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Hydrogen Fuel Cell Vehicle Electrical Protective Barrier Option:

Fuel System Safety

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16. Abstract

This report presents the results of an assessment of electrical protective barriers as a means of providing electrical safety in the event of a crash. Electrical protective barriers have been proposed as a means to protect occupants, first responders and the public against direct and indirect contact with high-voltage electrical sources in the event of a crash. NHTSA desires to investigate the protective barrier as an option for ensuring electrical safety and to understand failure modes associated with direct and indirect contact. NHTSA also desires to assess test methods for verifying that the electrical protective barriers are providing an adequate level of protection.

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Executive Summary

This report summarizes the results of an assessment and analysis of electrical protective barriers used to support electrical safety in the event of a crash. Electrical protective barriers have been proposed as a means to protect occupants, first responders, and the public against direct and indirect contact with high-voltage electrical sources in the event of a crash. Battelle conducted this effort to support NHTSA's investigation of the protective barrier as an option for ensuring electrical safety and to understand failure modes associated with direct and indirect contact. This effort also supports NHTSA's effort to assess test methods for verifying that the electrical protective barriers are providing an adequate level of protection.

In its comments to the Notice of Proposed Rulemaking (NPRM) to update FMVSS No. 305 that was published on October 9, 2007 (72 FR 57260), the Alliance of Automobile Manufacturers (AAM) requested the allowance of an additional new option for electrical safety, the use of physical barrier to avoid contact with high-voltage sources (NHTSA-2007-28517-0004). The AAM noted that this new option for physical barriers was not proposed in the April 2005 petition for rulemaking and requested that if the agency is unable to proceed directly to a final rule that includes this new option, the agency promptly issue the final rule with the three options in the April 2005 petition for rulemaking (electrical isolation, low voltage, low energy) and publish an NPRM for the physical barrier option for electrical safety. The AAM submitted supplemental comments in June 2009 reiterating its request for the need of a physical barrier option for electrical safety. The AAM stated that the inclusion of the physical barrier option in FMVSS No. 305 would provide for a harmonized standard since the ECE R100 and the Japanese regulations for electric vehicle safety include this option.

The June 14, 2010, final rule did not include a physical barrier compliance option for electrical safety since it was beyond the scope of the rulemaking. In addition, the agency stated in the final rule that it was uncertain whether indirect contact failure modes would be sufficiently accounted for by the physical barrier compliance option and noted that it had initiated a research program to better understand the issues.

In the final rule (76 FR 45436, published on July 29, 2011) responding to petitions for reconsideration of the June 14, 2010, final rule, NHTSA reiterated its position on the physical barrier option and noted that its research on the issue had not been completed. NHTSA stated that it was aware that other countries have adopted a physical barrier option in their regulations for electrical safety, but that does not eliminate the need for the agency to obtain the necessary supporting research to fully understand the consequences of adding this option as a means for providing electrical safety in FMVSS No. 305.

This report provides the findings of a research program funded by NHTSA to better understand the issues related to physical (protective) barriers as a means of providing electrical safety to the motoring public or first responders. This report presents an evaluation of the electrical protective barrier option that is included in the December 2011 Draft Global Technical Regulation on Hydrogen Fueled Vehicles (GTR HFV 2011 DRAFT 2011).

Following is a summary of the key observations and considerations resulting from this investigation as well as gaps identified.

Absence of High Voltage

One of the most fundamental protection measures to prevent electrical shock is to disconnect or isolate high-voltage sources from the electrical bus and chassis. This is commonly achieved through electrical disconnects. Electrical disconnects are indirect safety devices, in that they don't specifically sense an electrical failure, but sense other stimuli that may or may not cause failure, such as decelerations during a crash event. These devices are expected to activate in high speed crashes, but may fail or may not activate due to insufficient deceleration in low-to-moderate speed impacts. While it is expected that high speed impacts are more likely to damage the onboard electrical system and induce more severe damage than low speed impacts, the uncontrolled and unpredictable nature of vehicle crash events prevents ruling out electrical system damage in low-to-moderate speed impacts. Hence, electrical disconnects may not be sufficient by themselves to prevent contact with energized components in all crash conditions. Hence, additional safety precautions, such as electrical isolation, appear prudent to provide redundant protection in the case disconnects are not present on all sources, in event of electrical disconnect failure, or in the case that electrical disconnects do not activate.

