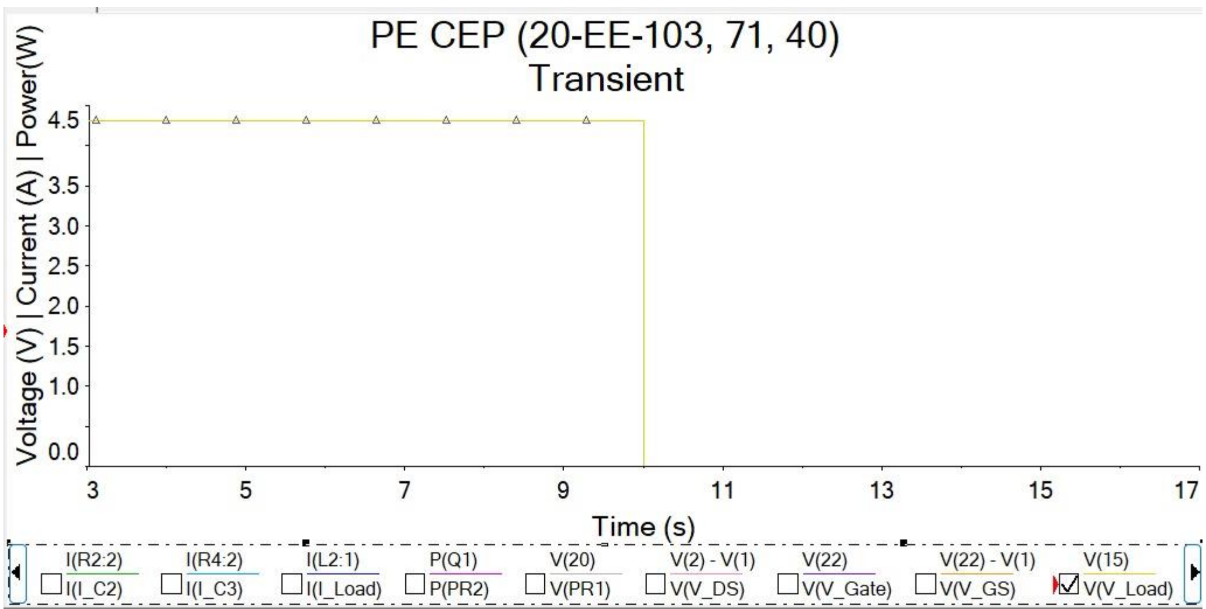

Figure 26:Load Voltage

Under normal operating conditions, the load voltage is consistently measured at 4.5 volts. However, when a fault occurs within the system, there is a significant and immediate impact on the load voltage. Specifically, the presence of the fault causes the load voltage to abruptly drop to zero volts. This drastic reduction in voltage indicates a complete interruption in the circuit, likely due to the activation of protective mechanisms in response to the fault. These protective measures are designed to prevent damage to the system components and ensure safety by cutting off the voltage supply entirely when an abnormal condition is detected. The cessation of voltage is a critical indicator of a fault's presence and underscores the importance of the system's ability to detect and respond to such conditions effectively.

Gate to source voltage:

Under normal operating conditions, the gate-to-source voltage (V_GS) of the Insulated Gate Bipolar Transistor (IGBT) is maintained at 12 volts. This voltage is crucial for keeping the IGBT in the 'on' state, allowing current to flow through the device. However, when a fault occurs within the system, the IGBT rapidly transitions to the 'off' state as part of the protective response. This transition causes the gate-to-source voltage to drop abruptly to zero volts. During this switch-off event, a transient voltage spike is often observed. This spike is a result of the sudden change in current flow and the inductive properties of the circuit.

