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Evaluating the Fault Response of Mechanical, Solid-State, and Hybrid Circuit Breakers in Residential and Industrial Applications

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Abstract: The primary function of a circuit breaker is to protect an electrical circuit from damage caused by overcurrent, short circuits, or overloads. It does this by automatically interrupting the flow of electricity when a fault is detected. Conventional mechanical circuit breakers (MCBs) can be too slow to ensure safety, as their mechanical time constant causes a delay in responding to faults like short circuits or overloads. This study aims to compare the performance of three types of circuit breakers including MCB, solid-state circuit breaker (SSCB), and hybrid circuit breaker (HCB) in two different conditions, namely residential and industrial applications. A simulation is carried out using ETAP 19 software, in which arc flash analysis is conducted to evaluate the performance of each circuit breaker. A Time-Current Curve (TCC) is analyzed to determine how quickly a circuit breaker can respond to a fault condition. This curve illustrates the relationship between the magnitude of current and the time it takes for the breaker to trip. By examining the TCC, it is possible to assess whether the circuit breaker provides adequate protection by clearing faults within acceptable safety limits, helping to prevent equipment damage and ensure system reliability. To ensure a comprehensive and reliable analysis, the simulation includes various models for each type of circuit breaker. These models differ in specifications, performance characteristics, and manufacturers, enabling for a more thorough evaluation of how each type performs under fault conditions and various operational scenarios. The result shows that HCBs outperform both MCBs and SSCBs in terms of fault clearing time across both residential and industrial applications.

Keywords: Circuit Breakers, Fault Protection, Time-Current Curve (TCC), Arc Flash Analysis, ETAP Simulation

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1. INTRODUCTION

An electrical circuit breaker is a switching mechanism that can be used to control and protect an electrical power system both manually and automatically [1]. Because the modern power system deals with high currents, particular care should be taken while designing a circuit breaker to guarantee that it can safely stop the arc produced when a circuit breaker is closed.

SSCB stands for Solid-State Circuit Breaker. It's a type of circuit breaker that uses electronic components (like transistors) to interrupt current flow instead of the traditional mechanical components found in standard circuit breakers [2,3]. Operating Principle for SSCB is instead of physical contacts opening and closing, SSCBs use high-power semiconductor switches like Insulated Gate Bipolar Transistors (IGBTs) or Metal-Oxide Semiconductor Field-Effect Transistors (MOSFETs) to control the current flow [4]. These switches rely on electrical signals to turn on and off, enabling much faster tripping times compared to mechanical breakers. Paper in [5] compares between mechanical circuit breaker and solid -state circuit breaker under abnormal conditions for low voltage systems.

A Hybrid Circuit Breaker (HCB) combines mechanical and solid-state technologies, enabling significantly faster fault clearing than traditional MCBs [6]. The use of semiconductor switches for initial interruption reduces arc flash hazards by minimizing arc formation and associated risks [7]. HCBs combine mechanical and electronic components, offering higher interrupting capacity than SSCBs and better performance than MCBs [8]. While more expensive and complex, they provide a cost-effective solution for specific applications. Key considerations include voltage and current ratings, fault clearing time, and balancing performance with cost and maintenance. When selecting a breaker, compare MCBs, SSCBs, and HCBs to match your application’s safety, performance, and budget needs [9].

Solid-State Circuit Breakers (SSCBs) and Hybrid Circuit Breakers (HCBs) are emerging technologies aiming to replace traditional mechanical breakers with more advanced electronic or hybrid solutions, though they lack standardized topologies [10-11]. In contrast, Miniature Circuit Breakers (MCBs) are widely used in residential, commercial, and industrial systems for reliable overcurrent protection. Fault detection methods such as overcurrent, differential, ground fault, and voltage protection are critical for ensuring safe and reliable operation and can be applied individually or in combination based on application needs [12-13].

This study aims to conduct a comprehensive comparison of three types of circuit breakers: MCBs, SSCBs, and HCBs, focusing on their application in both residential and industrial electrical systems. While previous studies have examined individual breaker types or specific operating conditions, there is a lack of comparative analysis under unified simulation settings across diverse applications. The comparison is carried out through detailed simulations using ETAP 19 software, with particular emphasis on evaluating their performance in terms of fault clearing time, which is a critical factor in ensuring safety and system reliability. This proposed simulation model is significant as it provides a standardized framework for assessing circuit breaker performance under consistent conditions, enabling more informed selection for specific applications. The results demonstrate that advanced breakers such as HCBs and SSCBs outperform traditional MCBs in fault response time, offering enhanced protection, reduced risk of equipment damage, and improved operational reliability across both residential and industrial systems.

