EV-EVSE Fault Study

An Analysis of Thermal Events Caused by Electrical Faults during DC Charging

CHARGEX consortium

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Disclaimer

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Executive Summary

This report outlines multiple avenues of analysis of electrical faults associated with electric vehicles (EVs) during charging, focusing specifically on the interactions between EVs and EV supply equipment (EVSE). Key concerns include the identification and mitigation of overtemperature events that can result in fires, which are commonly initiated by localized heating of connectors, wiring, or high-impedance fault current paths.

Data from multiple studies, including a review of global incidents, highlights that although EV fires during charging are rare compared to traditional internal combustion engine (ICE) vehicle fires, their impact can be significant. Notable case studies from South Korea, Germany, and California underscore the risks posed by faults that originate in charging systems, emphasizing the importance of systems-level fault analysis of the integrated EV-EVSE system.

This report identifies critical points at which electrical systems are most vulnerable, including faults triggered by capacitor-sourced fault currents and battery-fed electrical shorts, which can lead to thermal runaway and fires. The vulnerabilities noted are balanced against inputs from stakeholders, including EV manufacturers, EVSE operators, and third-party maintenance providers, about fault protection mechanisms, current industry practices for EVSE hardware safety standards, experiences with field failures and the stated need for standardized fault codes and improved diagnostic tools.

Following analysis of a functional decomposition of the EV-EVSE integrated system, the electrical properties of capacitor-sourced fault currents, battery sourced fault currents, and fault currents fed by multiple sources; the report advocates for a systems engineering approach utilizing fault trees to map potential fault paths and prioritize risk reduction strategies across multiple components rather than isolating the focus on individual parts like batteries. This structured analysis improves diagnostic accuracy, efficiency, and training value, providing a more holistic perspective on EV charging safety. An illustrative fault tree analysis is provided in the report to demonstrate how a probabilistic risk assessment of the system could be used to perform risk-based mitigations. The illustrative analysis appears to comport with some intuitive input from industry about improving the richness and coverage of diagnostic fault codes used in the charging infrastructure.

The key takeaway from this report is that EV fires are less likely than traditional internal combustion engine vehicle fires and electrical components used in EVs, and EVSE are continually being improved and consequently becoming safer. Meanwhile, the risk of faults due to emergent system-level interactions could increase due to the growing complexity of the integrated charging system and tighter integration between onboard and offboard electronics. Tools to preempt, detect, and mitigate such complex fault types are still nascent and benefit from formal systems engineering and the judicious standardization of components.

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List of Abbreviations

Abbreviation	Description
AC	Alternating Current
BEV	Battery Electric Vehicle
BMS	Battery Management System
DC	Direct Current
DCFC	Direct Current Fast Charger
ETA	Event Tree Analysis
EV	Electric Vehicle
EVSE	Electric Vehicle Supply Equipment
FMEA	Failure Mode and Effective Analysis
FMVSS	Federal Motor Vehicle Safety Standards
FTA	Fault Tree Analysis
HA	Hazard Analysis
ICE	Internal Combustion Engine
IEC	International Electrotechnical Commission
IMD	Isolation Monitoring Device
NEC	National Electric Code
NFIRS	National Fire Incident Reporting System
NHTSA	National Highway Traffic Safety Administration
OBC	Onboard Charger
PRA	Probabilistic Risk Analysis
REESS	Rechargeable Electrical Energy Storage System
SAE	Society of Automotive Engineers
UL	Underwriters Laboratories

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1. Introduction

This report outlines the landscape of electrical faults that have been observed to cause overtemperature events during electric vehicle (EV) charging sessions when an EV is conductively coupled to an EV charger. Overtemperature events of particular concern were noted to have originated from abnormal spot heating of connectors and localized heating of wiring harnesses on the EV. High-impedance fault current paths between chassis ground and energized conductors on the EV were also noted to cause overtemperature events. In some cases, the spot heating was sufficient to ignite flammable plastics on the vehicle, resulting in combustion that was sustained even after the electrical supply from the charger ceased.

It is important to note that EV fires under all circumstances have been shown to be less likely than conventional fuel internal combustion engine (ICE) vehicles. A statistical review of vehicle fire data from 2010 to 2020 conducted by EV Fire Safe—an initiative of the Australian Department of Defence—concluded that the rate of EV fires was 1.2 out of 100,000 compared to about 100 out of 100,000 for conventional fuel ICE vehicles.[2] Sweden and Norway have EV sales rates exceeding 60% of all new passenger vehicles sold and significant deployment of public charging infrastructure to support the growing EV fleet. A fire risk review conducted by the Swedish Civil Contingencies Agency (MSB) notes that in Sweden ICE vehicle fires were 20 times more likely than EV fires between 2018 to 2023.[3] Manufacturing defects, vehicle submersion, and collisions are the most common triggers for EV battery fires.

However, the interest of this report is to address overtemperature and fire risk during charging. Data from EV Fire Safe indicates that 18–30% of all EV battery fires occur when the vehicle is charging or within an hour of being disconnected from a charger.[4] This is a significant yet small fraction of the total number of EV battery fires. However, concluding that charging an EV increases the risk of an EV fire is not appropriate since EVs spend a significant amount of their operational life connected to an EV charger—exceeding 30% in some cases. At the time of writing this report, it was not possible to compute statistical rates for EV-charging-related fires in the United States due to the low occurrence rate in standard U.S. data sources such as U.S. Fire Administration's (USFA) National Fire Incident Reporting System (NFIRS).[5] Besides the low rate of occurrence, root causes are sometimes conflated with electrical faults in the electrical wiring supplying the charger itself. Older residential electrical circuits may need to be upgraded to safely charge modern EVs. Compliance to Article 625 of the National Electrical Code (NEC) when installing a Level 2 AC charger would reduce the risk of an electrical fire traceable to the supply wiring to the charger.

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[2] https://www.evfiresafe.com/ev-fire-key-findings
[3] https://rib.msb.se/filer/pdf/29438.pdf
[4] https://www.evfiresafe.com/research-ev-fire-charging
[5] https://www.fema.gov/about/openfema/data-sets/fema-usfa-nfirs-annual-data

Instead, it is helpful to consider the epistemology of some of the factors known to increase the probability of battery failures applicable to EV charging such as damaging/excess cell potential, improper thermal management, deficient battery fault detection, and errors in the battery management system. While the rate of incidence is low, EV fires have drawn a lot of interest from the fire research community due to lack of field experience or established practices in suppressing EV battery fires.[6] Lithium battery fires have some unique characteristics compared to traditional ICE vehicle fires, including thermal runaway, self-sustaining combustion, and delayed re-ignition. EV battery fires also share many characteristics of ICE vehicle fires, including high temperatures, explosion risk, toxic vapor emissions, flammable gas ejecta, and jet-like flames. These characteristics cause reduced visibility, personnel protection, and secondary responder safety concerns while requiring updates to established vehicle fire suppression and fire mitigation tactics. As a result, the impact of an EV fire, in terms of damage and the effort needed to safely suppress it, is significantly higher than for ICE vehicles. EV charging is also a valuable area of focus from the perspective of impact since the EV is conductively and physically connected to a charger and associated charging infrastructure.

A significant overtemperature fault that causes a fire would damage the charging infrastructure and the nearby physical environment, including other parked vehicles. The impact of an EV battery fire in an enclosed parking structure (whether charging or parked) is very great and is highlighted by the number of high visibility accidents that have caused significant damage. Some examples of such incidents are listed below for reference. The actuarial measure of risk is the product of likelihood and impact; this definition of risk is applied in this report. The likelihood of an EV fire when charging is low, but the impact can be very high. Therefore, it is justified to investigate system improvements that would either forestall or abate the impact of an EV fire while charging.

1.1 Insights from Electrical Vehicle Fires During Charging

In 2024, there have been three high-profile fire incidents in parking structures in South Korea involving EVs. [7] One of the incidents, photographed by the local fire department and shown in Figure 1, involved an EV that was connected to a charger when an overtemperature event triggered a sustained battery fire. All three incidents involved different brands of vehicles and different battery vendors yet are notable in their impact. For example, one of the incidents damaged 140 vehicles and caused injuries to approximately 22 people, including a first responder. In cases such as the incidents in South Korea in which the battery was involved in sustaining—if not initiating—the fire, the focus of forensic investigations rightly remains on improving battery safety.

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[6] https://www.ntsb.gov/safety/safety-studies/Documents/SR2001.pdf
[7] https://www.kedglobal.com/electric-vehicles/newsView/ked202408210008

Battery safety is a large topic of study and development and will be discussed later in this report. Even if the root cause of the initiating overtemperature event is outside the battery pack (e.g., a component in the onboard charger module), it is fair for consumers to expect that the battery pack does not propagate or accelerate the thermal event. But, how safe should a battery be and within what environmental limits must a battery be assured to operate?

Figure 1: August 2024, South Chungcheong Province, South Korea (Yonhap News Agency)

The parameters to which a battery must be tested to be deemed safe enough for an EV have to be realistic to not unduly stymie battery development and adversely affect cost and power density. Perhaps the overall risk of fire could be more effectively lowered by reducing the likelihood of overtemperature events or short-circuit faults in external components such as the onboard charger in the hypothetical case mentioned earlier.

A systems engineering approach could offer insight to help a system designer balance risk across all interacting components involved in EV charging, including the EV charger and the EV and to find more effective risk reduction strategies that do not focus on a single component such as a battery. The thesis statement of this report is that by deductively mapping all fault pathways that lead to an unmitigated vehicle fire, the overall risk of a terminal fault (such as a vehicle fire) may be more effectively lowered by balancing improvements over multiple components along a causal fault path instead of focusing on the most visible (or distracting) faulted component. As borne out in other complex engineering systems, committing to a systematic map of fault paths, referred to as a fault tree, provides other benefits from the perspective of fault analysis:

- Efficiency: Ensure fault finding is conducted efficiently and minimize time and resources required to identify and rectify faults by factoring the diagnostic process into manageable steps

- Accuracy: Reduce the likelihood of overlooking or misdiagnosing faults, leading to more accurate fault identification and resolution
- Consistency and Comprehensiveness: Ensure fault finding is performed uniformly and that no potential cause is overlooked across phenomenologically different faults and varied component taxonomy, thereby enhancing the reliability of the diagnostic process
- Documentation, Training, and Knowledge Representation: Provide structured documentation of observed prior fault paths, fault finding procedures, outcomes, and resolutions, which has direct training value while facilitating the recognition and concatenation of novel or unforeseen fault paths.

Returning to the incident pictured in Figure 1 and the two other high-profile fires in South Korea, there is evidence of the concepts of a systems approach being used to reduce risk in the response from authorities. New measures considered include improving transparency for the consumer about the manufacturing source and vendor of the vehicle battery. This step would improve the efficiency of a fault analysis by documenting a fault path from the terminal fault of an EV fire to potential manufacturing deficiencies with a particular vendor. Other proposals include limiting EV state of charge and charging limits in enclosed parking structures and restricting EVs from underground parking lots. Both measures illustrate a balanced risk mitigation approach by considering components in the fault path external to the battery. Limits on state of charge and charging limits are aimed at reducing the likelihood of overcharging-related thermal failure, while restrictions on the number and location of EVs in enclosed parking structures are aimed at reducing the impact of a vehicle fire. As noted earlier, risk is computed as the product of likelihood and some metric of impact. Including component-level risk factors in a structured fault tree would be valuable to not only identify contributing critical components but also to quantitatively determine the reduction of overall risk in terms of changes to specific components or groups of components.