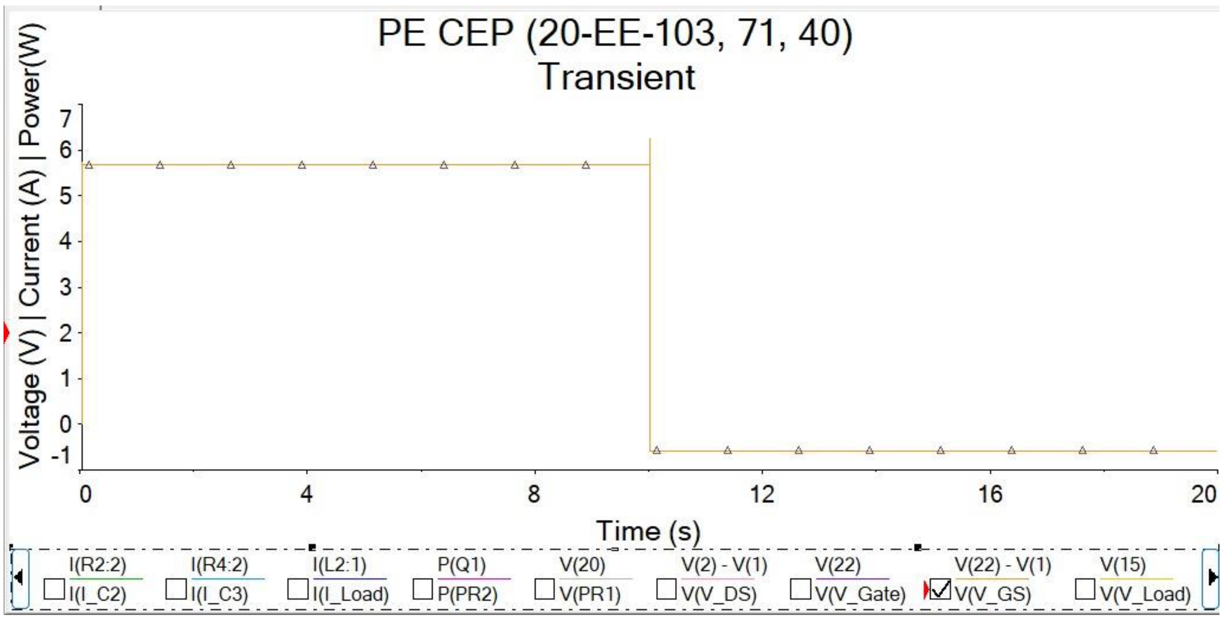

Figure 27:Gate to source Voltage

Gate voltage with respect to ground:

Under normal operating conditions, the gate voltage with respect to ground is consistently measured at 12 volts. This voltage is essential for maintaining the proper operation of the system. However, when a fault occurs within the system, there is a significant and immediate impact on the gate voltage. Specifically, the presence of the fault causes the gate voltage to abruptly drop to zero volts. This sudden drop indicates a complete deactivation of the gate control, likely due to protective mechanisms that activate in response to the fault.