Electrical Isolation

Electrical isolation resistance is the composite isolation resistance of all components in the complex vehicle electrical system between high-voltage sources and the chassis and between high-voltage returns and the chassis. The failure modes analysis in Chapter 5 demonstrate that electrical isolation resistance is a fundamental and critical protection that limits current flow through the body in most of the cases of direct and indirect contact with high-voltage sources. In those cases where the body is in series with and protected by sufficient isolation resistance, the isolation resistance is sufficient by itself to ensure body currents are within acceptable thresholds. Isolation resistance can also augment and cover gaps in other protection measures, providing redundancy.

Protective Barriers

While not specifically required in industry standards, electrical protective barriers are a fundamental and necessary component of all high-voltage vehicle systems, preventing direct body contact with high-voltage sources and returns during routine service and maintenance, as well as during and after crash.

Protective barrier enclosures commonly contain multiple high-voltage components. To ensure safety, the components must be electrically isolated from conductive enclosures and barriers. This isolation resistance must be sufficient to ensure currents in contacting bodies are within acceptable thresholds for safety.

Electrical bonding of conductive protective barriers to the vehicle electrical chassis is also a fundamental and necessary component of high-voltage systems, ensuring the potential of exposed surfaces are equal to the vehicle electrical chassis, and providing low resistance path for current in the case of isolation resistance is lost for both voltage source and return.

Need for Electrical Isolation of Protective Barriers

The analysis performed here indicates that protective barriers may not limit currents through a contacting body to acceptable levels without complementary electrical isolation. This applies during service as well as post-crash. Electrical isolation may be necessary in conjunction with conductive barriers to limit currents through the contacting body.

The analysis performed here suggests that diverse imperfections in electrical isolation allows current to flow through a body in contact with conductive protective barriers and the chassis and that they may exceed acceptable thresholds without sufficient electrical isolation. The analysis indicates that conductive protective barriers do not limit body currents to acceptable thresholds in all cases even when bonded to the chassis.

Indirect contact occurs when a body comes in contact with a protective barrier that has lost its internal electrical isolation. Requirements for electrical isolation along with protective barriers are expected to mitigate this hazard.

IPXXB Protection

IPXXB protection defines a consistent criterion for gaps and breaches in protective barriers. Gaps and breaches are permitted by IPXXB protection as long as the articulated finger cannot contact an energized high-voltage source or return. It augments requirements for physical protection, providing a standardized tool and method for verification of physical protection adequacy in preventing direct contact.

IPXXB does not verify the electrical isolation of a protective barrier surface or that current flowing through a body in contact with barrier surfaces are within acceptable levels.

Electrical Chassis Bonding of Protective Barriers for Indirect Contact Protection

In the event of isolation loss within multiple protective barriers such that they become energized, a low resistance electrical path from the barriers through the chassis may activate electrical fuses or current limiting devices, if present, thereby preventing a shock hazard. The analyses performed here indicates that, if isolation is lost within multiple protective barriers and fuses do not activate, the low resistance electrical path from the barriers through the chassis may reduce the current flow through a contacting body, but will not limit current flow through the body to acceptable levels in all cases.

In the indirect contact case of isolation loss within multiple protective barriers, the body is electrically in parallel with the isolation resistance of the source. As discussed in Chapter 6, the current through the body is not limited in the parallel case as it is by isolation resistance in series circuit and does not provide the same level of protection. The body current in a parallel circuit depends upon a number of factors, including the source voltage, the source resistance, the chassis resistance and the body resistance. These factors may be sufficient in some cases to limit body current to acceptable thresholds, but may not be in others.