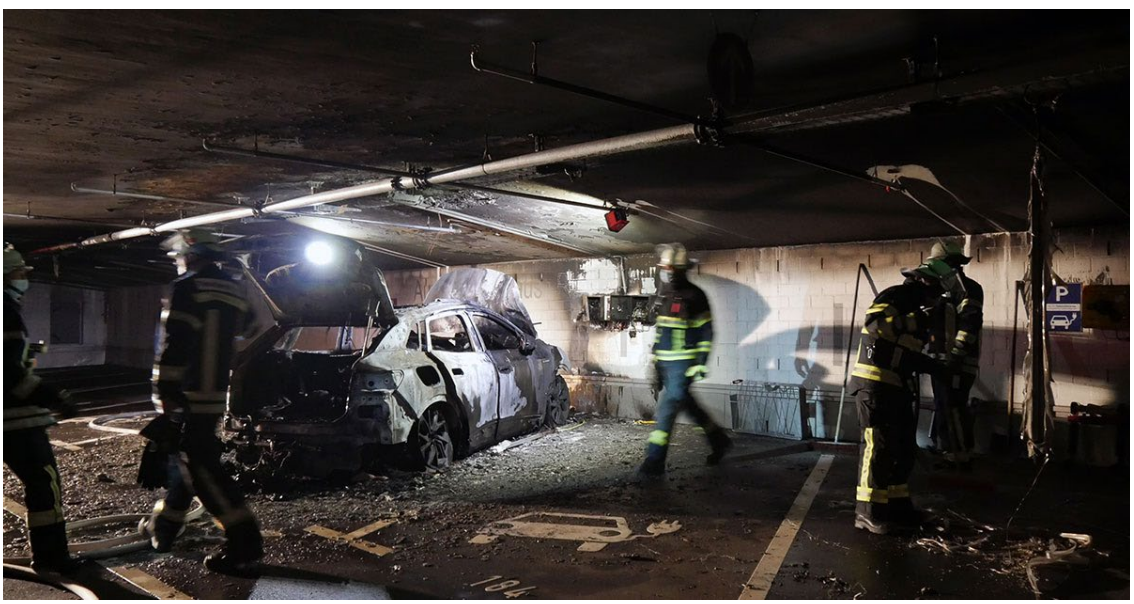

Figure 2: November 2021, Ravensburg, Germany (Wochenblatt News)

In contrast to the cases discussed earlier where the terminal state of the EV charging fires was a sustained lithium battery fire, many EV charging fires do not terminate in thermal runaway and combustion of the battery cells. Figure 2 shows a widely reported incident in a parking garage in Ravensburg, Germany.[8] This incident had significant damage impact, including exposure ignition of adjacent vehicles and damage to the building structure. Indications from preliminary analysis indicate that the primary ignition may not have directly been caused by a battery fire. Instead, it is likely that the trigger condition was an electrical short or arcing event near the point of connection between the EV and the charging connector, which is referred to as the connector-inlet interface. In fact, a similar make and model of the EV displayed an electrical fault originating near the connector-inlet interface when charging at a DC fast charger in California in 2023. In the latter case, a bystander was able to record video of the onset and progression conditions, shown as a sequence of screenshots in Figure 4. The flames first appear around the connector-inlet interface. Damage after fire suppression also appears to be localized around the connector-inlet interface and the rear quarters of the vehicle.

Referring to the high-level functional diagram of all the components that are active in an EV during a charging session, shown in Figure 3, there are multiple components along the critical electrical and thermal pathways required for safe charging along with necessary control and safety monitoring devices required to execute a safe shutdown prior to overtemperature events that might cause a vehicle fire.

Analyzing the seemingly similar incidents in Figure 2 and Figure 4 against the functional diagram in Figure 3 yields some inferences. It appears that in the 2021 incident, the EV was charging at an AC charger, while in the 2023 incident the EV was charging at a DC fast charger. Figure 3 shows the electrical pathways and connections are similar for AC and DC charging; however, these two charging modes are functionally very different. AC charging requires a vehicle component called an onboard charger (OBC) to convert AC to DC to charge the battery. An OBC is typically a modular connectorized unit that contains an AC to DC rectification stage, high-voltage DC-to-DC converter(s), and some filter stages.

From conversations with OBC vendors, it was found that OBC modules have been noted to fail in the field due to thermal failure of power transistors, water ingress into the module, indirect lightning strikes, voltage surges from the AC power grid, failure of DC bus capacitors, and failure of high-voltage insulation. All these OBC failure modes could trigger arcing or conduct large fault currents, which would induce spot heating, cause further damage, and consequently ignite polymeric materials or alike. Early EV models may have been more prone to OBC faults. The vendors contacted in preparation for this report state that testing requirements for OBCs have significantly improved over recent years and that OBCs do not individually contribute to a significant increase in the likelihood of EV fires. Following this direction, the report will focus on DC fast charging for the remainder of this report since DC charging also carries the added risk of higher charging currents and tighter closed loop interaction between the

[8] https://www.wochenblatt-news.de/region-ravensburg/ravensburg/elektroauto-loest-feuer-in-marienplatzgarage-ravensburg-aus/

EV and electric vehicle supply equipment (EVSE) to dynamically control current and voltage. Because of the higher currents and dynamic control, both EV and EVSE protection mechanisms play a more critical role in preventing the terminal fault of an EV fire.

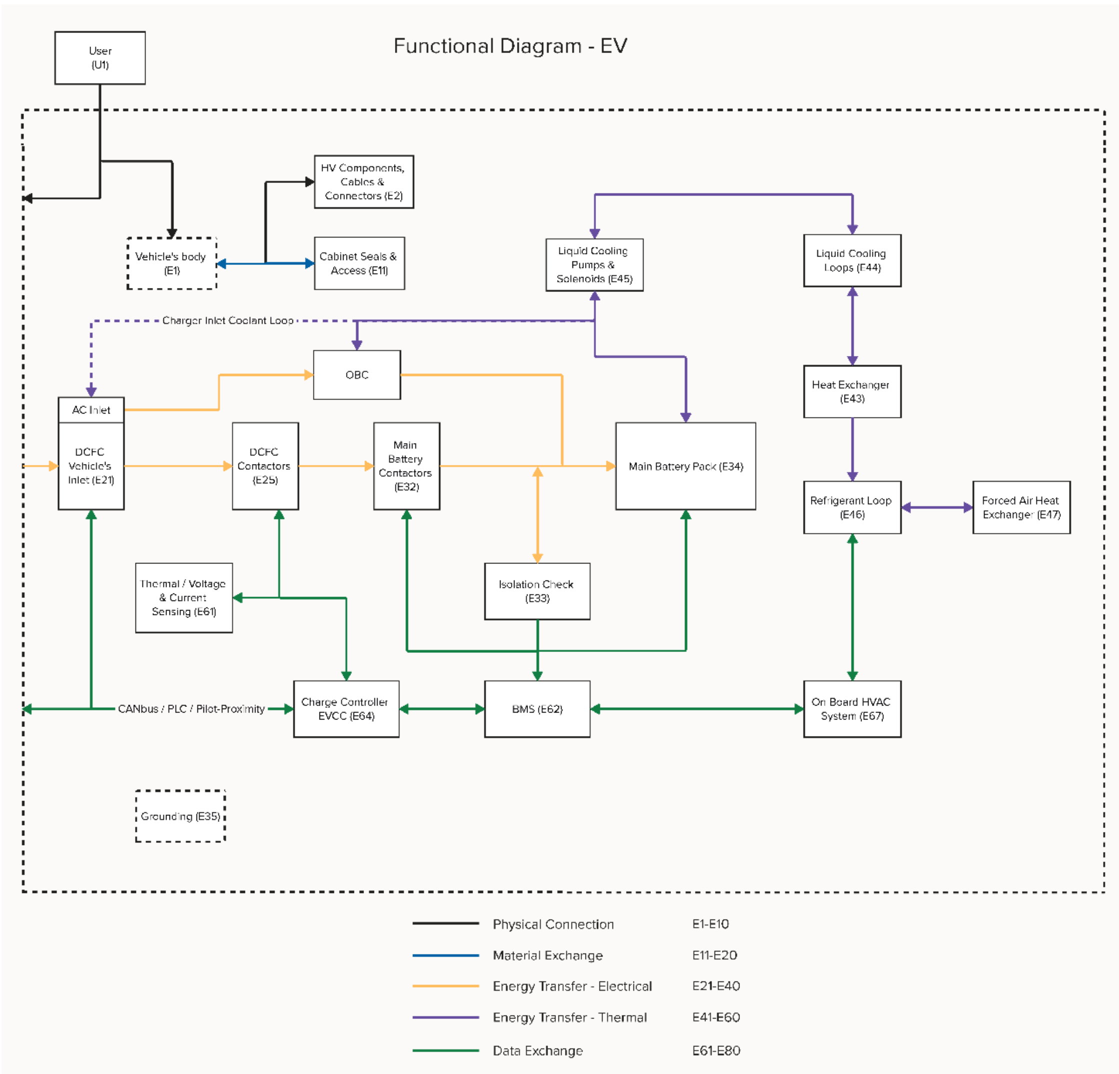

Figure 3: A functional dependency diagram showing all the EV components typically active during an EV charging session

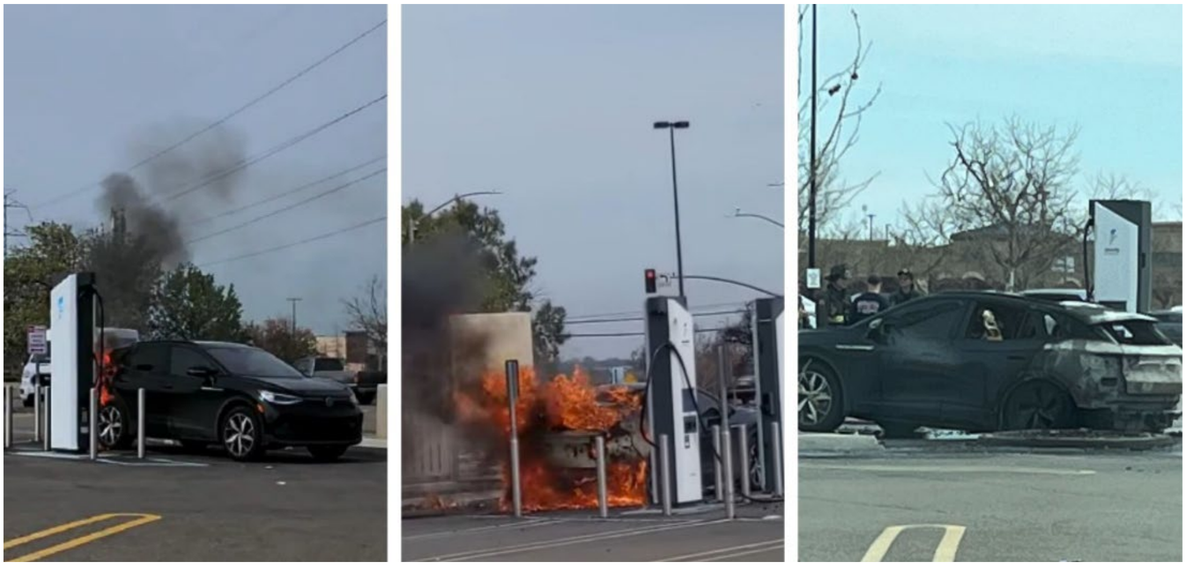

Figure 4: March 2023, Tracy, California (Auto Revolution 03/24/2023)

Returning to the incidents in Figure 2 and Figure 4, assuming that the originating faults were the same for both incidents and comparing the observations in the two events two years apart, a diagnostician may conclude that some component other than the OBC may have a role. There are several components in the charging circuit to consider. In several cases that seem to present a similar fault evolution pattern as the incidents in Figure 2 and Figure 4, it has been noted that failure of grommets, connectors, and cables between modular components in the charging path had contributed to the eventual faults to ground. As can be seen in Figure 3, the EV battery can serve as a source for fault currents depending on the location of an electrical wiring fault to ground causing what is called a battery-fed electrical short. Modern EV batteries store around 100 kW-h or 360 Megajoules of energy, which in thermal terms would be equivalent to approximately 15 liters of burning gasoline. Coupled with the rapid heat release rate of an electrical fault, there is sufficient energy in the battery to cause a fully involved vehicle fire even if the battery itself did not ignite. A determination that wiring defects and insulation failures could trigger battery-fed electrical shorts has motivated some manufacturers to issue voluntary inspection recalls;[9] for example, a recent National Traffic and Motor Safety Act mandated 49 CFR Part 573 Safety Recall.[10]

While defect monitoring and part improvements are an important feedback loop to reduce likelihood and impact of an electrical fault, there is also a role for active countermeasures in the form of circuit interrupters, surge protectors, clamping protection, fuses, isolation monitors, thermal monitoring, and logical interlocks. Some of these active safety functions are shown in Figure 3. Circuit interrupters are particularly relevant to arresting the discharge of residual energy in an EV battery after the detection of an electrical short. EV electrical systems pose a unique challenge to

[9] https://static.nhtsa.gov/odi/rcl/2023/RCRIT-23V867-7302.pdf
[10] https://static.nhtsa.gov/odi/rcl/2024/RCLRPT-24V228-1895.PDF

circuit breaker design owing to the need for large dynamic currents for propulsion motors and regenerative braking. There is also a cost, weight, and complexity consideration that is amplified for an automotive component.

