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Avoiding EVSE Destruction: Efficient charging solution for 800V battery systems with 500V rated equipment

Arun Chandrasekharan Nair [1], Surender Elumalai [1], Mark Renner[2], Urs Boehme[2] , Jay Pandya[1] , Anilkumar Davu [1], Neethu Mohan [1]

[1]*Mercedes Benz Research & Development India, Whitefield, Bangalore, India*

[2]*Mercedes Benz AG, Bela-Barenyi-Str Tor 14, 71063 Sindelfingen, Germany*

Executive Summary

Electric vehicle adoption continues to rise globally due to advancements in battery technology and power electronics. The need to charge batteries in times comparable to conventional refueling has led many OEMs to adopt battery packs with voltages of 800V and higher. However, many charging stations, especially in the USA and Japan, still use chargers with a maximum rated voltage of 500V. To charge vehicles with battery packs rated at 800V using EVSE units rated below 500V, a power converter is introduced in the charging path to adjust the voltage levels. The introduction of this converter can result in a unique use case with CHAdeMO-compliant EVSEs, where a body fault in the vehicle may lead to both the EVSE and the charging cable getting damaged. This paper proposes a solution to this problem without affecting the charging efficiency.

Keywords: CHAdeMo, DC-DC Booster, Thyristor, PE Wire

1 Introduction

The transition to higher voltage (HV) battery systems in electric vehicles (EVs) has emerged as a critical development to enable faster charging, improve energy efficiency, and extend driving range [1]. By increasing the operating voltage, EVs can reduce current requirements for power transfer, leading to lower resistive losses and improved thermal management [2]. These advantages are essential for supporting long-distance travel, enhancing vehicle performance, and ensuring user convenience. However, the integration of HV batteries with the existing electric vehicle supply equipment (EVSE) infrastructure presents several technical challenges, particularly in terms of safety, efficiency, and compatibility with fast-charging architectures [3].

A key challenge in this integration arises when connecting HV battery systems to lower-rated EVSE through non-isolated DC-DC converters [4]. Non-isolated converters, while offering benefits such as reduced cost, compact design, and high efficiency, introduce several technical concerns that must be addressed to ensure safe and reliable operation. One of the primary issues is the potential for ground loops and unwanted leakage currents, which can lead to electromagnetic interference (EMI), safety hazards, and reduced system performance.

Additionally, insulation coordination and voltage stress on components must be carefully managed to prevent failures and ensure compliance with regulatory standards [5-7].

This paper explores the technical challenges associated with integrating HV battery systems that are rated for 800V with EVSE infrastructure rated for less than 500V using non-isolated DC-DC converters. It provides a detailed analysis of the safety concerns involved in such configurations. The concerns addressed in the paper are twofold: 1) The potential risks to the equipment due to the flow of a very large current through the protective earth (PE) wire in the charging cable and 2) The probability of electric shock for users through the generation of touch voltage at the chassis of the vehicle. The potential mitigation strategies, including advanced protection mechanisms, and system design considerations, are discussed to facilitate the seamless adoption of non-isolated converters to facilitate dc charging from EVSEs rated less than the battery voltage.

The remainder of the paper is structured as follows: Section 2 outlines the design of the charging system, which incorporates a DC converter to facilitate high-power charging from EVSEs with a lower voltage rating. It also discusses the associated safety concerns and further reviews existing solutions to address these safety challenges. Section 3 presents the proposed solution, while Section 4 provides the simulation results with the proposed solution. Description of a proof of concept (POC) developed in the laboratory and experimental results are detailed in section 5. Finally, Section 6 concludes the paper.

2. Structure of the charging system using high power DC converter in the charging path

In electric vehicles (EVs) equipped with high-voltage battery systems of 800V or more, the fast-charging infrastructure must be capable of delivering power at compatible voltage levels. However, certain existing fast-charging standards, such as CHAdeMO 2.0 and earlier versions, are limited to a maximum voltage rating of 500V. This discrepancy presents a challenge when attempting to charge high-voltage EV batteries using lower-rated electric vehicle supply equipment (EVSE). In order to bridge this gap, a DC-DC converter circuit is integrated into the EV charging system. This power electronic circuit also called as a booster in certain cases, steps up the voltage from the EVSE output to match the required voltage level of the vehicle's battery. The booster ensures that the battery receives the correct charging voltage without exceeding the limitations of the existing charging infrastructure.