The analysis shown in Chapter 6 could not confirm that the requirement that a chassis resistance less than or equal to 0.1 Ω is sufficient to ensure that body currents are within acceptable levels in the event of an indirect contact exposure. More information is needed concerning the engineering rationale and basis for this requirement in the standards.

Physical Protection as a Standalone Option

ELSA 2010 Draft and GTR HFV 2011 Draft offer physical protection from direct contact and indirect contact as a standalone option for electrical safety without need for either absence of high voltage or electrical isolation. The analyses performed here cannot confirm that standalone physical protection is sufficient to limit body currents to acceptable thresholds for safety. The analysis indicates that protective barriers do not provide protection equivalent to electrical isolation requirements of 100 Ω/V for DC sources, and 500 Ω/V for AC sources or 500 Ω/V for conductively connected AC-DC buses. This observation applies before crash or damage is induced, as well as post-crash.

As noted above, the analysis performed here indicates that protective barriers may not limit currents through a contacting body to acceptable levels without complementary electrical isolation.

Physical Protection as an Alternative for AC Isolation

In the case of conductively connected AC-DC bus, ELSA 2010 Draft and GTR HFV 2011 Draft propose 100 Ω/V isolation on the connected bus plus physical protection for AC sources as an alternative to 500 Ω/V isolation for the connected bus. The results of this investigation suggest that a barrier protecting an AC source does not limit AC current through a contacting body to the 2mA threshold unless the source has at least 500 Ω/VAC isolation.

Absence of Voltage as an Alternative for AC Isolation

In the case of conductively connected AC-DC bus, ELSA 2010 Draft 2010 and GTR HFV 2011 Drafts propose 100 Ω/V isolation on the connected bus plus absence of high voltage from AC sources as an alternative to 500 Ω/VAC isolation for the connected bus. Absence of voltage from an AC source and/or an AC bus is expected to prevent AC current flow through a body in contact with the source and associated barriers, thereby supporting safety. However, absence of voltage is commonly achieved through electrical disconnects that are expected to activate in high speed crashes. However, they may not be sufficient by themselves to prevent contact with energized components in all cases, such as failure to activate in low-to-moderate speed impacts.

Y Capacitor Discharge

Because vehicles are not electrically connected to an earth ground, the vehicle chassis potential floats with respect to the DC bus voltage, meaning that the chassis voltage magnitude is somewhere between the maximum DC voltage and zero volts ($V_{source} \geq V_{chassis} \geq 0$). The voltage on the chassis with respect to each polarity of the DC bus is dependent on the isolation resistance between each leg of the circuit and the chassis. Consequently, the two Y capacitors will be charged unequally. Following a crash or other shutdown these capacitors discharge through the isolation resistance. The analysis shown here indicates that current through the body from this discharge is limited and protection may be provided by isolation resistance. Y capacitors may be considered similar to other sources for consideration of failure modes in Chapter 5. Similar conclusions with regard to safety protection apply.

1. Introduction and Overview

. Battelle was tasked to support an assessment of electrical protective barriers as a means of providing electrical safety in the event of a crash. Electrical protective barriers have been proposed as a means to protect occupants, first responders and the public against direct and indirect contact with high-voltage electrical sources in the event of a crash. NHTSA desires to investigate the protective barrier as an option for ensuring electrical safety and to understand failure modes associated with direct and indirect contact. NHTSA also desires to assess test methods for verifying that the electrical protective barriers are providing an adequate level of protection.

The introduction of hydrogen fuel cell vehicles (HFCVs) equipped with a pressurized hydrogen container presents new challenges to NHTSA's compliance testing. Previous electrical safety work under this contract focused on compliance testing without hydrogen, leaving the fuel cell in an inactive or de-energized state during and after crash testing. The inactive fuel cell provides the opportunity of using different instrumentation and electrical isolation measurement techniques. This task order focuses on an option for protective barriers of providing electrical safety.