DC contactors are traditionally intended to isolate the battery or the DC supply but may not be rated to break the large inrush currents associated with electrical shorts. DC contactors have been known to fail due to arcing, contact welding, and contact bounce, making them unreliable as a safety critical component. Recent innovations, such as the advent of the breaker-contactor (or Breaktor), may allow protection schemes that are mode-dependent, enabling different current, voltage, and thermal limits to be enforced during charging versus driving or at rest. This device class addresses some of the concerns with breakers serving as fault current interrupters by providing protection-rated active interruption of fault currents as well as configurable autonomous response to ensure that the device passively triggers in case of power loss.

1.2 Considering the Coupled EV-EVSE System

Structured fault trees help catalog risk across components by providing a system-level perspective on methods to reduce the likelihood and impact of an EV fire. A systematically documented risk map also helps compare different instances of low-probability fault events like EV fires to draw meaningful inferences about common fault modes.

The focus of this report is a specific class of EV fires that has occurred when an EV is conductively connected to an EV charger, so this analysis must also consider the role and impact of an EV charger in the fault path to a terminal EV fire. The term EV charger is ill-defined since it encompasses all modes of charging and could include multiple power conversion and communication systems. Therefore, the scope of this analysis is limited to the EV and the part of the charger equipment that directly interfaces with the EV. In industry parlance, this component is called EVSE. **This report's interest, therefore, is to study overtemperature faults that cause damage to the electrically coupled union of an EV and an EVSE. This damage may be more pronounced on the EV or EVSE or may involve both systems.**

Returning to the illustrative examples in Figure 1 and Figure 2, the EVSE was also damaged in the resulting vehicle fire. While it is unclear in these cases if the damage was due to thermal exposure after the EV ignited or if an electrical fault also occurred in the EVSE, there are several examples of cases in which faults similar in origin to the example in Figure 4 caused damage to the coupled EVSE. Another example is shown in Figure 5. The opposite causality is also common in which an electrical short originating in an EVSE has caused damage to an EV. An EVSE installation failure has been posited as a possibility in the EV fire shown in Figure 6.

Given the interdependence of the EVSE and EV, these should be considered as an integrated system and have the same system-level thinking applied as before with the intention to balance mitigations and minimize cumulative system fault risk. Analyzing the coupled EV-EVSE system also helps to identify systemic deficiencies from field observations of EV charging fires under seemingly disparate circumstances and from a variety of equipment manufacturers. Figure 7 shows a functional dependency diagram of the integrated EV-EVSE system showing all the components that are active during a charging session. Note that there are multiple connection pathways, including data exchanges, electrical energy transfer, and user interactions that cross between the boundary between the EV and EVSE. Additionally, there is a thermal interaction between these two systems, which will be ignored since a terminal overtemperature fault in either the EV or EVSE is a failure of the integrated system.

Figure 5: July 2021, Munich, Germany (Lisa Brack/EFAHRER.com 07/30/2021)

Figure 6: November 2022, Los Alamos, California (Santa Barbara County Fire Department)

The added advantage of analyzing the integrated system is that it provides the opportunity to identify circuit protection features shared between the EV and EVSE that would produce mutually beneficial risk reduction. Looking at the functional diagram in Figure 7, there are several functions, such as ground fault detection and overcurrent protection, that are present in both the EV and EVSE. These redundancies are not guaranteed to collectively add up to reduce risk unless their configuration and thresholds are coordinated.

The need for harmonizing protection schemes between the EV and EVSE stands out as frequent piece of feedback during of the authors' interactions with industry stakeholders, charging station operators, and EV equipment manufacturers. To ensure provable, functional safety improvements across the diverse set of EVs and EVSEs, the first thing needed is to perform fault analysis of the integrated system and then explore mitigations where settings for circuit protection components, such as overcurrent and isolation detection, can be tuned. An introduction to fault current analysis is presented later in this report. Following a system-level fault analysis, it may also be possible to tune circuit protection settings for each EV make and model, effectively broadening the function of circuit protection by incorporating the communication interfaces between the EV and EVSE to provide a verifiable reduction of risk.

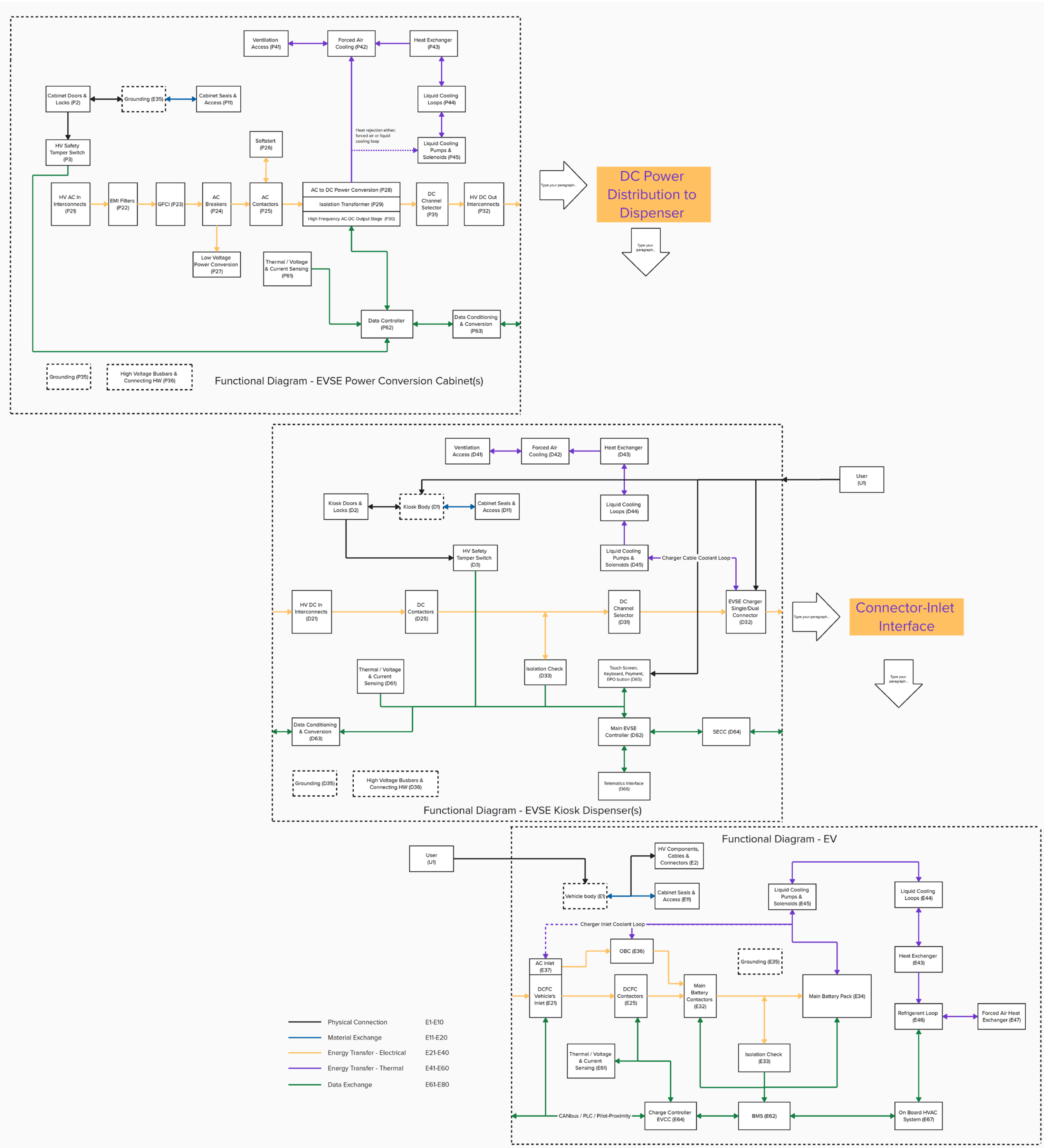

Figure 7: A functional dependency diagram for the integrated EV-EVSE system

Analysis of the integrated system is perhaps most valuable when diagnosing terminal overtemperature faults where the root cause is not clearly attributable to either the EVSE or the EV. In interactions with industry experts, they highlighted some examples of such failures due to an ambiguity in the tolerances for startup transients in voltage and current on the DC supply bus. They noted that the variation in startup behavior for different EVs and EVSEs required them to apply deadbands or holding off periods for configurable overcurrent and over-voltage thresholds within the charging circuit to prevent nuisance tripping. Overestimating the magnitude and duration of normal startup transients reduces the likelihood of detecting malfunctions such as a loose connection between the EV and EVSE or electrical arcing due to debris in the electrical contacts within the EVSE connector assembly. Continued operation of the charging session in the presence of an improper connection is known to have caused overtemperature damage and contact welding in the connector-inlet interface (as shown in Figure 8).

This failure mode often results in permanent physical damage to the connector and inlet as well as causes the vehicle to be stranded while connected to the EVSE since the latch release mechanism for the connector does not release from the vehicle either due to latch deformation from overheating or from contact welding. There is a need to improve the design of the connector and inlet; however, a system-level risk analysis would help focus improvements to minimize the risk of fires originating from the EVSE connector assembly. A systems analysis of connectors, inlets, and adapters to delineate failure modes has been taken up by the ChargeX hardware task force and a detailed failure mode and effects analysis has been conducted with industry participation.[11] The ChargeX analysis reveals several new design requirements that will lead to the development of a new testing standard to improve the safety of the connector-inlet interface.

In discussions with engineers responsible for reducing the risk of connector failures at two major EVSE manufacturers, it was postulated that the likelihood of damage to the connector and vehicle inlet could be further reduced with better design of soft start algorithms and pre-charge circuits and better definition of transients during the charging session. All three of these improvements would require expanding the scope of the systems analysis to include coordination between protection functions in both the EV and EVSE, which would motivate EV and EVSE manufacturers to harmonize vendor-agnostic requirements for the functions in the integrated functional decomposition in Figure 7.

The need for industry-wide consensus on system-level risk assessment for the specific failure mode discussed above is highlighted by the examples of field failures in which localized arcing and/or heating of the connector-inlet interface was unmitigated or undetected by both EV and EVSE until localized heating of the region around the connector caused progressive damage well beyond the connector-inlet interface.

[11] https://www.nrel.gov/docs/fy24osti/91017.pdf

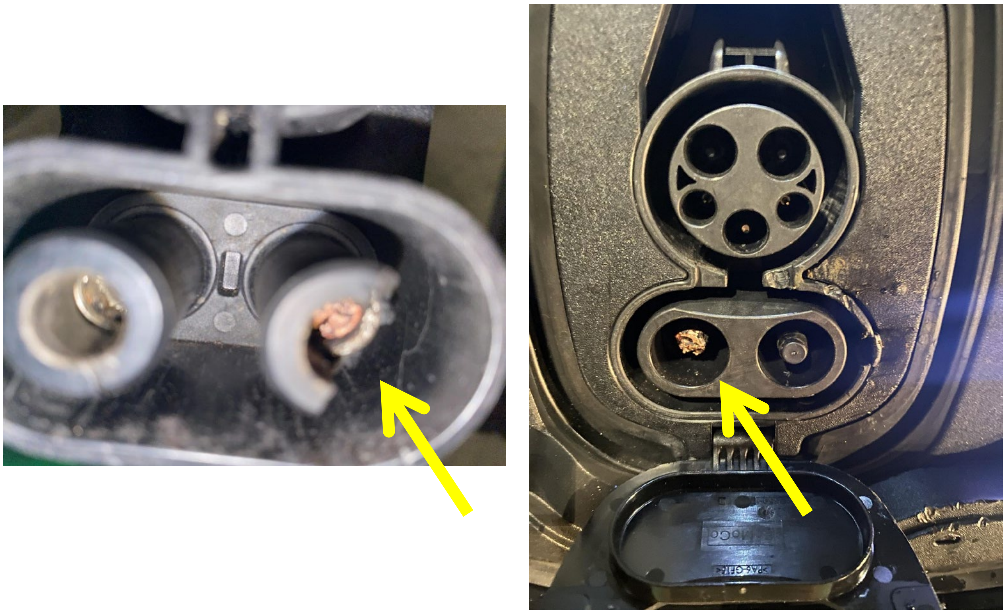

Figure 8: Damage to EVSE connector and vehicle inlet caused due to arcing and welding of the DC+ pin. (User provided image, posted online at https://imgur.com/a/cE1rRgN)

Such a fault progression has been suggested for the terminal fault seen in Figure 9. While the specific fault path to the terminal state in Figure 9 cannot be determined without compromising proprietary vendor information, the authors' conversations with engineering experts on this failure indicate that a system-level risk assessment would have revealed the need for additional temperature monitoring and a consensus on precursor signals in current and voltage measurements that would have aided in early detection and isolation, reinforcing the conclusion of this section that a system-level perspective on fault current analysis is required for balanced risk reduction.