This paper is composed of four sections. Section 2 discusses the simulation conducted using ETAP 19, while Section 3 presents the comparison results among the three types of circuit breakers: MCBs, SSCBs, and HCBs. Finally, the conclusions are presented in Section 4.

2. SIMULATION USING ETAP 19

ETAP 19 offers a comprehensive suite of tools for designing and analyzing electrical power systems, including residential and industrial circuits. For residential circuit design, single-line diagrams can create detailed schematics depicting your residential electrical system layout, including service entrance, panels, branch circuits, loads, and grounding connections.

Figure 1 illustrates a simplified single line diagram of a residential electrical distribution system, where electrical power is supplied from an 11 kV utility grid and stepped down to 0.4 kV using a 250 kVA, 2-winding transformer [14-15]. The system includes three main buses: Bus 1 at 11 kV, and Buses 2 and 3 at 0.4 kV, connected through protective devices such as miniature, solid-state, and high-capacity circuit breakers. Power is distributed via a 150-meter, 16mm² 4-core XLPE-insulated cable (Cable 1) to a 3-phase, 4-wire distribution panel (Panel 1) rated at 0.4 kV, 100 A. This panel supplies a 2 kVA residential load, ensuring safe and reliable delivery of electricity for household use. The details for each component are summarized in Table 1.

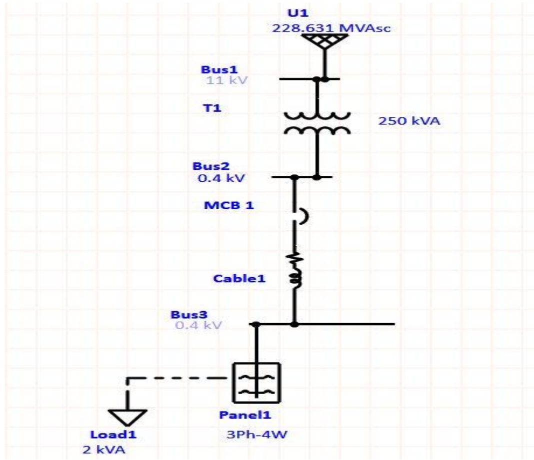

Figure 1. Simplified single line diagram for residential electrical distribution system (Circuit 1)

Table 1. Electrical parameters for residential electrical distribution system (Circuit 1)

Parameters	Description
Power Grid	Rating 11 kV
Bus 1	11kV
2 Winding Transformer 1	11kV/0.4kV – 250kVA
Bus 2	0.4kV
Circuit Breaker	MCB, SSCB & HCB
Cable	BS5467 4/C XLPE 150m, 16mm
Bus 3	0.4kV
Panel Schedule	0.4kV, 100A
Load	2kVA

Figure 2 presents a simplified single line diagram of an industrial electrical distribution system, where electrical power is received from a 15 kV utility grid and stepped down to 0.4 kV using a 250 kVA, 2-winding transformer (11 kV/0.4 kV) [14-15]. The system consists of three buses: Bus 1 at 11 kV, and Buses 2 and 3 at 0.4 kV, with protection provided by miniature, solid-state, and high-capacity circuit breakers. Power is distributed through a 200-meter, 25 mm² 4-core XLPE-insulated cable (Cable 1) to serve two industrial loads: Motor 1 and Motor 2, each rated at 200 horsepower (hp), 0.4 kV. This configuration ensures safe and efficient power delivery suitable for industrial applications involving high-power motors. The details for each component are summarized in Table 2.

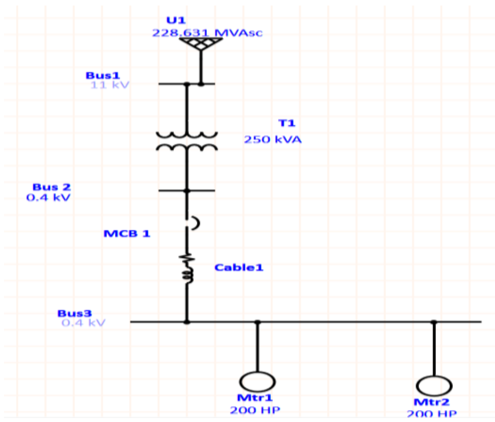

Figure 2. Simplified single line diagram for industrial electrical distribution system