In its comments to the Notice of Proposed Rulemaking (NPRM) to update FMVSS No. 305 that was published on October 9, 2007 (72 FR 57260), the AAM requested the allowance of an additional new option for electrical safety, the use of physical barrier to avoid contact with high-voltage sources (NHTSA-2007-28517-0004). The AAM noted that this new option for physical barriers was not proposed in the April 2005 petition for rulemaking and requested that if the agency is unable to proceed directly to a final rule that includes this new option, the agency promptly issue the final rule with the three options in the April 2005 petition for rulemaking (electrical isolation, low voltage, low energy) and publish an NPRM for the physical barrier option for electrical safety. The AAM submitted supplemental comments in June 2009 reiterating its request for the need of a physical barrier option for electrical safety. The AAM stated that the inclusion of the physical barrier option in FMVSS No. 305 would provide for a harmonized standard since the ECE R100 and the Japanese regulations for electric vehicle safety include this option.

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This report provides the findings of a research program funded by NHTSA to better understand the issues related to physical (protective) barriers as a means of providing electrical safety to the motoring public or first responders. This report presents an evaluation of the electrical protective barrier option that is included in the December 2011 Draft Global Technical Regulation on Hydrogen Fueled Vehicles (GTR HFV 2011 DRAFT 2011).

1.1 Task Order Objectives

The specific objectives of this task order are to:

- Assess the need for the protective barrier option for hydrogen fuel cell vehicles.
- Determine failure modes of the protective barrier associated with shock to vehicle occupants and rescue workers due to direct contact.
- Determine failure modes of the protective barrier associated with shock to vehicle occupants and rescue workers due to indirect contact:
  - When electrical isolation is lost for multiple high-voltage sources within protective barriers.
  - When multiple rescue workers are in contact with different parts of the vehicle and electrical isolation is lost for a high-voltage component.
  - When high-voltage source contacts a protective barrier in a crash thus losing electrical isolation.
- Evaluate the practicability and feasibility of procedures to test for direct contact of high-voltage sources using the IPXXB probe.
- Evaluate the practicability and the feasibility of protective barrier test procedures to ensure that no dangerous potentials are developed within the vehicle and are conducted onto the vehicle chassis.
- Evaluate whether potential indirect contact failure modes are prevented by complying with proposed protective barrier electrical safety requirements.

1.2 Technical Approach

As is elaborated in more detail in Chapter 2, the fundamental question addressed in this investigation is whether the proposed physical protection option is sufficient to prevent ventricular fibrillation of occupants, first responders or the public coming in contact with high-voltage sources, protective barriers, the vehicle chassis or other high-voltage components. The approach taken to address this question included the activities described in the following.

Following initiation of this project, Battelle met with engineering staff experienced on this topic area from AAM members General Motors and Toyota. Battelle conducted separate telephone discussions with knowledgeable staff from Honda. In these discussions, auto manufacturers outlined the technical issues and challenges that they had identified concerning achieving adequate electrical isolation on AC buses on fuel cell vehicles when the DC and AC electrical buses are conductively connected through DC/AC inverters. They further outlined the basis and rationale for proposed electrical protective barriers as an optional means of achieving electrical safety on AC buses and on the entire system.

As it has in other investigations for NHTSA, Battelle used failure modes and effects analysis as a tool to organize and characterize potential failure modes that could affect safety. Battelle used its staff expertise in fuel cell technology to develop the detailed block diagrams of HFCV electrical systems, leveraging past work for NHTSA. From this diagram, Battelle characterized the vehicle power system and the high-voltage sources and components that have protective barriers. Battelle staff then worked through the system, identifying failure modes that could impact safety to the occupants, first responders or the public. This effort focused primarily on hazards wherein a body could come in direct or indirect contact with energized high-voltage sources. Following this assessment, Battelle staff compared the potential failure modes identified to electrical safety requirements in the FMVSS No. 305, ELSA 2010 Draft and GTR HFV 2011 Draft documents. The results of this assessment are summarized in this report in Chapter 7.