The following sections explore system-level approaches to analyze some of the faults and failures described in this section. To systematically address the multifaceted challenges outlined—from the specific failure modes like connector overheating and battery-fed shorts to the overarching need for a systems-level perspective on the coupled EV-EVSE architecture —the subsequent sections of this report will provide a structured examination. Section 2 will delve into the fundamental electrical characteristics of critical fault currents, including capacitor-sourced and battery-sourced faults, as well as the complexities of high-impedance fault paths. Building on this technical foundation, Section 3 will incorporate vital real-world perspectives by presenting input gathered from EV manufacturers, charging network operators, and third-party maintenance providers concerning field failures and safety practices. Section 4 will contextualize these issues within the existing regulatory and normative framework by reviewing the current standards landscape.

Finally, Section 5 will introduce and demonstrate the application of structured fault analysis methodologies, such as fault tree analysis and probabilistic risk analysis, to illustrate a quantitative approach for identifying critical failure pathways and prioritizing risk reduction strategies across the integrated EV-EVSE system, thereby paving the way for enhanced charging safety.

Figure 9: June 2023: Mill Valley, California (Electrek.co, 06/06/2023)

2. EV-EVSE Fault Current Analysis

Fault current is a general classification of anomalous currents that flow through an electrical system when a fault, such as a short circuit, occurs. This can happen due to various reasons, such as insulation failure, equipment malfunction, or external factors like lightning strikes. These currents may not always be clearly classified based on magnitude, though large over-currents—as arrested by fuses or magneto-thermal breakers—are usually caused by faults. In a complex system of interacting power conversion and distribution components, a detailed model of the electrical system is needed to accurately estimate fault propagation dynamics in response to simulated fault conditions and to derive the time constants, sensing locations, and peak magnitudes that define the design requirements for protection devices, fault detection and location methods, and protection coordination.

Faults in DC power systems, as in DC chargers used for EV charging, have unique characteristics when compared to AC systems due to the absence of natural zero-crossings, making fault interruption challenging. The rise times for DC fault currents (di/dt), sourced by capacitors and batteries, are much shorter than for AC systems, necessitating faster response times from protection devices. DC fault currents typically comprise two components: an initial capacitive discharge transient current characterized by large magnitude and rate of rise and a subsequent static fault current supplied by power sources, such as batteries and DC power supplies, characterized by the static impedance of the fault path and the current versus voltage equilibrium condition for the DC sources in the faulted circuit. The design requirements for protection devices, fault peak, time to peak magnitude, and current paths are heavily dependent on the electrical properties of the batteries, line inductances, and converter capacitors in use. To summarize, the objective of fault-current analysis is as follows:

- Ensure that protective devices, such as circuit breakers and fuses, are appropriate for the expected fault current
- Consider possible locations where faults can occur and calculate the fault currents at other points in the system
- Improve reliability of the electrical system design by identifying potential weak points
- Identify fault signatures for high-impedance fault paths that require coordination between multiple protection elements to detect, localize, and isolate.

This section of the report will outline some notional fault current dynamics for the integrated EV-EVSE DC power system, as illustrated in Figure 10, which considers a fault somewhere in the section of the circuit between the EVSE dispenser contactor set S1-S2 and the EV contactor set S3-S4, as illustrations of the real-world examples described in Section 1.2.

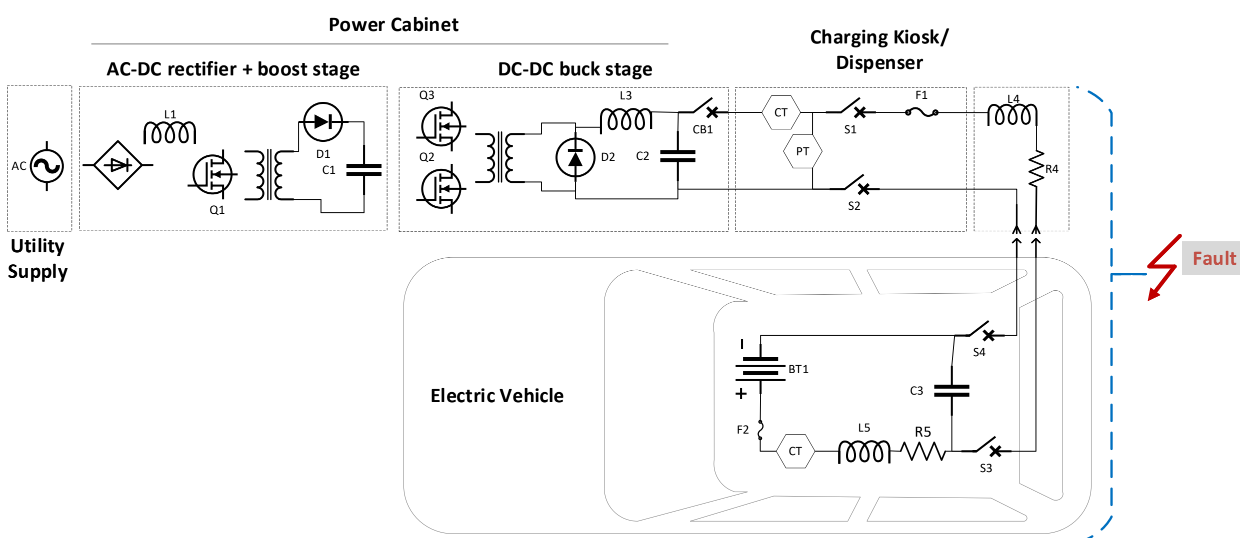

Figure 10: A notional electrical schematic showing key components of an integrated EV-EVSE charging system

2.1 Capacitor-Sourced Fault Current

DC EVSE requires multiple stages of power converters to convert grid-supplied AC to DC and then to regulate DC supply to the EV at the required charging voltage. Output power capacitors at each of these stages are needed to smooth the DC voltage supply. Given the high-power levels of DC fast chargers, these capacitors are likely to store a large amount of energy. During DC faults, the discharge of the converter capacitor is uncontrollable and can contribute high fault currents within a few microseconds. This rapid discharge can lead to system-wide undervoltage, causing equipment to trip, but more critically, these capacitors can contribute large instantaneous fault currents that could damage other power semiconductors in the charging circuit and trigger the overtemperature events this report is pledged to study. Figure 10 considers the capacitor C2, which is the output capacitor for the DC-DC power converter and is located closest to the EV in the charging circuit. DC fault current initially appears as the capacitor discharging to the fault location. Once the capacitor voltage reaches close to zero, the diode D2 of the converter is forward biased and begins conducting the fault current. Transistors Q2 and Q3 may also contribute fault current, particularly when the fault is electrically close to C2, causing it to discharge quickly. This fault progression could rapidly damage the switching transistors, causing thermal breakdown of those devices.

Thermal failure of the EVSE converter stage switching transistors is in addition to the direct heating and physical damage caused to the region around the fault location due to the large capacitor discharge current from C2. If the fault location were physically close to the connector-inlet interface (including within the high-voltage charging circuit of the EV), an EV fire (like the examples in Section 1.2) is a possible outcome. In conversation with EVSE design engineers, it was proposed that a similar failure mode is possible due to fault currents sourced by capacitor C3 (located in the EV). It was also proposed that some EVs include a DC-DC power converter in their charging system that could source currents during an undervoltage fault. In other words, faults between the dispense contactor set and the EV contactor set could be fed by capacitors on the EV or the EVSE; the progression of this fault scenario is rapid due to the relatively low impedance of the power conductors coupling the EV to the EVSE.

Regardless of which capacitor sources the fault current, the capacitor current, (i_{cap}) from a nominal operating voltage (V_0), depends on the relationship between the discharging resistance (R_{fault}), series inductance (L), and capacitance (C). Readers are directed to the included reference, Kizilyalli et. al (2023), for a more detailed treatment of capacitor-sourced faults. The reports note that the discharge dynamics of a capacitor following a fault can either be an exponentially decaying DC or decaying AC—as is the case for the circuit in Figure 10—depending on the fault magnitude. The time domain dynamics for both fault cases can be derived from Equations (1–2).

$$i_{\mathrm{cap}}\,(t) = \frac{1}{L}\frac{V_0}{p_1 - p_2}\left(e^{p_1 t} - e^{p_2 t}\right),\ \text{ if } R_{fault} > 2\sqrt{L/_C} \qquad (1)$$

$$i_{\mathrm{cap}}\,(t) = \frac{V_0}{\omega L} e^{-\left(R_{fault}/_{2L}\right)t} \sin(\omega t)\,,\ \text{ if } R_{fault} \le 2\sqrt{L/_C} \qquad (2)$$

where $\omega = \sqrt{\left(1/_{\sqrt{LC}}\right)^2 - \left(R_{fault}/_{2L}\right)^2}$, $\quad p_{1,2} = -R_{fault}/_{2L} \pm \sqrt{\left(R_{fault}/_{2L}\right)^2 - \left(1/_{\sqrt{LC}}\right)^2}$

Equation (1) illustrates that the exponential decay constant $R_{fault}/_{2L} \pm \sqrt{\left(R_{fault}/_{2L}\right)^2 - \left(1/_{\sqrt{LC}}\right)^2}$ determines the response time required for any protection measure in the system that is intended to detect capacitor undervoltage or the rate of current rise. Considering the additional case of an exponential envelope for an oscillating capacitor as described in Equation (2), the required protection time constant can be simplified to $\tau_{response} = \frac{2L}{R_{fault}}$, which is the ratio of the total inductance to the resistance in the fault path. While EVSE manufacturers did not share specific proprietary electrical parameters for this public report, the authors were able to corroborate that the analytical time constant $\tau_{response}$ translates to a practical fault peak rise time of a few microseconds, as compared to a few milliseconds for a comparable AC circuit. It is also important to highlight the fault-induced excitation of the tank circuit $1/_{\sqrt{LC}}$ and the corresponding alternating fault current (shown in Equation [2]) when $R_{fault} \le 2\sqrt{L/_C}$. This current has a frequency close to the switching frequency for Q2–Q3, so it can be as high as a few hundred kilohertz. High-frequency currents can cause significant secondary damage to downstream electronic components, including AC blocking, ripple protection, and electromagnetic interference (EMI) filters in the EV charging circuit. Many of these components are designed for DC or limited AC ripple but are known to fail to short circuit under large AC currents.