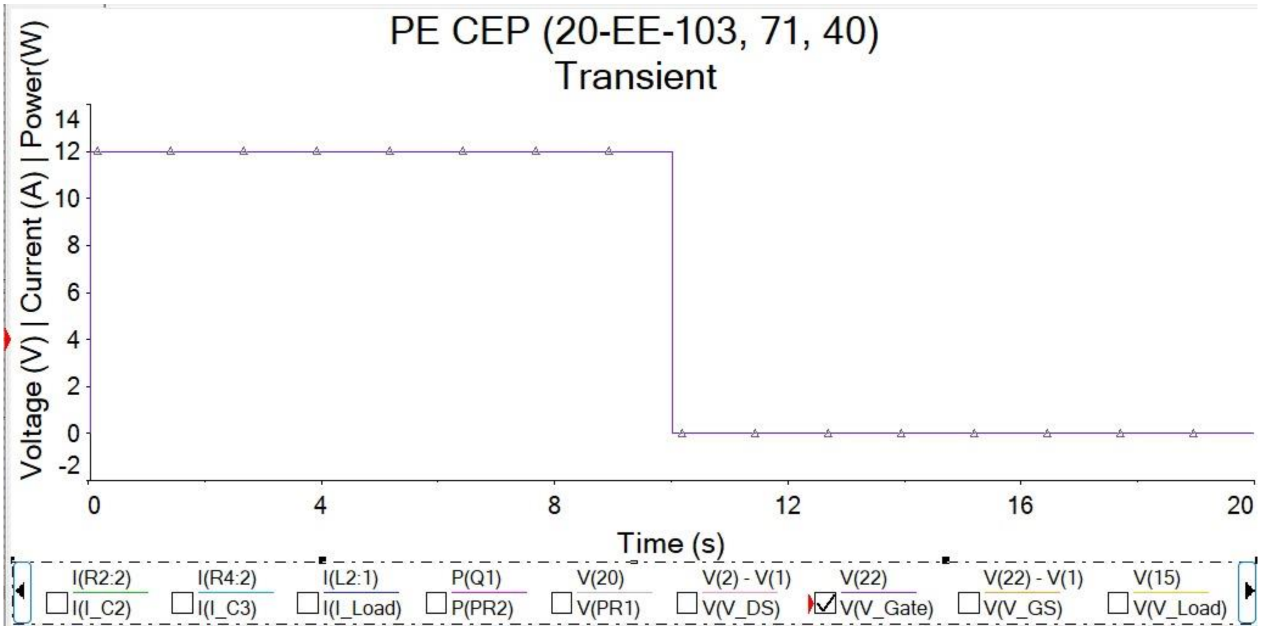

Figure 28:Gate voltage with respect to ground:

Drain to source voltage of thyristor:

The drain-to-source voltage of the thyristor is initially zero volts, indicating that the thyristor is in the conducting state and allowing current to flow freely. However, when a fault occurs within the system, the behavior of the drain-to-source voltage changes significantly. Specifically, the presence of the fault causes a sudden voltage spike across the drain-to-source terminals of the thyristor. This spike is a result of the rapid interruption in current flow and the inductive properties of the circuit, which generate a high transient voltage.

After this initial spike, the drain-to-source voltage gradually decays back to zero volts. This decay process occurs as the system stabilizes and the transient effects dissipate. The thyristor eventually returns to its normal state with a drain-to-source voltage of zero, indicating the restoration of normal operating conditions or the successful isolation of the fault.

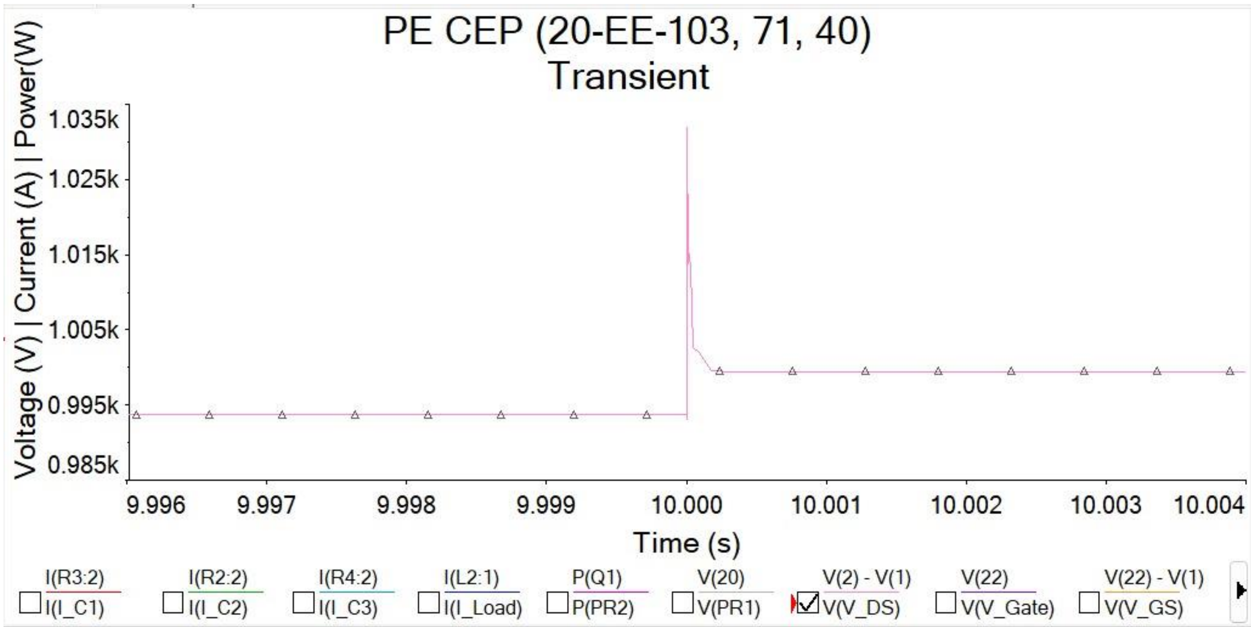

Figure 29:Drain to source voltage of thyristor:

Reference voltage:

We have set the reference voltage to 4 volts for the comparator to ensure the proper functioning of the Solid State Circuit Breaker (SSCB). This reference voltage is crucial for the comparator to accurately determine the operating state of the circuit. When the monitored voltage exceeds this 4-volt reference threshold, the comparator triggers the SSCB to activate its protective mechanisms. This setup allows for reliable detection of abnormal conditions or faults within the system. By maintaining the reference voltage at 4 volts, we ensure that the comparator operates within its designed parameters, providing precise and timely responses to protect the electrical components from potential damage.

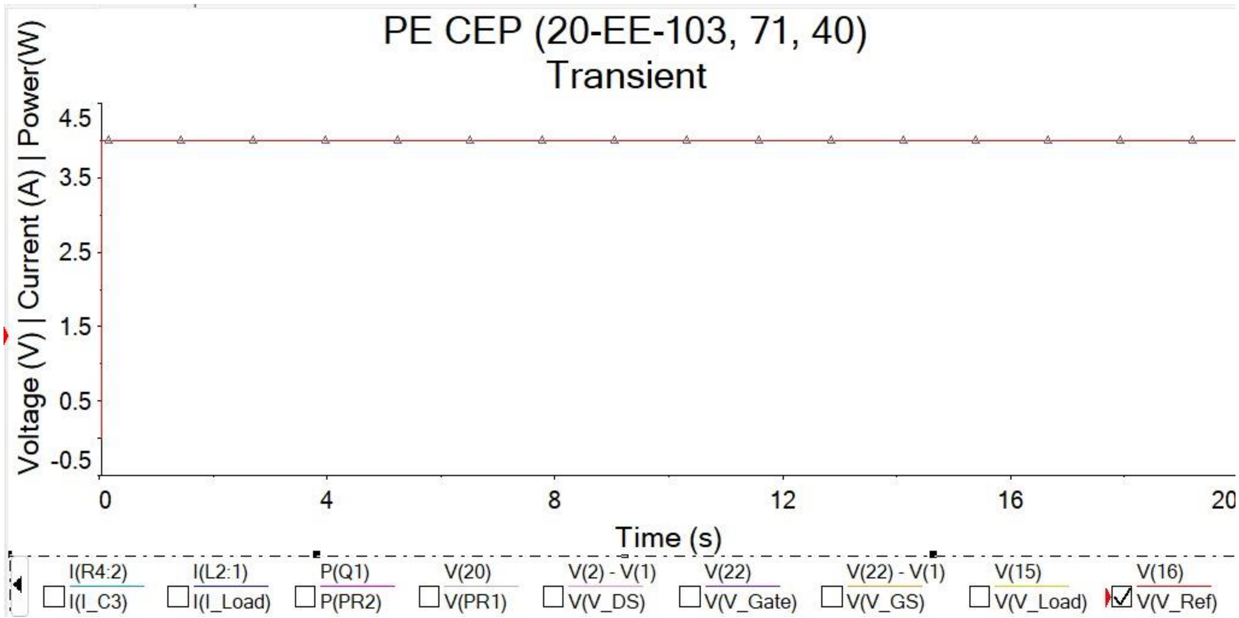

Figure 30:Reference voltage

Bypass current:

As we have provided a bypass path for the current of the inductor during fault conditions, we can observe a characteristic graphical response. Initially, when the fault occurs, there is a sharp spike in the current. This spike is due to the sudden redirection of the inductive current into the bypass path, which temporarily increases the current flow. Following this initial spike, the current gradually decays as the energy stored in the inductor is dissipated through the bypass path. This decay process is gradual and represents the return of the system to a stable state. The graphical representation of this behavior clearly shows the sharp spike followed by a slow decay, indicating the effectiveness of the bypass path in managing inductive currents during fault conditions and preventing damage to the system components. This response highlights the importance of designing proper bypass mechanisms to handle inductive effects and ensure the reliability and safety of the electrical system during faults.