Battelle staff reviewed and provided comments on test procedures in the GTR HFV 2011 Draft document. In conjunction with the review, Battelle performed electrical conductivity experiments to provide clarification and support for its analyses, including chassis conductivity testing of 2002 Nissan Sentra as an example of an older vehicle, as well as 2012 Honda Civic Hybrid. The comments and test results are provided in Appendix A. Three crash-tested Chevy Volts located at the NHTSA Vehicle Research Test Center (VRTC) in East Liberty, Ohio, were tested to measure isolation resistances and chassis resistances in various locations on each vehicle. The results of these tests are provided in Appendix B.

A key element of physical protection evaluation is a standardized finger-shaped probe used to assess if live components may be contacted when there is a breach in a protective barrier. Another key element of physical barrier protection is their proposed ability to provide protection during indirect contact by providing a low resistance path for current, reducing the current through the body. These concepts are not necessarily intuitive. Battelle staff developed a demonstration kit that illustrates the function and operation of the finger-shaped probe and illustrates proposed indirect contact protection. Appendix C provides and introduction and overview of the Indirect Contact Protection Demonstration Kit.

1.3 Outline of the Report

This report is organized according to the following outline.

- Introduction and Overview
- Electrical Shock Safety Requirements and Electrical Characterization of the Body
- Summary of Relevant Standards Safety Requirements
- Fuel Cell and Battery Vehicle Electrical System Design Schematics
- Potential Electrical System Safety Failure Modes
    - Electrical Disconnect Failure
    - Protective Barrier Failure Modes
    - AC-DC Bus Conductive Connection
    - Y-capacitor Discharge on an Asymmetric HV Bus
- Analysis of Failure Modes and Protection Measures

- Summary of Assessments, Observations and Considerations
- References
- Appendix A: Review and Comment on GTR HFV 2011 Draft Test Procedures
- Appendix B: Electric Vehicle Isolation and Chassis Resistance Testing
- Appendix C: Indirect Contact Protection Demonstration Kit
- Appendix D: AC Waveforms Induced on a DC Bus by Inverters and Converters

2. Electrical Shock Safety Requirements and Electrical Characterization of the Body

As noted previously, the fundamental question addressed by this investigation is whether the proposed physical protection option is sufficient to prevent ventricular fibrillation of occupants, first responders or the public coming in contact with high-voltage sources, protective barriers, the vehicle chassis or other energized components. The body is an electrical conductor with relatively small resistance. When the body contacts an energized voltage source and return, current will flow through the body. The resulting current through the body may induce physiological effects ranging anywhere from slight pricking sensation to involuntary muscular reactions to cardiac arrest, breathing arrest, and burns. The effects and probability of ventricular fibrillation increase with magnitude of current flow and time through the body.

The International Electrotechnical Commission (IEC) Technical Standard (TS) 60479-1; 2005-07 titled Effects of Current on Human Beings and Livestock (IEC TS 60479-1) provides a comprehensive summary of the effects of electric current on the human body and on livestock, including values of body impedance[1] as a function of key variables. This chapter summarizes key observations from this document and other relevant standards as background for subsequent electrical safety analysis.

2.1 Effects of AC and DC Currents on the Body

Consideration of the safety requirements to prevent ventricular fibrulation in a contacting body begins with Figure 1 and Figure 2 below which are widely used diagrams from IEC TS 60479-1 that define the effects on the human body of current I_B, and duration of current flow. This standard categorizes the effects of DC current into four zones shown in Figure 1:

- DC-1: Slight pricking sensation possible when making, breaking, or rapidly altering current flow;
- DC-2: Involuntary muscular contractions likely especially when making, breaking, or rapidly altering current flow, but usually no harmful electrical physiological effects;
- DC-3: Strong involuntary muscular reactions and reversible disturbances of formation and conduction of impulses in the heart can occur, increasing with current magnitude and time. Usually no organic damage to be expected; and
- DC-4: Patho-physiological effects can occur such as cardiac arrest, breathing arrest, and burns or other cellular damage. Probability of ventricular fibrillation increasing with current magnitude and time.