Table 2. Electrical parameters for industrial electrical distribution system

Parameters	Description
Power Grid	Rating 15 kV
Bus 1	11kV
2 Winding Transformer 1	11kV/0.4kV – 250kVA
Bus 2	0.4kV
Circuit Breaker	MCB, SSCB & HCB
Cable	BS5467 4/C XLPE 200m, 25mm
Bus 3	0.4kV
Motor 1	200 hp, 0.4kV
Motor 2	200 hp, 0.4kV

The selection of circuit breakers for this analysis is based on common applications in residential and commercial installations. MCBs are compact and provide protection against overloads and short circuits. SSCBs use semiconductors for fast, precise current control, unlike traditional mechanical breakers. HCBs combine mechanical durability with electronic intelligence, making them suitable for critical infrastructure, renewable energy systems, and advanced industrial applications. Table 3 provides an overview of the circuit breaker types examined in this study.

Table 3. Types of circuit breaker analyzed

Circuit Breaker	Name	Model & Type	Rating	Short Circuit current rating
MCB	MCB 1	ABB – S200-D (AC)	40A, 0.415kV	11.25kA
	MCB 2	Merlin Gerin – C120H – C Curve (IEC)	63A, 0.415kV	11.25kA
	MCB 3	ABB – S700-E	100A, 0.4kV	11.25kA
SSCB	SSCB 1	Schneider Electric – NSX100-B	100A, 0.415kV	15kA
	SSCB 2	Merlin Gerin - NS100N	100A, 0.415kV	15kA
HCB	HCB 1	Terasaki – TL 100E	50A, 0.415kV	15kA
	HCB 2	Schneider Electric - NSX100-L	100A, 0.415kV	15kA

Arc flash analysis is used to identify the fault protection device (circuit breaker) and evaluate the Time-Current Curve (TCC) for each breaker type. The arc flash boundary is the minimum safe distance from energized parts, used to calculate incident energy and ensure compliance with safety regulations. ETAP simplifies fault analysis by allowing users to add a fault on the one-line diagram, automatically generating time-current curves and calculating the operation time of protective devices. The sequence of events is displayed in the Event Viewer, linked to the diagram, with curves adjusted based on fault contribution levels. In a TCC curve as presented in Figure 3, the x-axis represents the current flowing through the circuit, typically expressed as multiples of the breaker's rated current. The y-axis shows how long it takes for the breaker to trip at that current level. This curve helps visualize how quickly a breaker responds to different levels of overcurrent; higher currents lead to faster trip times.

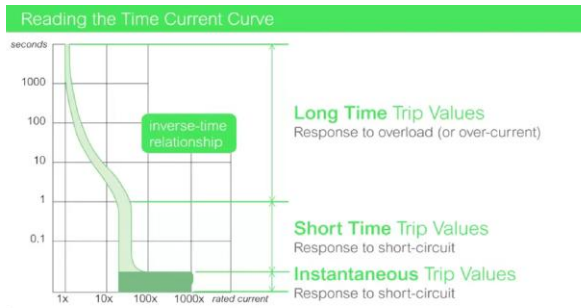

Figure 3. Reading the time current curve (TCC) from ETAP

3. RESULTS AND DISCUSSION

The analysis demonstrates the response of different circuit breakers in residential and industrial electrical designs, highlighting differences in performance, particularly in tripping time, to identify the most efficient option.

3.1 Performance Analysis for Conventional Miniature Circuit Breaker (MCB)

Table 4 shows that MCB 3 consistently outperforms the other models in both the residential circuit (15.8 kW) and the industrial circuit (496.6 kW) by having the shortest Fault Clearing Time (FCT), indicating a quicker response to faults. In the residential case, MCB 3 clears the fault in just 0.196 seconds at a fault current of 0.919 kA, while MCBs 1 and 2 take significantly longer. Similarly, in the industrial case, MCB 3 clears the fault in 0.203 seconds at 0.877 kA, much faster than MCBs 1 and 2. This rapid response reduces fault energy and potential damage, making MCB 3 the most effective option for protecting both low and high-power systems.