2.2 Battery Sourced Fault Current

Earlier in this section, it was identified that fault currents in the EV-EVSE integrated system contain a transient component as well as a static battery-sourced component. EV batteries at terminal voltage V_{batt} can source persistent fault current (i_{batt}), which typically rises to a peak value in a few milliseconds (as in Equation [3]) following the transient component (i_{cap}). Until the battery current is interrupted by a fuse or circuit breaker in the battery pack (shown as component F2 in Figure 10), the battery continues to feed fault current to faults in either the EV or EVSE circuitry. The steady-state peak value for a battery fault is limited by the effective fault path resistance R_{fault} and the internal resistance of the battery itself. Industry practitioners note that batteries are tested against bolted faults close to the battery pack to determine the tripping curves for F2. However, in cases where the fault location is close to the connector-inlet interface or in the EVSE system or when an onboard DC-DC stage is employed, the combination of the path resistance R_{fault} and the path inductance L may be that neither the magnetic nor thermal tripping curves for F2 are reliably violated, enabling the fault to persist until a secondary protection measure, such as a temperature violation, triggers a fault arrestor. Noting the concern about larger R_{fault} values, a simplified notation is used for Equation (3) considering only the path impedance values.

$$i_{\text{batt}}(t) = \frac{V_{\text{batt}}}{R_{fault}}\left(1 - e^{-\frac{t}{\tau}}\right) \tag{3}$$

$$where, \quad \tau = L/R_{fault}$$

The IEC 61660-1:1997 standard covers a more comprehensive review of the characteristics of short circuit currents in auxiliary DC power systems and notes alternate models for battery-sourced fault currents. Given the variety of battery chemistries and configurations currently deployed in the EV fleet, empirical assessment of battery-sourced fault currents remains a knowledge gap for system-level fault analysis and exposes the challenge in designing a single protection element to detect battery-sourced fault currents. For example, it is unlikely that fault parameters R_{fault} and L are known a priori when designing a fault protection scheme. This would make it impossible to classify fault currents based on Equation (3), which is why coordination between fault detection algorithms in the EVSE and EV would be needed to better identify and localize faults even with uncertain fault path parameters. One approach to achieve fault characterization with multiple measurement points is described in Section 2.4. First, however, the next section will briefly describe system-level considerations for improving battery safety in response to electrical faults external to the battery pack.

2.3 A Note on Battery Safety

In the functional diagram for the EV charging system (Figure 7), the EV battery pack is one represented as a functional component (E34). Since this report is intended to present system-level techniques for fault analysis and risk mitigation, specific improvements to individual components are not within the report's scope.

However, battery failures tend to be the most visible failure in an EV owing to the often-dramatic fault propagation associated with thermal runaway failures in batteries and the nascency of fault detection and mitigation techniques currently deployed on battery modules. Battery safety concerns pose an outsized role in the determination of EV system reliability; therefore, the conditions under which a battery-sourced fault current i_{batt} (as outlined in Section 2.2) might trigger a battery fire should be considered. Besides manufacturing defects in the battery construction, the onset condition for thermal runaway in a battery is often related to Joule heating $Q_{bat} \propto i_{\text{batt}}^2 R_{batt} t$ of the battery internals. R_{batt} is a linear approximation of the battery's internal resistance, which is a combination of ohmic resistance and polarization resistance affected by factors such as battery material and structure. Without quantifying failure thresholds, a bounding function $\beta(t)$ is assumed, such that a battery-sourced fault current, when $\frac{R_{fault}}{R_{batt}} > \beta(t)$, is unlikely to induce thermal runaway failure in a battery. In the inverse case of bolted faults, a detection threshold $\alpha(t)$ exists so when, $\frac{R_{fault}}{R_{batt}} < \alpha(t)$, a battery protection circuit breaker or fuse is likely to trip sufficiently quickly to prevent thermal runaway. Then, the interval expressed by Equation (4) would represent a gap in protection, causing Q_{batt} inside the battery to increase due to an increase in i_{batt} .

$$\alpha(t) < \frac{R_{fault}}{R_{batt}\left(1 - e^{-t/\tau}\right)} < \beta(t)\ \forall t \tag{4}$$

If the battery cooling system is insufficient to meet the thermal flux rate, $\frac{dQ_{batt}}{dt}$, then the internal battery temperature quickly rises to the point at which the battery electrolyte undergoes thermal decomposition. This decomposition itself is often exothermic, releasing more heat. This increases the likelihood of separator breakdown. The separator is a porous membrane that allows ions to migrate through the electrolyte while preventing internal short circuits. The onset of internal short circuits accelerates spot heating within the electrolyte and induces a breakdown of the solid electrolyte interphase layer on the battery anode. The solid electrolyte interphase layer is critical for stable battery operation, and its decomposition generates more heat and exposes the anode to further reactions with the electrolyte. This combination of high current flow, heat generation, and accelerated side reactions creates a dangerous positive feedback loop, where the heat from the initial short circuit, along with the heat released by side reactions, further increases the battery temperature. This self-heating accelerates the breakdown of more battery components, releasing more heat and leading to a rapid, uncontrollable temperature increase called thermal runaway.

As temperature continues to increase and as pressure from the gaseous products from electrolyte decomposition continues to rise, the electrolyte can ignite, and the battery can rupture, potentially leading to fire and explosion, which is the terminal fault state illustrated in Figure 1.

Readers are directed to research data from the Idaho National Laboratory's vehicle battery testing program[12] and Sandia National Laboratory's battery safety program[13] for empirical quantification of the external-fault-current-induced failure criteria and bounding functions here described.

To protect a lithium battery from thermal runaway, EV battery packs often incorporate safety mechanisms like active cooling, pressure relief vents to release built-up gases, advanced diagnostics in a battery management system (BMS) to monitor and control charging/discharging and to trigger circuit breakers, temperature sensors to detect overheating, positive temperature coefficient devices or thermal fuses, and other mechanical protections against penetration and cascade failure. The extent and nature of the measures taken to improve battery safety are currently vendor-specific and often proprietary to the design agreement between EV manufacturer and battery vendor. This report, however, focuses on system-level fault mitigations, abstracting the specific failure conditions of individual components to incident fault criteria such as the

[12] https://avt.inl.gov/sites/default/files/pdf/fsev/batteryFocus1700.pdf
[13] https://www.osti.gov/servlets/purl/1336278

protection gap in Equation (4). As is the case with battery-sourced faults in Section 2.2, specific parameters, such as fault path resistance needed to compute Equation (4), are unknown a-priori, which is why multiple sensing, detection, and mitigation sites in the system will have to work in coordination to identify the parameters needed to flag a fault and to provide overlapping or redundant schemes of protection to reliably detect, avoid, mitigate, and/or arrest terminal faults such as thermal runaway.

2.4 Characterization of High-Impedance Faults

Consider a line-to-line fault where the path resistance R_{fault} is high enough that the observations of induced fault current from the EV battery or the EVSE power converter alone are insufficient to conclude that a fault has occurred. This type of fault is considered a high-impedance fault since the fault would have to be classified based on detecting an abnormal path for current flow rather than merely current magnitude. Further consideration should be given to the added complexity that multiple power sources (e.g., capacitors, batteries, DC power supplies) all contribute fault current into the fault location simultaneously. Noting that the nominal power level for some DC EVSE exceed 200 kW, the summation of currents at the fault location could be in the order hundreds of amperes. As a comparison, the flux level in a standard arc welder is approximately 200 amps. Therefore, the energy dissipation rate at the fault location would likely be high enough to cause significant damage while evading single-point detection at the contributing sources. To detect and arrest such high-impedance faults, abnormal current flow paths will have to be detected using the same conceptual coordinated system-level strategy as was outlined in the conclusions of Sections 2.2 and 2.3. One such strategy is sketched below.

Referring to the electrical schematic in Figure 10, the high-impedance fault scenario described above has been known to occur between the EVSE dispenser contactor set S1-S2 and the EV contactor set S3-S4 during an active charging session. Many of the terminal faults cited as examples in Section 1 may have involved a high-impedance fault in this section of the charging circuit. Since this section of the charging circuit spans the boundary between an EV and EVSE, fault localization requires coordination between the two systems.

Figure 11 is a simplified representation of this fault scenario where an unknown fault impedance R_{fault} is fed by two DC sources contributing i_{cap} and i_{batt} as fault currents sourced by the EVSE DC supply (V_{cap}) and the EV battery (V_{batt}), respectively. The fault path impedances for i_{cap} and i_{batt} are $R_4 + j\omega L_4$ and $R_5 + j\omega L_5$, respectively, and together approximate the electrical path length for the two superimposed current sources. Comparing path length estimates could help determine if the fault is on the EV or EVSE side of the circuit boundary. Since fault path impedances are unique to the fault location and type and are a priori unknown, these parameters are estimated from time synchronized measurements of $\left[V_{cap}^k, V_{batt}^k, i_{cap}^k, i_{batt}^k\right]_{k \in K}$ (i.e., a sequence of K voltage and current measurements shared between the EV and EVSE). With these synchronized measurements, the fault identification and localization problem can be formulated as at least squares parameter estimation problem for $[R_4, L_4, R_5, L_5, R_{fault}]$ as in Equation (5).

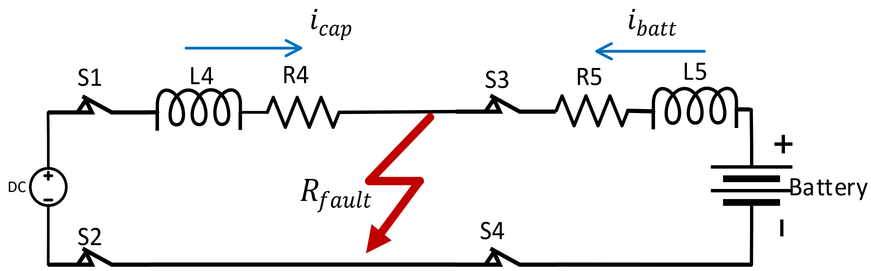

Figure 11: A line-to-line fault fed from two DC sources

$$\min_{[R_4,L_4,R_5,L_5,R_{fault}]^T} \left\| \begin{bmatrix} \vdots \\ V_{cap}^{k-1} \\ V_{batt}^{k-1} \\ V_{cap}^{k} \\ V_{batt}^{k} \\ V_{cap}^{k+1} \\ V_{batt}^{k+1} \\ \vdots \end{bmatrix} - \begin{bmatrix} \frac{di_{cap}^{k-1}}{dt} & i_{cap}^{k-1} & \cdot & \cdot & i_{batt}^{k-1} + i_{cap}^{k-1} \\ \cdot & \cdot & \frac{di_{batt}^{k-1}}{dt} & i_{batt}^{k-1} & i_{batt}^{k-1} + i_{cap}^{k-1} \\ \frac{di_{cap}^{k}}{dt} & i_{cap}^{k} & \cdot & \cdot & i_{batt}^{k} + i_{cap}^{k} \\ \cdot & \cdot & \frac{di_{batt}^{k}}{dt} & i_{batt}^{k} & i_{batt}^{k} + i_{cap}^{k} \\ \frac{di_{cap}^{k+1}}{dt} & i_{cap}^{k+1} & \cdot & \cdot & i_{batt}^{k+1} + i_{cap}^{k+1} \\ \cdot & \cdot & \frac{di_{batt}^{k+1}}{dt} & i_{batt}^{k+1} & i_{batt}^{k+1} + i_{cap}^{k+1} \end{bmatrix} \begin{bmatrix} L_4 \\ R_4 \\ L_5 \\ R_5 \\ R_{fault} \end{bmatrix} \right\|^2 \quad (5)$$

3. Industry Input

In determining the scope of this report, input was gathered from a variety of stakeholders, including EV manufacturers, charging network operators, third-party maintenance, and service providers as well as experts that are involved in the design, commissioning, and operation of EV charging systems. The authors sought specific examples and associated root cause findings from charging station operators that have experienced field failures of charging equipment and were able to speak to one EV manufacturer who encountered thermal events in their charging subsystem during charging. General statistics were also collected on repair and field service logs from a third-party EVSE maintenance service provider.

While the specifics of individual failures or the associated causal faults have not been cleared by the respective sources for publication in this report, this report highlights some overarching observations.

3.1 Electric Vehicle Manufacturers

The prevailing consensus among the contacted manufacturers was that EVs protect their internal systems and that bolted faults, including large faults to ground, caused because of insulation failure or physical damage to isolation (e.g., after a collision) are addressed by the onboard fault protection system. Manufacturers often close-the-loop with suppliers to improve component designs when they encounter unexpected failures in the field, including when customers report overtemperature failures; such failures are present in electrical systems used in ICEs as well as EVs. The examples they provided in which field data were used to improve component design were overwhelmingly focused on thermal failures in the battery. Some engineers that were contacted agreed that a fault progression in which an EV battery discharges into an external high-impedance fault (including a fault location in the EVSE) is possible during charging but noted that in such a case, the EVSE is expected to detect anomalous current flow and to break the current path.