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[1] Electrical impedance is the measure of the resistance that a circuit presents to the passage of a current when an AC voltage is applied. AC impedance possesses both magnitude and phase while DC resistance has only magnitude. For the purposes of this investigation both are measured in units of ohms (Ω)

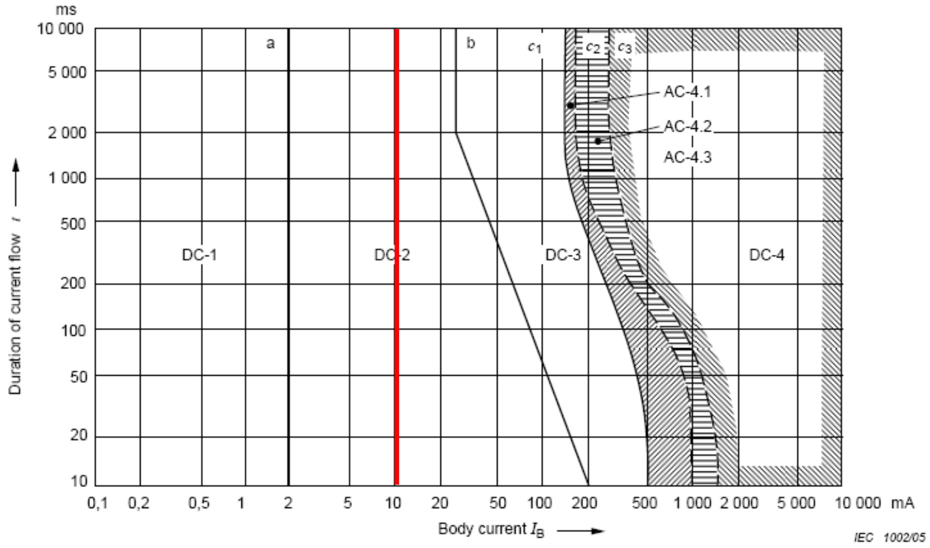


Figure 1. Conventional time/current zones of effects of DC currents on people
(Figure 22 from IEC TS 60479-1) (Red line added representing 10mA safety criterion)

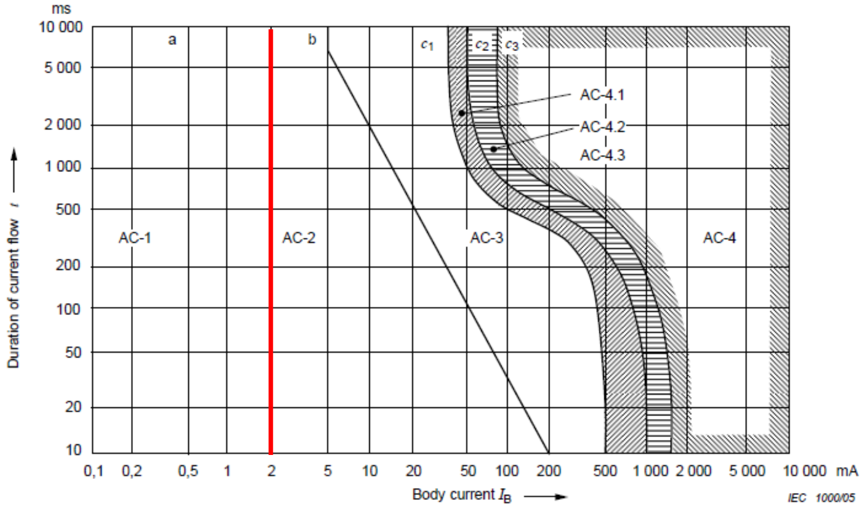


Figure 2. Conventional time/current zones of effects of AC currents (15 Hz to 100 Hz) on people
(Figure 20 from IEC TS 60479-1) (Red line added representing 2mA safety criterion).

Figure 2 illustrates similar zones for AC currents. Note that the currents at the boundaries for each of the AC zones are lower than for each DC zone, indicating that AC currents may be more hazardous than the same nominal current level.