Table 4. Fault Clearing Time for different models of MCBs

Case Study	MCBs	FCT	Ia @ FCT	Power
		(sec)	(kA)	(kW)
Residential	MCB 1	2.826	0.781	15.8
	MCB 2	3.455	0.781	15.8
	MCB 3	**0.196**	**0.919**	**15.8**
Industrial	MCB 1	2.982	0.745	496.9
	MCB 2	3.645	0.745	496.6
	MCB 3	**0.203**	**0.877**	**496.6**

3.2 Performance Analysis for Solid-State Circuit Breaker (SSCB)

Table 5 shows that both SSCBs provide significantly faster fault clearing times compared to MCBs. In the residential circuit (15.8 kW), SSCB 2 clears the fault in just 0.06 seconds, outperforming SSCB 1, which clears it in 0.08 seconds, both at a fault current of 0.919 kA. Similarly, in the industrial circuit (496.6 kW), SSCB 2 again shows the quickest response at 0.06 seconds, while SSCB 1 clears in 0.068 seconds. These results highlight that SSCBs, particularly SSCB 2, offer superior speed and reliability in fault interruption, making them more suitable for protecting sensitive or high-power electrical systems.

Table 5. Fault Clearing Time for different models of SSCBs

Case Study	SSCBs	FCT	Ia @ FCT	Power
		(sec)	(kA)	(kW)
Residential	SSCB 1	0.08	0.919	15.8
	SSCB 2	**0.06**	**0.919**	**15.8**
Industrial	SSCB 1	0.068	0.745	496.9
	SSCB 2	**0.06**	**0.877**	**496.6**

3.3 Performance Analysis for Hybrid Circuit Breaker (HCB)

Table 6 shows that Hybrid Circuit Breakers (HCBs) offer very fast fault clearing times in both residential circuit (15.8 kW) and industrial circuit (496.6 kW). In the residential case, HCB 1 responds the fastest at 0.021 seconds, while HCB 2 is slower at 0.06 seconds, both at a fault current of 0.919 kA. In the industrial case, HCB 1 again demonstrates superior performance with a fault clearing time of 0.021 seconds at 0.877 kA, compared to HCB 2's 0.052 seconds. These results highlight HCB 1 as the most efficient in minimizing fault duration and potential system damage, making it a highly effective solution for both low and high-power applications.

Table 6. Fault Clearing Time for different models of HCBs

Case study	HCBs	FCT	Ia @ FCT	Power
		(sec)	(kA)	(kW)
Residential	**HCB 1**	**0.021**	**0.919**	**15.8**
	HCB 2	0.06	0.919	15.8
Industrial	**HCB 1**	**0.021**	**0.877**	**496.9**
	HCB 2	0.052	0.877	496.6

3.4 Comparative Study

Table 7 compares the performance of MCB, SSCB, and HCB in both residential (15.8 kW) and industrial (496.6 kW) settings, focusing on fault clearing time (FCT) and fault current. Across both cases, HCB 1 consistently provides the fastest fault response, clearing faults in just 0.021 seconds, followed by SSCB 2 at 0.06 seconds, and MCB 3 with the slowest response—0.196 seconds in residential and 0.203 seconds in industrial applications. All devices operate at similar fault current levels, but the significantly shorter FCT of HCB 1 highlights its superior capability in quickly interrupting faults, reducing equipment stress and enhancing system protection in both low and high-power environments.

Table 7. Comparison between MCB, SSCB, and HCB

Case Study	Circuit Breaker	FCT	Ia @ FCT	Power
		(sec)	(kA)	(kW)
Residential	MCB 3	0.196	0.919	15.8
	SSCB 2	0.06	0.919	15.8
	HCB 1	0.021	0.919	15.8
Industrial	MCB 3	0.203	0.877	496.6
	SSCB 2	0.06	0.877	496.6
	HCB 1	0.021	0.877	496.9

4. CONCLUSION

This paper compares the performance of three types of circuit breakers which are MCBs, SSCBs and HCBs using ETAP 19 software. Based on the findings, it is evident that HCBs outperform both MCBs and SSCBs in terms of fault clearing time across both residential and industrial applications. HCB demonstrated the fastest response at 0.021 seconds, significantly reducing the duration of fault exposure and enhancing protection. While SSCBs also showed quicker performance than MCBs, they were slightly slower than HCBs. MCBs, although commonly used, had the slowest response times, making them less effective for scenarios requiring rapid fault interruption. Overall, HCBs offer the most efficient and reliable protection, particularly in systems where minimizing fault energy is critical.