EV manufacturers also use mature systems engineering and systematic fault diagnosis methods, particularly when their systems are comprised of components from multiple vendors. Systems engineering principles around safety focus on identifying, analyzing, and mitigating risks through the following methods:

1. Hazard Identification and Analysis: Identify hazards early in the design process and analyze their causes and effects
2. Risk Management: Assess the severity and likelihood of identified hazards and implement measures to mitigate or eliminate them
3. Safety Integration: Integrate safety considerations into the initial design through development and testing
4. Iterative Process: Analyze field failure data and maintenance data to iteratively deploy product improvements
5. Documentation and Communication: Maintain thorough documentation of safety analyses, decisions, and actions
6. Compliance with Standards: Adhere to relevant internal safety standards and regulations, including Federal Motor Vehicle Safety Standards No. 305 that establishes national standards for electrical shock risk reduction for humans operating in and around EVs in both normal and post-collision conditions.

3.2 Charging Station Operators

EVSE operators who provided feedback noted that the EVSE hardware they currently source is subject to the safety regulations of the authorities having jurisdiction for the site where the equipment is to be installed. Often these requirements are equivalent to ANSI and NEC standards for outdoor power conversion equipment. Some jurisdictions are beginning to develop requirements specifically for EVSE such as testing to the Underwriters Laboratories (UL) 2594 and UL 2202 standards.

Beyond mandatory standards, EVSE operators have begun to update their procurement requirements from their EVSE vendors to include improvements to address some of the faults they have seen in the field. Based on their experience, the operators recommended standardizing procurement requirements for isolation monitoring device (IMD) logic, weld detection and pre-charge settings, overcurrent detection settings in the DC supply, and overcurrent sensing devices in the dispenser. Many of these settings can only be standardized in consensus with EV manufacturers, which is why there is still ambiguity.

At least one EVSE operator noted the following concerns based on their experience with overtemperature failures in the field:

- EV battery-sourced fault currents could significantly damage EVSE, and EV batteries are able to sustain current flow into a high-impedance electrical fault that would otherwise trigger an undervoltage trip.
- Better documentation is needed of the protection offered by an EV to the offboard power source from and during reverse power flow (in the case of a vehicle capable of power export).
- The IMD on the EVSE often misidentifies isolation failures, these false positives can be due to high chassis capacitance of some EVs. The industry should reach consensus on EV chassis capacitance and whether IMD should trip on high chassis capacitance or only on low resistance. These two conditions are conflated by IMD algorithms but have different causes and parameters. High capacitance is a design issue while low resistance is likely a pollution problem with isolation.
- Some multi-port EVSE tie the DC minus the lines of the ports together, which is not advisable but is not a violation of the electric code for DC supply equipment. This issue must be clarified and written as a requirement.

3.3 Third-party Maintenance Service Providers

The community of third-party maintenance and service providers for EVSE is still in its nascency. Many providers are specialized to a specific brand, technology, or territory. The contacted providers report that most of their service calls are for problems that were remedied by a single component or subsystem replacement, and they unanimously cite challenges with the parts supply chain as a top concern. Common component failures include the connector and cable assembly, the payment device, modems, display components, control circuit boards, and fuses/circuit breakers.

ChargerHelp's report on service calls[14] records that component failure or damage is the most common symptom reported by the systems they maintain, followed by communications and software failures. Together these account for more than two-thirds of the reasons that trigger service calls. By contrast, electrical problems and site damage (e.g., vandalism) combined accounted for less than 2% of service calls. Overtemperature events are included in the report as a fraction of the component

[14] 2024 Annual EV Charging Reliability Report

failure category, thermal events that resulted in multiple failed systems remain rare for systems already deployed. The report also provides some recommendations, including the need for better diagnostic tools and standardized fault codes so they can source parts and diagnose problems efficiently. The report also highlights the need to standardize some parts of the EVSE across manufacturers to improve serviceability and recognize that efficiencies in the bill of materials used across manufacturers should improve as the industry matures. Component standardization will help offset some of the diagnostic challenges with growing complexity in charging systems. Another major recommendation in the report aligns with the feedback received from every contacted provider that there is a need for a trained workforce. There is a nationwide shortage of electricians and technicians trained to install and repair high-power direct current fast chargers (DCFCs) and a dearth of training materials, troubleshooting instructions, and service manuals for EVSE. Systematic fault analysis tools, standardized components and better diagnostic information have all been vital to building a robust maintenance workforce in other domains such as automotive repair and building automation.

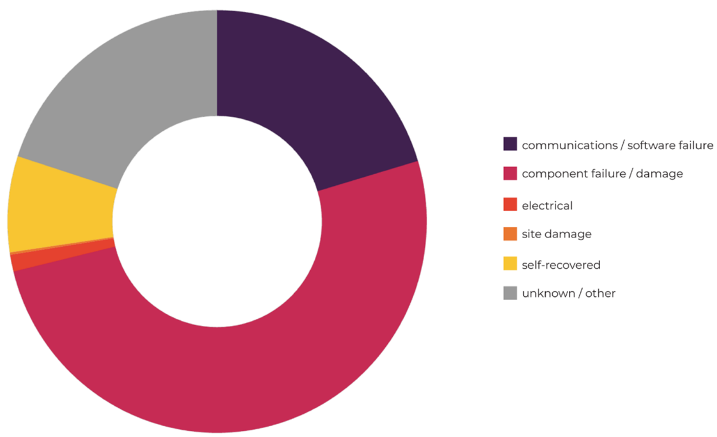

Figure 12: Fractional distribution of fault types reported to ChargerHelp. (Figure extracted from page 24 of this report)

4. Standards Landscape

The industry perspectives shared in Section 3 underscore a need for enhanced standardization in diagnostics, safety protocols, and component interoperability within the EV-EVSE ecosystem. In this section the current standards landscape is reviewed against the requirements voiced by manufacturers and operators. A few gaps and opportunities for updates to standards to address the complex fault scenarios previously detailed in Section 2 are identified, thereby providing a critical foundation for the system-level safety analyses and solutions proposed later in Section 5.

The key safety related standards that apply to DC EVSE in the United States are as follows:

1. **IEC 61851:** This series of standards covers the general requirements for EV conductive charging systems, including safety aspects such as protection against electric shock, overcurrent protection, and requirements for the charging cable and connectors.

2. **IEC 62196:** This series of standards specifies the safety requirements for plugs, socket-outlets, vehicle connectors, and vehicle inlets for conductive charging of EVs. It includes tests for mechanical strength, temperature rise, and resistance to aging.

3. **SAE J1772:** In addition to defining the physical connector, this standard includes safety requirements for the charging process, such as communication protocols, to ensure safe power transfer and disconnection.

4. **ISO 15118:** While primarily focused on communication, this standard also includes safety features such as secure communication to prevent unauthorized access and ensure safe operation of the charging system.

5. **NEMA 3R, 4, and 250:** These enclosure ratings specify the level of protection for electrical equipment, including EV chargers, from environmental factors and cover the construction, testing, and use of enclosures that protect personnel from hazardous parts and protect the equipment from the environment.

6. **NFPA 70 (National Electrical Code):** The NEC includes provisions for the installation of EV charging equipment, ensuring that installations are safe. The NEC codifies the minimum requirements for safe electrical installations in a single, standardized source. The NEC is commonly mandated by state or local law or the authority having jurisdiction over the EV charging location. Both UL 2202 and 2251 standards are referenced in NFPA 70, providing more granular requirements for components in the EV charging system.

7. **UL 2202:** This standard sets safety requirements for DC (under 1500 VDC) charging equipment for EVs by merging the typical safety requirements for large DC power supplies with safety requirements specific to EV charging. It includes minimum requirements for safety devices for personnel protection such as isolation monitors and ground leakage detection.

8. **UL 2251** is a standard for the safety of EV plugs, receptacles, and couplers. It covers the following: plugs, receptacles, vehicle inlets, and connectors rated up to 800 amperes and up to 600 volts AC or DC. A revision of this standard was approved in 2022, which increases the voltage limit to 1,000 VDC, which adds the option for active cooling and dynamic current reduction to reduce the risk of overtemperature failure.

Some other standards that relate to grounding and ground fault concerns include IEC 62196-1 and IEC 62196-1-3 for testing cables and connectors, IEC 60364-5-54 for earthing and protective conductors, and UL 2231 testing requirements for protective systems.

States and local governments have ultimate authority for regulating minimum codes and standards applicable to EV charging installations. Several states have made material improvements to their minimum requirements for new EVSE installations. For example, the state of California's guidebook for new DC EVSE installation permits[15] covers a range of standards requirements, including compliance with the California Electric Code, SAE connector standards, and testing of EVSE to UL standards.

At the federal level, there is ongoing work being done to assist consumers and installers with making procurement decisions, including guidance from the Consumer Product Safety Commission[16] and via updates to the U.S. Environmental Protection Agency's ENERGY STAR program.[17] ENERGY STAR certification requirements include safety-related tests conducted by a nationally recognized testing laboratory. ENERGY STAR has limited testing requirements for DC EVSE.[18]

As established earlier in this report, the safety of the charging system requires coordination between EV and EVSE fault protection and safety standards. On EV side of the safety standards landscape, there is significantly more variation of procurement requirements and most of the stakeholders determined that the safety standards and testing requirements they expect from their vendors are proprietary. Instead, this report will focus on the safety standards enforced by the National Highway Traffic Safety Administration (NHTSA), which has a mandate to enhance the safety standards for EVs by law.

4.1 Federal Motor Vehicle Safety Standards

Federal Motor Vehicle Safety Standards (FMVSS) No. 305 (aligned with United Nations Global Technical Regulation No. 13) outlines requirements to prevent electrolyte spillage and electrical shock during and after crashes and during normal vehicle operation. Focusing on parts of the FMVSS related to electrical safety and fire risk reduction and isolation of high-voltage sources, the standard specifies onboard DC high-voltage assemblies must be tested to show isolation of at least 100 ohms/volt. When a vehicle is charging, isolation between the chassis and the high-voltage source must be greater than 500 ohms/volt when disconnected from the external power supply.[19] The FMVSS also specifies test methods to verify compliance, including high-voltage circuits on the vehicle. Figure 13 shows the simplified electrical topology from Section 7.6.3 through Section 7.6.7 of FMVSS. This topology is also used as the basis for isolation test methods.

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[15] https://static.business.ca.gov/wp-content/uploads/2019/12/GoBIZ-EVCharging-Guidebook.pdf
[16] https://www.cpsc.gov/Regulations-Laws--Standards/Voluntary-Standards/Topics/Batteries
[17] ENERGY STAR® program
[18] ENERGY STAR V1.1 DC EVSE Final Test Method.pdf
[19] eCFR :: 49 CFR 571.305 -- Standard No. 305; Electric-powered vehicles: electrolyte spillage and electrical shock protection.

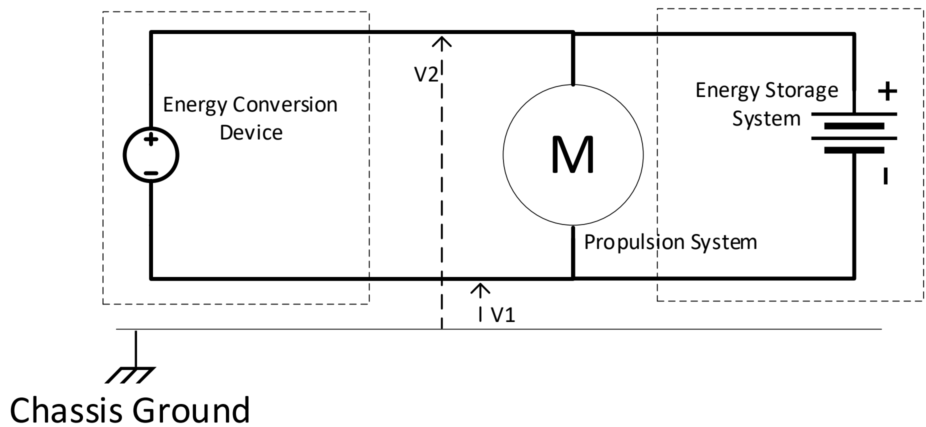

Figure 13: Voltage measurements for high-voltage modules on an EV

The isolation test procedure involves the application of a test resistor between DC supply (+) and chassis ground and between DC return (-) and chassis ground and measuring the perturbation to V2 and V1, respectively. Equation (6) relates the measurement of voltage perturbation (V_2') to the isolation resistance R_i in ohms/volt.

$$R_i = R_o \frac{1 + {V_1}/{V_2}}{(V_2 - V_2')/{V_2'}} \tag{6}$$

Of relevance to the analysis in this report is the application of the test methods in the FMVSS for the case of an EV conductively coupled to a DC EVSE. In other words, this report analyzes whether Equation (6) accurately verifies isolation when the vehicle is connected to electric supply equipment, as illustrated in Figure 14.