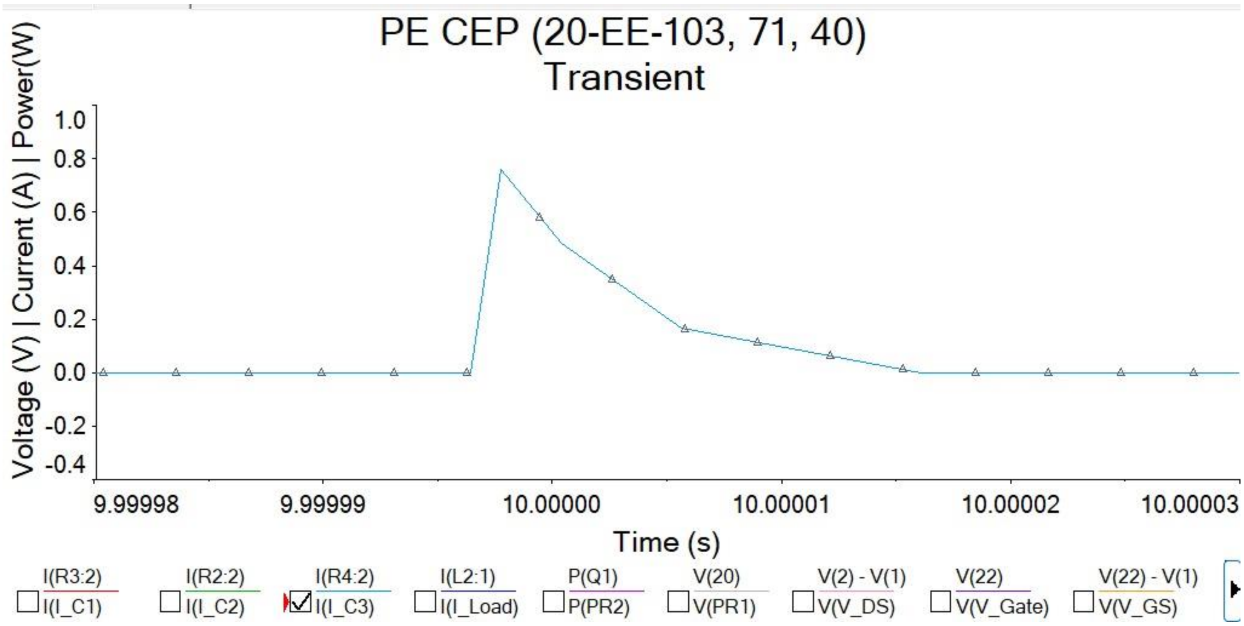

Figure 31:Bypass current across c3

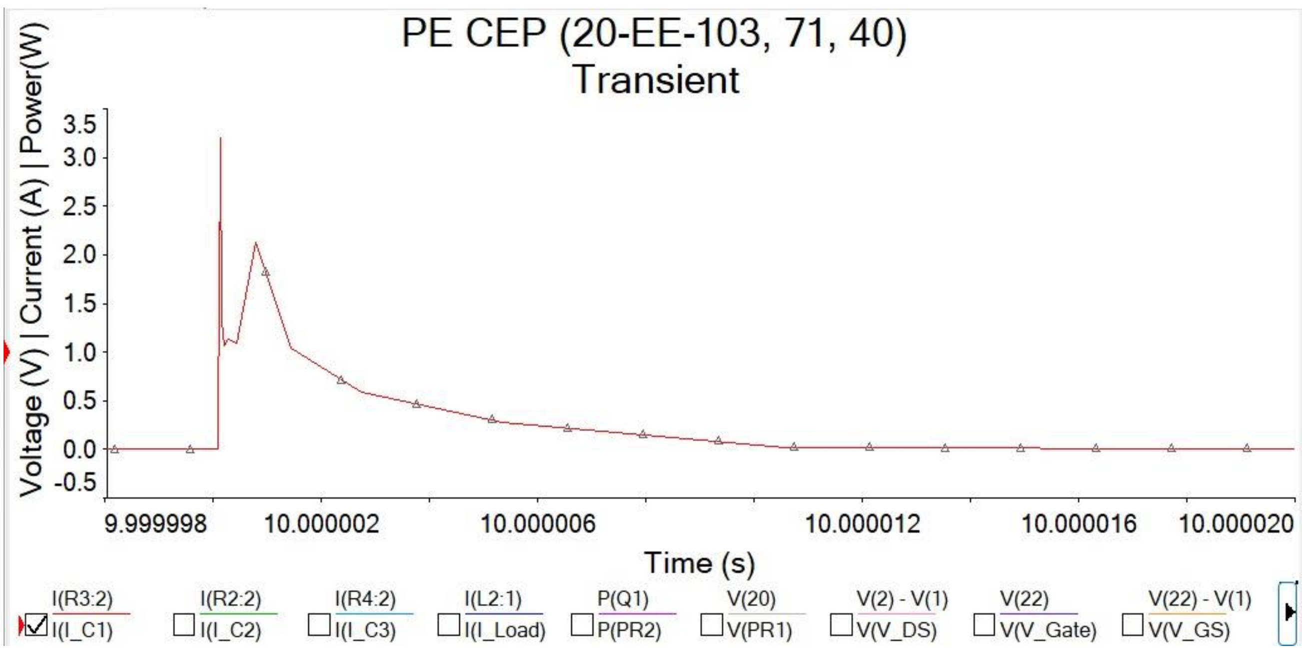

Figure 32:Bypass current across c1

Fault detection and clearing time:

Fault detection and clearing time refers to the duration from the moment a fault is detected by the circuit to when it is completely cleared. In our system, this entire process is designed to be exceptionally fast, ensuring that the fault detection and clearing time does not exceed 1 