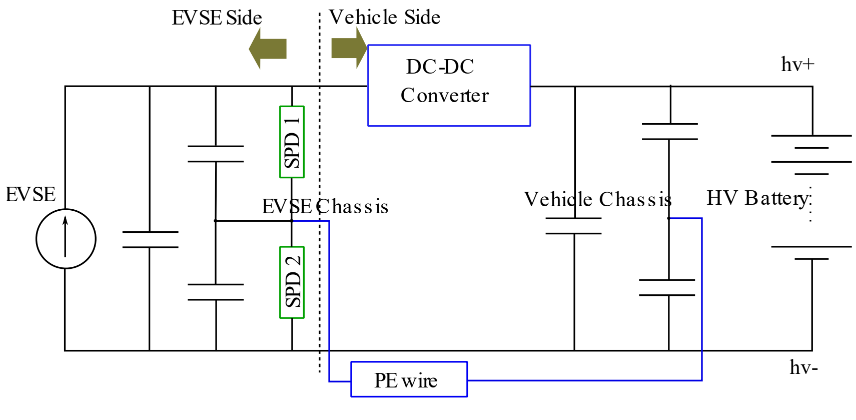


Fig. 1 Single line diagram during charging 800V battery from a EVSE rated less than 500V.

A single line diagram of the charging system, in this case that used for CHAdeMo chargers is shown in Fig. 1. At the EVSE side, two elements are of interest. The first element is a protective earth (PE) wire within the charging cable that establishes a connection between the chassis of the EVSE and the chassis of the vehicle. This grounding mechanism plays a crucial role in ensuring user safety by preventing potential differences that could lead to electrical hazards. In the event of a fault or insulation failure, the PE wire provides a low-impedance path for leakage currents, reducing the risk of electric shock.

The second element of interest is the surge protection device (SPD) that is integrated into EVSE units to safeguard against transient high-voltage events, such as lightning strikes or switching surges. These protective devices help prevent damage to the EVSE and the connected vehicle's charging components. The SPD rating can vary depending on the specific EVSE model and manufacturer, influencing the level of transient voltage suppression provided by the system. It is important to note that the EVSE chassis is connected to the midpoint of the series capacitors at its output. Likewise, on the vehicle side, the chassis is connected to the midpoint of the series capacitors placed across the high-voltage (HV) bus. This is the main cause of the safety issue described below.

2.1 The use case of body fault

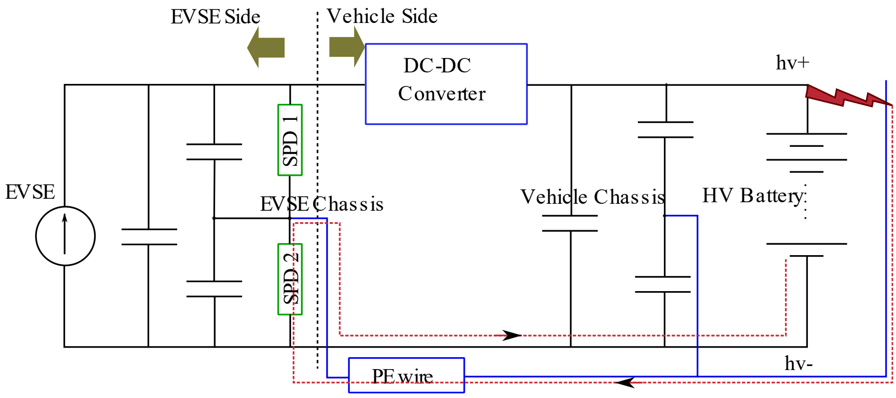


Fig. 2 Single line diagram during a body fault while charging 800V battery from a EVSE rated less than 500V

One of the critical challenges in integrating high-voltage when charging through the system shown in Fig. 1 arises in the event of a body fault—a scenario where one of the HV battery terminals (specifically HV+ in this case) comes into unintended contact with the vehicle chassis. This is depicted in Fig. 2. This type of fault creates a potential safety hazard, particularly in fast-charging architectures that employ a non-isolated booster circuit.