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REFERENCES

[1] Ms. Mayuri A. Rode, Ms. Mayuri V. Jadhav, Mr. Bhavesh S. Zade, Mr. Pranay M. Kakde, Mr. Yash S. Mahajan, Dr. U. E. Hiwase, "Study and Analysis of Different Types of Circuit Breaker," in International

Journal of Advanced Research in Science, Communication and Technology (IJARSCT), 2022, 2(1), doi: 10.48175/IJARSCT-3041.

[2] R. Rodrigues, Y. Du, A. Antoniazzi and P. Cairoli, "A Review of Solid-State Circuit Breakers," in IEEE Transactions on Power Electronics, 2021, 36(1), 364-377, doi: 10.1109/TPEL.2020.3003358.

[3] Mehdi Moradian, Tek Tjing Lie, Kosala Gunawardane, Enhanced LV solid-state DC circuit breaker design with divided surge absorption technique, Electric Power Systems Research, 2025, 241, 111280, https://doi.org/10.1016/j.epsr.2024.111280.

[4] Tiezhou W., Zhikun W., Chang F., Sizhe L., Research on current limiting solid state circuit breaker for DC microgrid, Electric Power Systems Research, Volume 209, 2022, 107950, https://doi.org/10.1016/j.epsr.2022.107950.

[5] Qunhai Huo, Jiawang Xiong, Ningyu Zhang, Xinming Guo, Lixin Wu, Tongzhen Wei, Review of DC circuit breaker application, Electric Power Systems Research, Volume 209, 2022, 107946, ISSN 0378-7796, https://doi.org/10.1016/j.epsr.2022.107946.

[6] Jaafari A., Mohsenzade S., Razi-Kazemi A.A, An adaptive current commutation for hybrid DC circuit breaker, Electric Power Systems Research, 2025, 247, 111828, https://doi.org/10.1016/j.epsr.2025.111828.

[7] Jallad, Jafar & Badran, Ola. Implement a multifunction smart miniature circuit breaker based on the Internet of Things. International Journal of Vehicle Information and Communication Systems, 2024, 1. 10.1504/IJVICS.2024.10062417.

[8] Zhaozi Z., Caizhi G., Weidong C., Qian W., Silei C., Xingwen L., Yinfang H., Zuoyong G., Multi-parameter optimization and design of self-triggered low voltage hybrid DC circuit breaker based on machine learning, Electric Power Systems Research, 2025, 244, 111560, https://doi.org/10.1016/j.epsr.2025.111560.

[9] Hongchun Shu, Zongxue Shao, Yue Dai, Research on the improved hybrid DC circuit breaker with voltage-limiting and current-limiting capability, International Journal of Electrical Power & Energy Systems,Volume, 2024, 158,109943,ISSN 0142-0615, https://doi.org/10.1016/j.ijepes.2024.109943.

[10] M.F. Roslan, M.S. Reza, M.S. Rahman, M. Mansor, A.Z. Arsad, Ker Pin Jern, Vigna K. Ramachandaramurthy, M.A. Hannan, State-of-the-art on advanced technologies of solid-state circuit breaker for reliable and sustainable power supply: A bibliometric analysis and future guidelines, Alexandria Engineering Journal, 2024, 104,636-664, https://doi.org/10.1016/j.aej.2024.08.034.

[11] Alashi M., Cooper T., Zhou Y., Shen Z.J., Brown I., Wong T. Design considerations of series type hybrid circuit breaker (S-HCB), IET Power Electronics, 2024, 17 (3), 364 – 374, DOI: 10.1049/pel2.12645

[12] T. L. Le *et al*., Solid-state Circuit Breaker for aircraft high voltage DC network, *2024 IEEE Applied Power Electronics Conference and Exposition (APEC),* 2024, 3100-3107, doi: 10.1109/APEC48139.2024.10509126.

[13] Mahmoud Alashi, Triston Cooper, Yuanfeng Zhou, Z. John Shen, Ian Brown, Thomas Wong, Design considerations of series type hybrid circuit breaker (S-HCB), IET Power Electronic, 2024, 17(3),364-374, https://doi.org/10.1049/pel2.12645

[14] Albert Marroguin, Assessing the Hazards of High and Low voltage Single-Phase Arch-flash. ETAP/Operation Technology, Inc, Jun 2008, Vol 4, Page 26-28.

[15] Eltechs, ETAP TIP-No.001 One-Line Diagram Presentations, www.etap.com.