millisecond (ms). This rapid response is crucial for protecting the electrical components and maintaining the stability of the system. By quickly identifying and isolating the fault, the circuit minimizes potential damage and prevents the propagation of the fault condition, thereby enhancing the overall reliability and safety of the electrical system. We get a clearing time of 0.169ms.

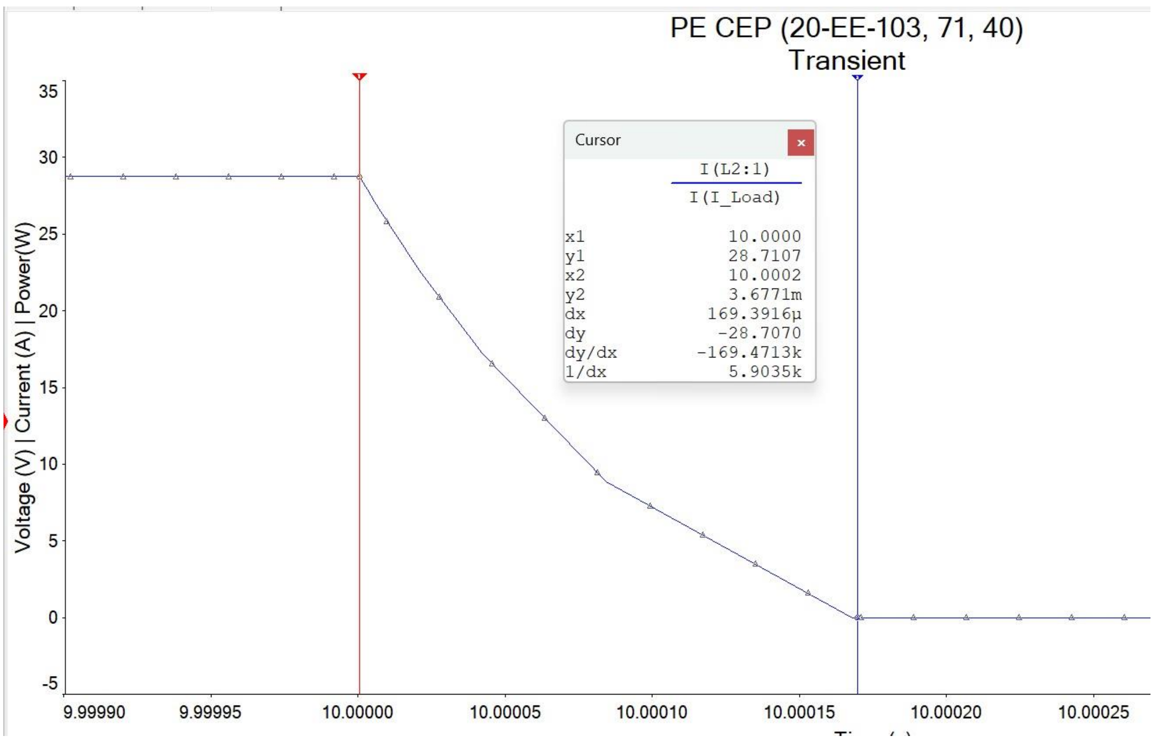

Figure 33:Fault Detection Time

Power losses:

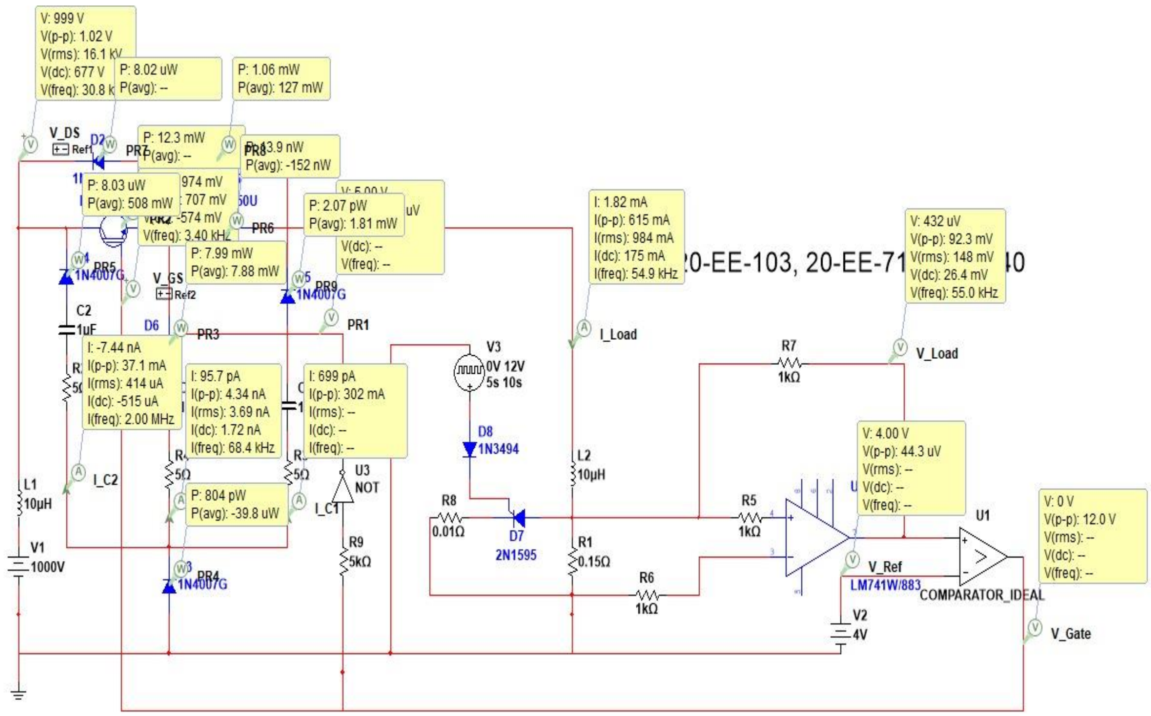

Figure 34:Power Losses

Table 1:Comparison Table

Parameters	**Required**	**Obtained**	**Comments**
Fault currents	30A	30A	Okay
Conduction loss	2 watts	1.6 watts	Okay
The detection and clearing time	1ms	0.16ms	Okay

5. ***Conclusion***

The solid-state circuit breaker designed and implemented in this study demonstrates reliable and efficient performance in protecting electrical circuits from overvoltage and overcurrent conditions. The circuit successfully handles fault currents of up to 30A, precisely meeting the required specification. It operates with a conduction loss of 1.6 watts, which is well within the acceptable range of the 2 watts requirement, indicating efficient energy use. Furthermore, the circuit achieves a remarkably fast detection and clearing time of 0.16ms, significantly surpassing the required 1ms. This ensures a swift response to fault conditions, effectively protecting sensitive electrical components. Overall, the results confirm that the solid-state circuit breaker meets or exceeds all key performance metrics, validating its suitability for applications that demand precise and rapid circuit protection.

6. References:

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