When a body fault occurs, the battery voltage is directly applied to the SPD located on the EVSE side. Since the EVSE is designed to operate at voltages below 500V, and CHAdeMO chargers utilize a series configuration of two SPDs, the voltage rating of each individual SPD can be as low as 250V. Thus, the applied voltage during a body fault may exceed the rated threshold of the SPD. Many EVSE manufacturers incorporate varistors as SPDs. A varistor is a voltage-dependent resistor that remains non-conductive under normal conditions but becomes conductive when exposed to voltages beyond its clamping threshold. In this case, most varistors used in EVSEs become conductive at voltages between 500V and 550V. This means that if the battery voltage (800V or higher) is applied due to the fault, the varistor will short-circuit itself to protect the EVSE. This short-circuiting behavior unintentionally creates a direct connection between the hv+ and hv- terminals of the battery. This causes a very high current to flow through the shorted path, limited only by the resistance of the PE wire, which is designed for safety grounding rather than carrying high fault currents.

While the circuit breaker in the EV battery system is designed to detect and isolate such faults, it does not act instantaneously. The response time of the circuit breaker typically ranges between 2-20 milliseconds (ms), during which time, a very high fault current flows through the system.

During this short but critical window, three hazardous events can occur:

1. Destruction of the SPD on the EVSE Side
    a) If the energy dissipated in the SPD exceeds its mA-s rating (typically greater than 100 mA-s), the SPD can be permanently damaged due to excessive heating and thermal breakdown.
    b) This failure may render the EVSE unprotected against future voltage surges, increasing the risk of damage in subsequent charging sessions.
2. Destruction of the Protective Earth (PE) Wire
    a) The PE wire is not designed to carry prolonged high fault currents. If the energy in the wire exceeds its A^2s rating (typically greater than 7000 A^2s), it can overheat, melt, or burn out.
    b) A damaged PE wire compromises vehicle safety and may leave the vehicle chassis floating, increasing the risk of electric shock to users.
3. High Touch Voltage on the Vehicle Chassis
    a) Due to the high fault current flowing through the PE wire, a potential difference can develop between the vehicle chassis and the ground.
    b) This can lead to a touch voltage exceeding 60V, which is considered dangerous for human contact, especially in wet conditions or if a person is in direct contact with the metal chassis while standing on the ground.
    c) If the touch voltage exceeds safety thresholds, it can cause electric shock or severe injury to the user.

2.2 Solutions already available in the industry

Various methods can be used to handle short-circuit currents in EV charging systems, each with its advantages and disadvantages. One approach is the use of a diode in the blocking direction of the expected short-circuit current. While this prevents unwanted current flow, however does not allow bidirectional DC charging and adds to power losses in the fast-charging system. Additionally, the short-circuit current is limited to the value of the charging current, making it less effective in certain scenarios. Another method involves using a MOSFET with a body diode or an IGBT with a freewheel diode in the blocking direction. Although this approach allows controlled current flow, it also contributes to energy losses and necessitates a cooling system to manage the heat dissipation of the MOSFET or IGBT. A third option is the use of an e-Fuse, a fuse with semiconductor devices designed to interrupt short circuits. All of these solutions present an element in the charging path, that deteriorates the efficiency during normal charging process. Further, the semiconductor devices needs to be rated for the full charging current that increases the cost and size of the system.

3. The proposed Solution

The proposed solution involves using a thyristor-based short-circuit protection mechanism to redirect fault currents away from the PE wire and SPD. A thyristor is a semiconductor device designed to handle high transient currents while maintaining a fast-switching response. In this protection scheme, the thyristor is placed between the vehicle chassis and the common hv terminal shared between the EVSE and the battery as shown in Fig. 3. The primary function of this component is to act as a controlled short-circuit path in the event of an insulation fault, thereby protecting the SPD and PE wire from excessive current flow.