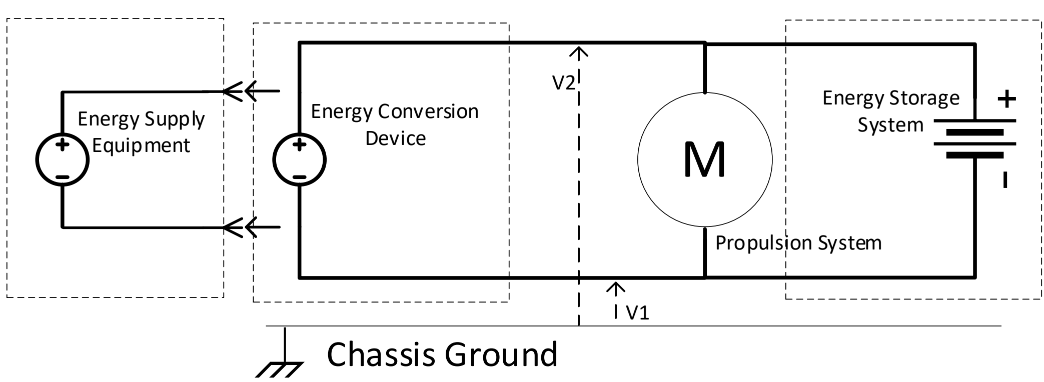

Figure 14: FMVSS isolation test schematic showing the conductive coupling between energy supply equipment and the energy conversion device on an EV

The dashed boundaries represent a modularized component

While a comprehensive analysis of the FMVSS test procedure is beyond the scope of this report, one aspect that can be included is that a DC-DC conversion is needed between the EVSE and the battery circuit. In this scenario, the DC return potential (V1) on the left of the energy conversion device would be different from the potential on the right of the energy conversion device. In such a case, the apparent isolation between modules is a function of the difference of DC return potential at different points in the circuit. This difference can be in the order of 10^2 volts, given DC charging voltages range approximately from 400–900 V. Computing isolation resistance R_i from Equation (6) for varying negative values of V1 reveals (and is depicted in Figure 15) that a corner case is possible in which the isolation between modules could reduce from 100 ohms/volt to 88 ohms/volt when the relative difference in V1 is ~100 volts.

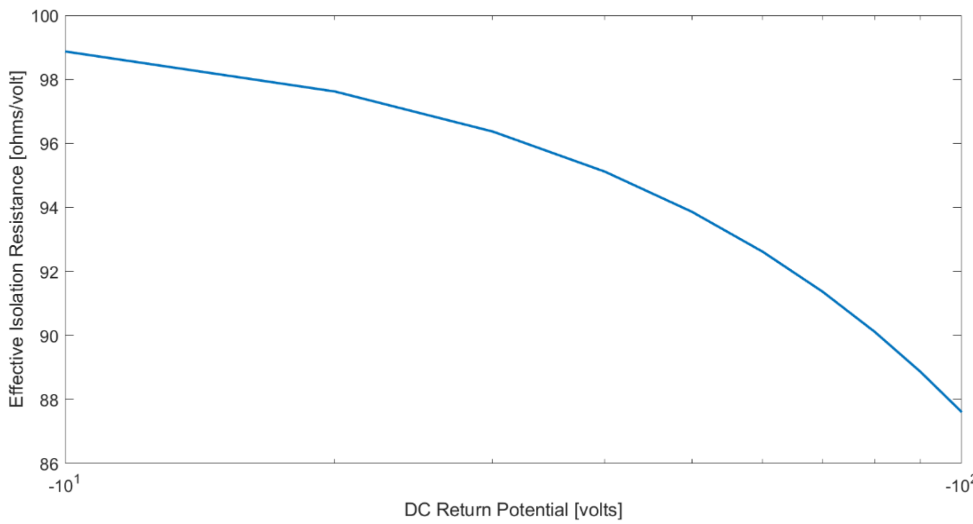

Figure 15: Effective isolation, as computed using Equation (6), expressed as a function of relative differences in DC return potential

The loss of isolation shown in Figure 15 is intended to be illustrative and not conclusive. Its inclusion in this report is to demonstrate a potential avenue for a more comprehensive evaluation of inter-module or inter-subassembly isolation criteria for the integrated EV-EVSE circuit during conductive charging.

4.1.1 FMVSS Update

In April 2024, the NHTSA issued a Notice of Proposed Rulemaking to establish FMVSS No. 305a, “Electric-powered Vehicles: Electric Powertrain Integrity,”[20] to upgrade and replace existing FMVSS No. 305. The proposed FMVSS No. 305a expands on FMVSS 305 in several ways, including introducing additional requirements and test procedures covering new aspects of EV safety, such as the performance and risk mitigation requirements for the propulsion battery, referred to in the standard as

[20] Federal Register: Federal Motor Vehicle Safety Standards; FMVSS No. 305a

the Rechargeable Electrical Energy Storage System (REESS). The update harmonizes U.S. requirements for EVs with the Global Technical Regulation No. 20.[21]

305a proposes new requirements for the REESS to be protected against external short-circuit (bolted) faults and risks such as thermal runaway and electrolyte leakage during normal operations, emergency response scenarios, and cases of water ingress. High-impedance faults are not explicitly identified.

305a also proposes some risk mitigations relevant to charging, such as requiring controls, to prevent overcharging the REESS. For vehicles capable of DC fast charging, the REESS must demonstrate protection from receiving a higher current than specified. In addition, the vehicle's controls should terminate charging if overcurrent is detected. The definition of overcurrent is left to the REESS manufacturer, which creates an opportunity to create a more nuanced and dynamic overcurrent constraint that captures some of the concerns related to high-impedance or multisource faults discussed earlier in this report. 305a also proposes that if the REESS temperature or pressure exceeds manufacturer-defined safe operating limits, charging should be terminated or limited.

This requirement elevates thermal monitoring to a functional safety requirement for EV charging, creating the opportunity to optimize risk at a system level by combining electrical and thermal sensing. In effect, 305a ostensibly recognizes the need for system-level safety strategies that span the traditional boundaries of physical, electrical, and thermal protections reflecting the need for better functional modeling, as illustrated in Figure 7.

5. Structured Fault Analysis

At multiple points, this report has proposed functional system modeling of the coupled EV-EVSE system as a first step to meaningfully reduce the risk of emergent faults. However, this proposal for functional modeling was made without recognizing the challenges in building a model, as shown in Figure 7. The industry experts contacted noted that the architecture for EV charging equipment is not standardized and that there are no efforts to harmonize architecture until procurement language or regulations require them.

While a full system model may not be imminently possible, there are obvious advantages to committing smaller sections of the integrated EV-EVSE system to a standardized architecture. In interactions with industry, there was tepid endorsement of better harmonization of the dispenser and EV circuit shown in Figure 11. Preliminary analysis of faults used as motivation for this report suggests that even limiting the harmonization of the protection architecture and associated component/function terminology between the DC contactors in the EVSE kiosk dispenser and the DC

[21] Global Technical Regulation (GTR) No. 20

contactor/breakers in the battery charging circuit would enable differential diagnosis and structured fault analysis at a level not yet possible.

This section aims to demonstrate the value of structured fault analysis through an illustrative example as justification for driving the standardization of functional architecture between the EV and EVSE and to spur industry consensus on a path to improving diagnosability and system-level risk reduction of overtemperature failures induced by high-impedance electrical faults. The term structured fault analysis covers a range of methods that are applicable risk reduction. The three most relevant to the analysis in this report are as follows:

1. **Failure Modes and Effects Analysis (FMEA):** An inductive method that examines potential failure modes of components and assesses their effects on the entire system. FMEA identifies and prioritizes risks based on their severity, occurrence, and detection ratings. This method of reasoning relies on subject matter experts to qualitatively estimate the impact of a component failure (or n-simultaneous component failures) on the system. FMEAs are valuable in the design and prototype evaluation phase since component expertise can help solve system-level issues. Recently, an FMEA was conducted to identify the failure modes and impacts of EV charging adapters.[22] FMEA was suited to this task since the adapter design was still being developed, and the collection of expert hypotheses was essential to develop a test and certification program that covered a range of electrical, mechanical, and thermal failure modes.

2. **Hazard Analysis (HA) and Fault Hazard Analysis:** While an FMEA purports to address all faults and then score them based on severity, likelihood, and detectability, HA specifically targets certain hazardous conditions by inductively connecting component faults to a specified hazardous outcome. In effect, an HA is an FMEA that focuses on documenting component failure modes that would likely result in a specific hazard of interest. In the work leading up to this report, the authors collected input on performing an HA with industry experts and determined that inductive reasoning to assess the risk of an unmitigated overtemperature failure either collapsed to the conclusion that every major component has a qualitive risk of causing the hazard or that every component would have to protect itself creating seemingly excessive redundancy in the system.

3. **Fault Tree Analysis (FTA) and Event Tree Analysis (ETA):** Unlike the inductive FMEA, an FTA is a deductive strategy that starts with a single failure event (called a top event) and identifies all possible causes leading to that event. Relevant to the terminal fault considered in this report, the FTA process would start with a top event (electrical fault causing unmitigated heating) and work downwards along a tree-like causal structure of faulted components where the branches are connected through Boolean logic. Noting that the EV-EVSE system has unique characteristics, such as overlapping protection zones and the multi-component

[22] https://inl.gov/content/uploads/2023/07/Charge-x-adapter-safety-paper.pdf

failure patterns, the FTA approach is well-suited to help identify root causes. Further, given the phenomenological diversity in the top event (as illustrated in Section 1), the process can begin with a core FTA pattern that can be appended concatenated or modified for each new type of top event encountered in the field. Starting from a core pattern would help us identify common fault sequences across different examples and update component failure probabilities as more examples are collected. Feedback received from industry experts indicate that not all components in a causal path need to be faulted for a fault to propagate through them (power routing modules could conduct fault currents without being faulted themselves). To accommodate this semantic nuance of mode-dependent fault paths, the FTA described in the following subsection does not assign specific failure models to components and so could also be called an ETA.

5.1 Fault Tree Analysis

An FTA can be applied to numerous components, subsystems, and interactions, illustrated in Figure 7, by decomposing the system from a top-level failure event down to its root causes. This clarity is crucial for understanding how individual failures contribute to system-wide risks. Complex systems often experience failures that are the result of multiple, interacting failure modes. An FTA accommodates these complex interactions by using logic gates (e.g., and, or) to combine events and model how different combinations of failures can lead to system-wide issues.

Figure 16 shows an example fault tree in which the top event is an unabated overtemperature failure induced by a high-impedance electrical fault. One step below the top event is a set of subsystem fault conditions (e.g., module isolation faults, connector isolation faults, isolation monitoring logic failures, and an independent fault rate assigned to battery faults using an exponential failure rate model). The root causes (shown as circles in the diagram) are probabilities sampled from Poisson, Binomial, and Exponential probability models to reflect the failure statistics associated with exposure over time, constant probability of malfunction, and lifetime reliability measures, respectively. The choice of which statistical measure was used for each component is purely illustrative for this analysis since these data are not yet available for EV-EVSE systems but can be computed as posterior probabilities using a Bayesian update, as described in Section 5.2.

Figure 16 fully expands the two highest criticality fault paths as noted by experts, which are fault paths corresponding to undetected or unmitigated battery-fed or EVSE-fed fault currents. Both these discharges are assumed to be triggered by a statistical failure in insulation or module. In engineering systems, such failures are commonly represented by a Lambda-Tau short-term reliability measure. This assumption is justified based on feedback that reliability testing programs often focus on component-level reliability, and there is limited knowledge about the aggregate lifetime failure rate of subsystems. Lamba-Tau models provide a good approximation of short-term risks of failure for otherwise well-maintained or regularly inspected components. For more information on statistical failure models, readers are directed to the included reference by Dezfuli (2011).