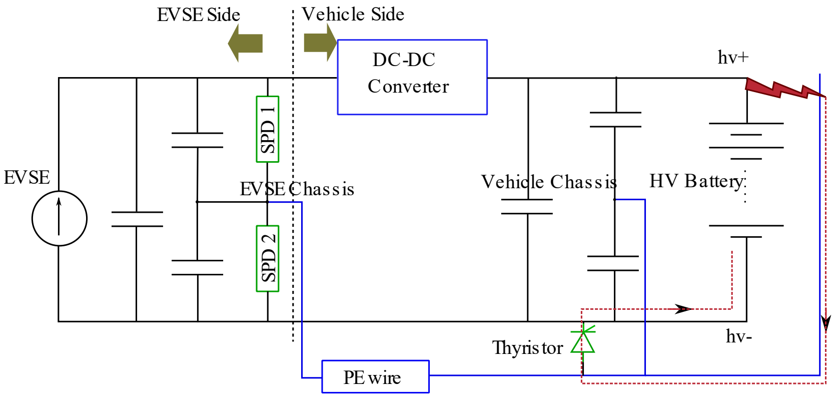


Fig. 3 Single line diagram of the proposed method and operation of thyristor during the fault

The thyristor should be able to withstand extremely high transient currents for a short duration. For instance, a thyristor with a nominal current rating of 500A can handle surge currents exceeding 10,000A, preventing excessive current from flowing through the PE wire. The I^2t rating (energy withstand capability) should exceed 100,000 A^2s to ensure durability during fault conditions. Further, the thyristor must activate within a few microseconds to effectively divert fault currents before damage occurs. A fast turn-on time ensures that the fault is quickly mitigated, significantly reducing the risk of SPD and PE wire failure.

When an insulation fault occurs within the vehicle's HV system, the thyristor is triggered into conduction. This enables the fault current to bypass the SPD and PE wire, flowing instead through the thyristor. The sequence of events is as follows:

1. Fault Detection – The insulation monitoring system (IMS) or a fault detection circuit identifies an unintentional connection between the hv+ terminal and the chassis.

2. Thyristor Activation – The thyristor is triggered within 10 microseconds, creating a low-impedance path for the fault current.

3. Current Diversion – The fault current is redirected through the thyristor, preventing excessive stress on the SPD and PE wire, which might otherwise suffer thermal damage or destruction.

4. Circuit Breaker Intervention – The circuit breaker in the battery circuit detects the fault and opens within 20 milliseconds, isolating the battery and stopping further current flow.

5. Thyristor Deactivation – Once the circuit breaker has opened, the thyristor ceases

conduction, and the system returns to a safe state.

3.1 **Control Circuit:**

To trigger the thyristor during a body fault, a control circuit is implemented. This circuit can be analog (using ICs) or digital (using microprocessors) and must detect and activate the thyristor rapidly. In this paper, the control circuit is analog, composed of two ICs: the AMC1311 isolated op-amp and the ULN2001 driver. A resistive potential divider senses the HV+ to chassis voltage, producing an output between 0 and 3.3V. This voltage is input to the AMC1311 IC, which provides a secondary ground for the control circuit's operation. The approximate time of operation from sensing to triggering the thyristor is less than 15 microseconds. The diagram of the circuit used to sense and trigger the thyristor in the event of a body fault is shown in Fig. 4.

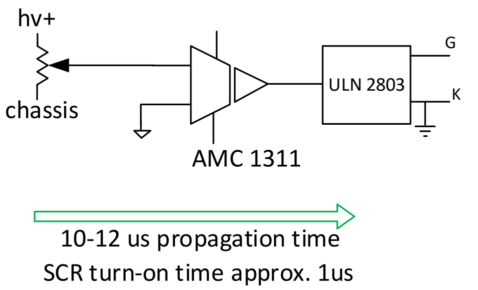


Fig. 4 Circuit diagram of the control circuit used to sense and trigger the thyristor in the event of a body fault

4. Simulation results

The simulation is performed in the circuit simulation software LTspice. This provides more realistic results compared to other simulation platforms as the behavior of actual components can be modeled easily in LTspice. The simulation setup uses a non-isolated simple boost converter operating at 50% duty cycle to achieve the required voltage boost from an EVSE operating at 400V to the battery operating at 800V. The EVSE is modeled by a current source as is the case in an actual scenario. The simulation parameters are depicted in Table 1.

Table 1. Simulation Parameters

Sl No	Component	Description /Value
1	EVSE Current	50 A
2	EVSE output capacitance	100 uF
3	Y caps at EVSE	385 nF
4	Varistor/SPD	B32K250 rated at 250V
5	Charging cable impedance	1.5 uH
6	EV side Xcap	500 uF
7	Thyristor	CS20-22 rated 1000A
8	Boost inductor	500 uH
9	Boost converter device	C3M0160120DU2 Mosfet

The simulation is started with the EVSE pumping about 100kW into the hv battery through the boost converter. At 10ms, a fault is generated by shorting the hv+ terminal to the chassis using a relay. This activates the control circuit consisting of AMC 1311 and ULN 2803, both of which are modeled by the spice files provided by Texas Instruments. The control circuit, then turns on the thyristor, which in turn bypasses the current that would have flown through the PE wire and SPD.

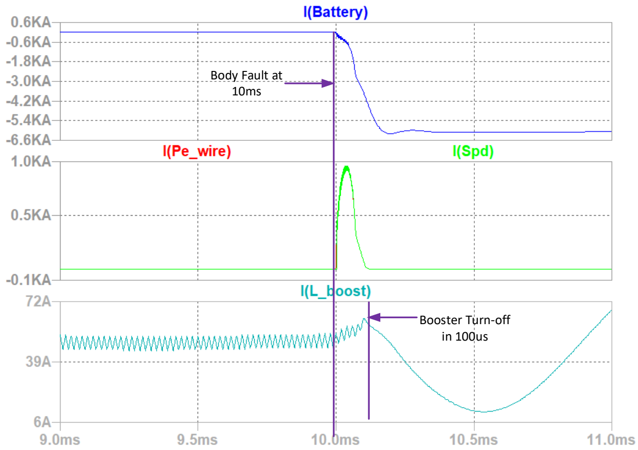


Fig. 5 Simulation Results showing battery current, currents in PE wire and SPD, and booster inductor current for a body fault occurring at 10m

This is shown in the simulation results depicted in Fig. 5. It is seen that a steady current is

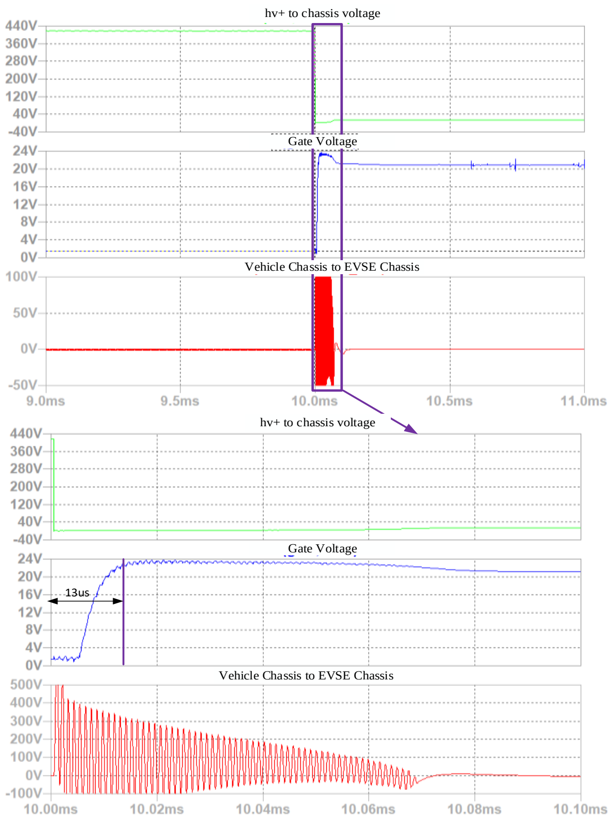


Fig. 6 Voltage between hv+ and chassis, gate voltage, voltage between vehicle chassis and EVSE chassis and zoomed at 10ms for a body fault occurring at 10ms

flowing into the battery prior to the fault with the booster inductor carrying an average current of 50A. Once the fault occurs, battery terminals are shorted through the PE wire and SPD, battery current reverses and reaches a value of about 6kA. This implies that battery is discharging and is feeding current to the fault. The current through the SPD and PE wire is shown in the second plot of Fig. 5. It is observed that current rises to about 1kA in a very short period. However, the action of the thyristor reduces this current, and it eventually comes to zero once the thyristor is fully ON and is conducting the entire fault current. The booster protection circuit acts and turns off the boost converter in about 100 µs.