Figure 16 references three other fault trees (shown as triangular nodes in the figure) corresponding to (1) high-impedance connector fault paths, (2) failures in the isolation detection logic in the EV, and (3) software or logic failures in the IMD used in the EVSE. The fault tree for connector and inlet faults has a flat structure (multi-port OR gate) since all fault sites have seemingly independent probability impact on the top event. Statistics for the failure rate of connectors and lifetime reliability statistics for other specific components (e.g., fuses or sensors) used in the charging system could not be obtained at the time of writing this report. A normalized value has been assumed for all component failures that fit an exponential failure probability model. Similarly, software malfunction rate was modeled as a black-box probabilistic element as there was no information available on the software architecture or functional decomposition of the isolation monitoring algorithms used in EVs or EVSE. A binomial distribution was used for isolation monitoring logic faults to represent a remote but constant rate of logic failure.

Manual calculations of system-wide risks can be overwhelming, but the use of structured graphs with Boolean nodes enables algorithmic calculation of the overall probability of system failure by combining probabilities of individual events. The fault tree structure also enables automated clustering of the critical components or failure modes (minimal cut sets) that are most likely to lead to system failure. This prioritization helps focus resources on mitigating the highest risk areas and balancing mitigation efforts by providing quantitative data to evaluate trade-offs using a probabilistic risk analysis (PRA).

5.2 Probabilistic Risk Analysis

PRA involves quantifying the likelihood of various failure scenarios as well as evaluating the relative benefit of module-level mitigations in reducing the risk of the top event. The mathematical framework starts with identifying prior statistics for the root causes in the fault tree and then systematically updating the probabilities of all upstream nodes in the fault tree by applying the corresponding logical operations (i.e., $P[A] \times P[B]$ for an AND gate and $P[A] + P[B] - P[A] \times P[B]$ for an OR gate). Ultimately, the framework computes chained probabilities for all fault paths (or scenarios) to the top event. The fault tree in Figure 16 enables the identification of minimal cut sets (minimal or necessary conditions) for a top event and the comparison of the cumulative probability of all faults M_i in each cut set, $P(TF) = P(\cup M_i)$, as a way of finding the most likely fault path. It is then possible to determine criticality of each node in the fault tree based on risk reduction worth $\mathbb{I}(M_i) = \frac{P(M_i)}{P(TF)}$.

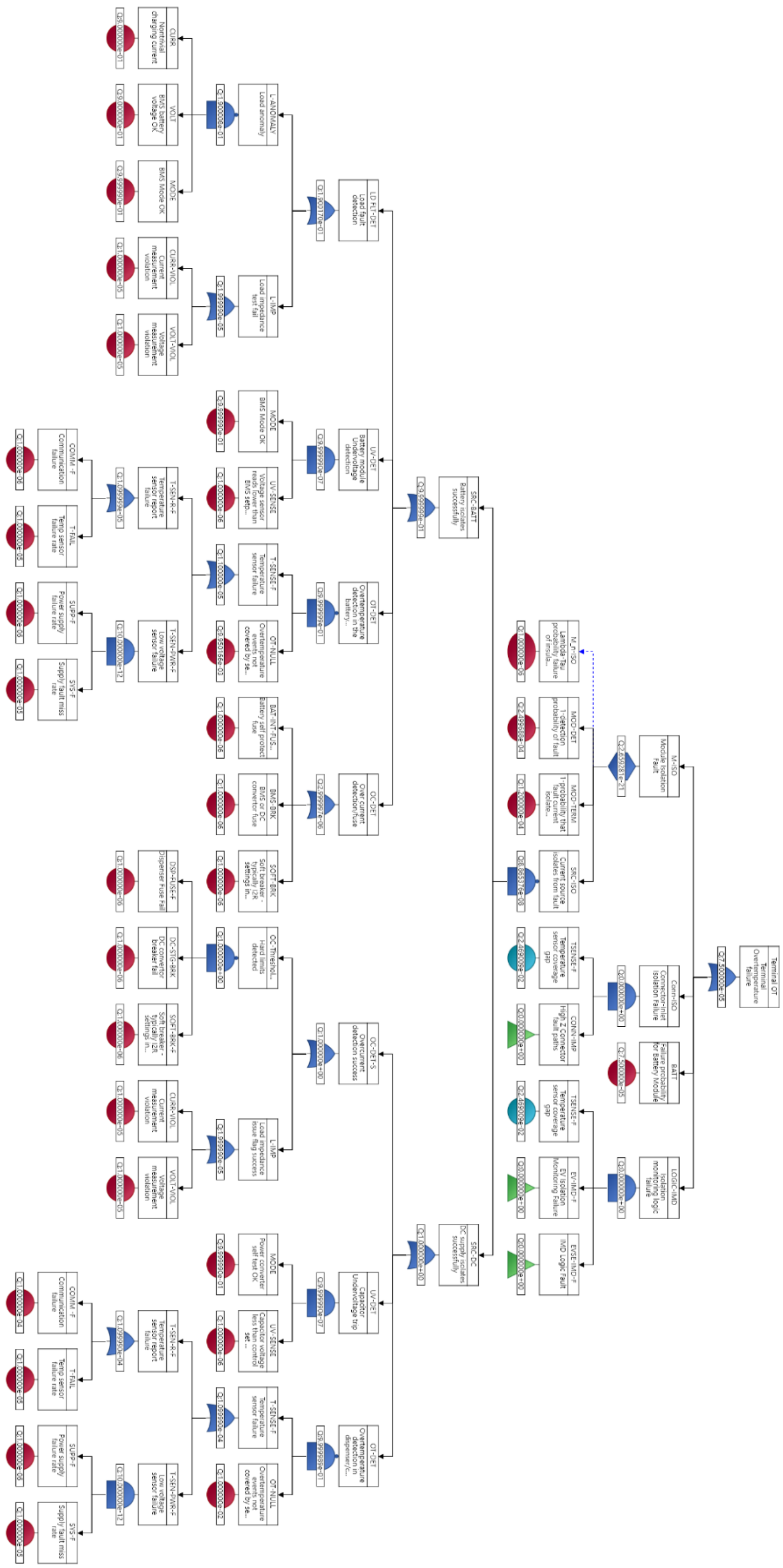

Figure 16: Fault tree for the top-level event of an electrical fault causing a terminal overtemperature event

A strong caveat must be noted that the FTA in this report is purely for illustrative purposes since the probabilities for most components were assumptions and the structure of the fault tree, while informed by input from several expert sources, is synthetic and abstracted. PRA of the tree in Figure 15 provides some preliminary insights—the most critical component to reducing the risk of a terminal overtemperature event is to reduce the failure probability of the temperature sensors in the EV. The next most valuable reliability improvement is to reduce the likelihood of connector faults, followed closely by reducing the fault rate in the isolation monitoring software. The minimal cut set that represents the most risk is the path {T-FAIL.TSEN-R-F.T-SENSE-F.OT-DET}, which is an obvious critical path since both the EV and EVSE share a similar temperature sensing hierarchy in the diagram. Failure of the sensing system increases the risk from all other fault sources. A counterfactual study can also be performed in this diagram to propose inhibition or diagnostic improvements along various paths to investigate where they would offer most risk reduction.

Interestingly, this analysis seems to suggest that more granularity in the mode state reported by the BMS or DC power converter on the EVSE would improve system risk. This is a non-trivial observation and related to the way probabilities are represented for undervoltage tripping in this report. In effect, the analysis highlights the nuance that if the system reports no fault codes but then sees a lower-than-expected voltage on the associated DC output bus, it is assumed there may be a fault somewhere in the circuit, and the fault is arrested. However, if the system reports a fault code, there is no clear indication if that implies the fault has been arrested (power disconnected) or allowed to propagate to a full thermal event. Some industry practitioners provided feedback about the issues they experience with nuisance tripping, and third-party maintenance providers have long advocated for better fault coding. In the context of this industry feedback, even this somewhat simple analysis coincides with industry insight by suggesting that improvements to the quality of fault reports from some modules will help improve the overall safety of the system.

As more data are collected about failure modes and fault probabilities, the system risks computed above can be updated continually using Bayesian inference to update the prior beliefs (the prior probability) with new evidence to provide the posterior probability, $P(\theta|D) = \frac{P(D|\theta)P(\theta)}{P(D)}$.

Where,

- $P(\theta|D)$ is the posterior probability, the updated probability of hypothesis θ (e.g., failure probability) given the data D.
- $P(D|\theta)$ is the likelihood, the probability of observing the data given the hypothesis θ.
- $P(\theta)$ is the prior probability, the initial belief about θ before observing the data.
- $P(D)$ is the marginal likelihood, the total probability of the data across all possible hypotheses.

Based on the probability models listed in Section 5.1 and used in the fault tree in Figure 16, common parametric distributions for priors include the lognormal, gamma, or beta-binomial distributions. Using the beta-binomial model here for illustration, consider the prior distribution of the performance of a circuit breaker to be $Beta(\alpha_{\text{prior}}, \beta_{\text{prior}})$, where α_{prior} and β_{prior} reflect prior knowledge about the number of failures and successes in interrupting a fault current. If new data show x failures in n trials, the posterior distribution is $Beta(\alpha_{\text{post}}, \beta_{\text{post}})$, where: $\alpha_{\text{post}} = \alpha_{\text{prior}} + x$ and $\beta_{\text{post}} = \beta_{\text{prior}} + n - x$. This allows the failure probability estimate to be updated as new data are observed. The mean of the updated (posterior) distribution is given by $\frac{\alpha_{post}}{\alpha_{post}+\beta_{post}}$.

6. Conclusion: Looking Forward to Safer Charging

The findings presented in this report highlight the critical need for a holistic and integrated approach to managing safety in EV charging systems. As EV adoption continues to grow rapidly, driven by both environmental policies and market demands, the risks associated with the interaction between EVs and EVSE become increasingly important. While the overall likelihood of EV fires during charging is statistically low, the potential impact of such incidents—particularly in confined spaces like parking garages—can be severe.

Key lessons from this report point to the complexity of the faults that can occur in the EV-EVSE ecosystem. Capacitor-sourced fault currents, battery-fed electrical shorts, and high-impedance faults are all significant contributors to overtemperature events and can potentially lead to fires. These risks are compounded by the high-power levels involved in modern DC fast chargers, which can trigger large, fast-rising fault currents that existing protection systems may not be fully equipped to handle.

The traditional approach of focusing on individual components, such as the EV battery, is insufficient. The report emphasizes the need for a system-level analysis that views the EV and EVSE as an integrated unit, with multiple points of potential failure that need to be analyzed in relation to one another. By employing FTA and PRA, engineers can identify critical fault paths and develop more comprehensive mitigation strategies. This systems-thinking approach enables designers to reduce overall risk not by focusing on one component alone, but by balancing improvements across the entire charging ecosystem, from the EV, to the charger, to the power cabinet.

Moreover, the report highlights the importance of coordinating protection mechanisms between EVs and EVSE. Fault detection and mitigation strategies should be aligned between the vehicle and the charging infrastructure to prevent cascading failures. This requires harmonizing safety features such as circuit interrupters, ground fault detection, and overcurrent protection. Failure to achieve this coordination could result in delayed detection of critical faults, leading to catastrophic outcomes like fires.

A key recommendation from this report is the need for industry-wide standardization of protection settings, including fault detection thresholds, isolation monitoring, and thermal management. Current standards and protocols, while improving, do not fully address the unique challenges posed by EV fast charging systems. Collaboration between EV manufacturers, EVSE providers, and regulatory bodies will be essential to ensure that safety measures are consistently applied across all makes and models of vehicles and chargers.

Finally, the report advocates for continuous improvement based on real-world data. The feedback loop between field observations, fault diagnostics, and design modifications must be strengthened. As the technology and infrastructure evolve, new fault patterns will emerge, necessitating ongoing updates to risk models and protection schemes. The development of better diagnostic tools, fault codes, and service protocols will enhance the ability of third-party maintenance providers to respond quickly and efficiently to issues as they arise.

In conclusion, as the EV market scales, the need for enhanced safety in charging systems becomes ever more critical. This report provides a foundation for a systems engineering approach to fault analysis and risk mitigation that will not only reduce the likelihood of overtemperature events and fires but also build the resilience of the overall EV charging ecosystem.

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About the ChargeX Consortium

The National Charging Experience Consortium (ChargeX Consortium) is a collaborative effort between Argonne National Laboratory, Idaho National Laboratory, National Renewable Energy Laboratory, electric vehicle charging industry experts, consumer advocates, and other stakeholders. The ChargeX Consortium's mission is to work together to measure and significantly improve public charging reliability and usability by June 2025. For more information, visit chargex.inl.gov.

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