The voltage between hv+ and chassis, gate voltage, voltage between vehicle chassis and EVSE chassis during this operation is shown in Fig. 6. The zoomed in waveforms at the time of occurrence of fault is also shown. This demonstrates the effectiveness of the control circuit. It is seen that once the hv+ to chassis voltage drops down to zero on the occurrence of the fault, gate voltage of the thyristor rises to a sufficient value to turn on the thyristor in about 13 µs. This value can is the propagation delay of the control circuit, which is the delay between the occurrence of the fault and the time a gate signal is given to the thyristor.

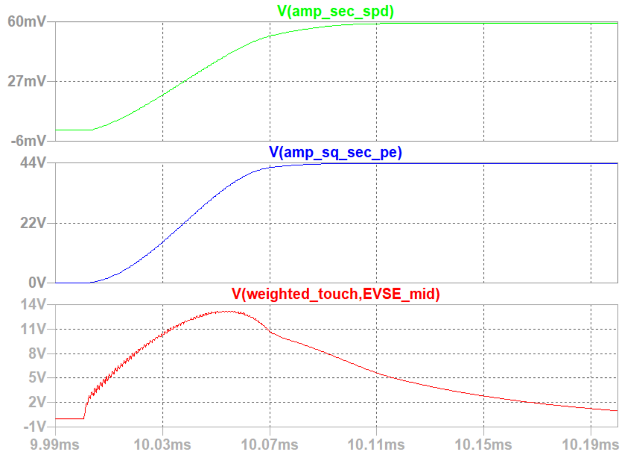


Fig. 7 Amp-s in SPD, A^2s in the PE wire and the touch voltage presented to the user on clearing the fault using a thyristor.

drops down to zero on the occurrence of the fault, gate voltage of the thyristor rises to a sufficient value. The Amp-s in the SPD once the fault occurs and is cleared using the proposed system is shown in the first plot of Fig. 7. It is seen that the value of A-s is much lower than that which most SPDs are rated. The A^2s in the PE wire reaches to a value of about 44, which is much lower than its threshold value of 7000. The touch voltage shown in the third plot has a peak value of 14V, whereas the safety limit is 60V. Thus, the proposed solution eliminates all the three potential safety hazards listed in section 1. Moreover, it does not affect the normal charging as the thyristor is not placed in the charging path and is activated only in the event of a body fault.

5. Experimental Results

A proof of concept is developed in the laboratory to experimentally prove the findings. A single line diagram of the experimental setup is shown in Fig. 8. A dc power supply of 80V, 1000A rating is used for this purpose. The system operation begins by electronically closing the breaktor, with the load drawing a specified current from the power supply. To establish the fault, the contactor is closed which shorts the hv+ to chassis. The control circuitry continuously monitors the voltage, and a sudden drop in voltage is used to detect the occurrence of a short-circuit fault. Upon detection, the control circuit immediately triggers the thyristor, diverting the fault current through a thicker, low-impedance cable to safely manage the high current. Following the successful diversion of the fault current, the breaktor device actuates to open the circuit, interrupting the current flow and fully isolating the fault.

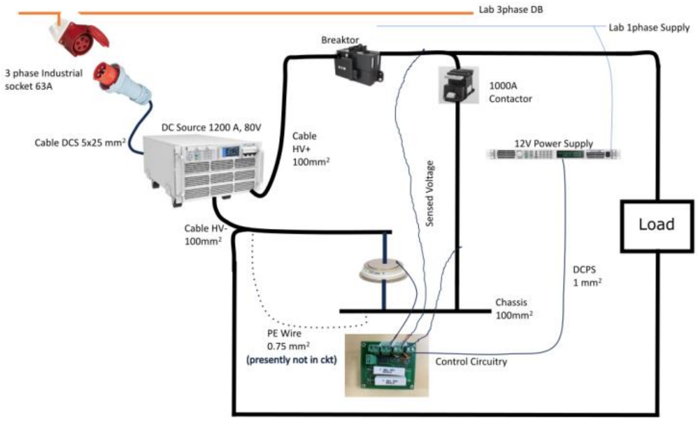
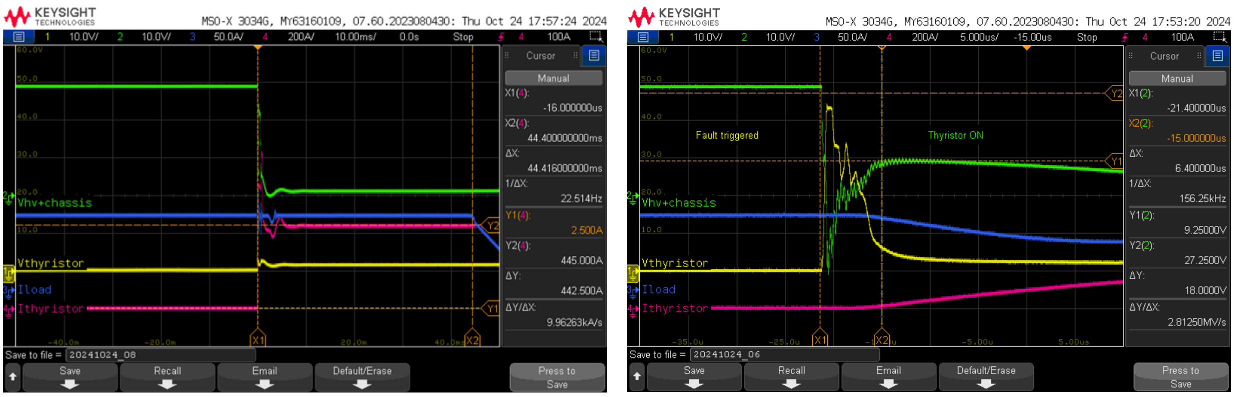


Fig. 8 Single line diagram of the experimental setup.

The experimental results are shown in Figures 9 (a) and (b). Upon detection of the fault, the gate drive circuitry activated the thyristor within 200 µs, leading to successful diversion of current from the SPD and PE wire without causing harm to any devices involved. It is important to note that the total time required for thyristor turn-on is influenced by the applied voltage and available fault current and may vary under different conditions.



(a) (b)

Fig. 9 (a) Plots showing hv+ to chassis voltage, voltage across thyristor and current through the thyristor and (b) Zoomed in at the instance of fault. Occurrence of fault to turn on of thyristor (time for sensing and gate driver) → 6.4us

6. Conclusions

This paper proposes a protection system, which provides a fast-acting alternative current path to prevent excessive fault currents from damaging the PE wire and SPD in the event of a body fault while charging a 800V battery from a lesser rated EVSE through a non-isolated converter. A thyristor is used to create the fast-acting alternate current path due to its high short circuit current capability. By rapidly diverting fault currents away from sensitive components like the SPD and PE wire this approach saves the equipment and the user by limiting the touch voltage less than 60V. While existing solutions hamper efficiency, the thyristor-based solution is activated only on the occurrence of a fault and does not come into play during normal charging operation. The effectiveness of the solution is validated using simulations performed in LTspice.

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Presenter Biography

Arun Nair is a Senior Technical Lead with Mercedes Benz R&D, India. He holds a PhD in Power Electronics from IIT Bombay, India. He is leading the charging simulation topics and an expert with computational studies charging systems, with multiple patents and publications.

Surender Elumalai is a Senior Engineer with Mercedes Benz R&D, India. He holds an M.Tech degree in from NIT, Surathkal, India. He is working in charging system for electric vehicles.

Mark Renner is an Engineer with RD/E division of Mercedes Benz AG, Sindelfingen, Germany. He primarily works on charging technology and efficiency focusing on wireless power for EV.

Urs Boehme is an Engineer with RD/E division of Mercedes Benz AG, Sindelfingen, Germany. He primarily works on next gen concept development and hv architectures for EV.

Jay Pandya is an Engineer with Mercedes Benz R&D, India.He holds an M.Tech degree in from NIT,Tiruchirappalli, India. He is working in charging system for electric vehicles.

Anilkumar Davu is a Technical Manager with Mercedes Benz R&D, India. He holds an M.Tech degree in Power Electronics from IIT Bombay, India. He is leading the battery and charging simulation topics and an expert with computational studies for battery and charging systems

Neethu Mohan is a Senior Program Manager with Mercedes Benz R&D, India. She holds an M.Tech degree in power Electronics from National Institute of Technology, Calicut, and an executive M.B.A from IIM Kozhikode, India.