The application of this information to vehicle safety requirements is summarized in the Isolation Resistance note in paragraph 7.7.1 from ISO 6469-3 Electrically Propelled Road Vehicles – Safety Specifications, Part 3: Protection of Persons Against Electric Shock (ISO 6469-3) as follows:

> Hazard of electric shock occurs when electric currents depending on value and duration pass through the human body. Harmful effects can be avoided if the current is within Zone DC-2 for DC or Zone AC-2 for AC as shown in IEC/TS 60479-1:2005, Figure 20 and Figure 22, respectively…The isolation resistance requirements of 100 Ω/V for DC and 500 Ω/V for AC allow body currents of 10mA and 2mA respectively.

Red lines have been added to Figure 1 and Figure 2 to represent the safety criteria for maximum body currents of 10mA DC and 2mA AC, respectively.

ISO 6469-3 also defines the two following classes of voltage.

Voltage Class	Maximum Working Voltage	
	VDC	VAC (rms value)
A	$0 < V \leq 60$	$0 < V \leq 30$
B	$60 < V \leq 1{,}500$	$30 < V \leq 1{,}000$

Here Voltage Class A is consistent with the range of voltages specified in FMVSS No. 305 and other standards that may be considered safe and for which high-voltage safety requirements under consideration do not apply. Here Class B voltage is understood to represent the possible voltage range over for which high-voltage safety requirements under consideration apply. While the DC voltage in most electric vehicles is below 800 volts, the entire range up to 1,500 must be considered in analysis.

Hence, the basic requirements for electrical safety used for this investigation are summarized as:

Voltage	$V \leq 60$ VDC $V \leq 30$ VAC
Current	$I_B \leq 10$ milliamps(mA) DC $I_B \leq 2$ milliamps(mA) AC
Isolation Resistance	$R_i \geq 100$ Ω/VDC $R_i \geq 500$ Ω/VAC

These values of voltage, current and isolation are understood to represent conservative thresholds that are unlikely to induce ventricular fibrillation if experienced by a body. IEC TS 60479-1 provides more detailed technical support for these parameters.

Both direct and alternating current are found in high-voltage vehicle systems. While fuel cells and batteries deliver direct current, vehicle traction motors are alternating current devices. Fuel cell and battery electric vehicles use DC/AC inverters to convert DC current to AC current to drive AC traction motors. The speed of AC motors is controlled by the frequency delivered by the inverters. It is noted here that AC frequencies in vehicles vary from zero to thousands of cycles per second (Hertz, Hz).

2.2 Overview of Body Impedance

In later sections of the report, estimates are made of the current flowing through a body for direct and indirect contact with energized electrical components. The body current is a function of the body impedance and other factors. In addition to the effects of current shown above, IEC TS 60479-1 provides a series of tables and graphs that may be used to estimate body impedance. Graphs from IEC TS 60479 show that body impedance is dependent on contact area, person-to-person variance, dry-wet-saltwater environment, voltage, frequency (if AC), and other factors. Figure 3 through Figure 6 below excerpt some of the key plots from the standard to estimate a conservative threshold value for use in subsequent analysis.

First, Figure 3 illustrates body impedance and resistance as a function of voltage. Impedance is over 2,000Ω at approximately 100V or below and decays to approximately 800Ω for 600V and above. The DC resistance is indistinguishable from AC impedance above 200 volts.

Figure 4 compares impedance as a function of contact area for dry conditions. As would be expected, impedance is greater for small contact areas. For large contact areas of the order of 10,000 mm^2, the body impedance decays to less than 1,500Ω at 200V.

Figure 5 illustrates the effects of moisture conditions, showing that impedance decreases as moisture increases with saltwater-wet conditions having the least resistance. Moisture has less influence on body resistance above 400V. Impedance decays to approximately 700Ω at 700V.

Finally, Figure 6 compares the effects of frequency on body impedance, indicating that impedance decays with increasing frequency and increasing voltage. It decays to approximately 600Ω at high voltage and frequency.

In reviewing these results from IEC TS 60479-1, the range of 500Ω to 500,000Ω appears to be a suitable range for estimated body impedance for analyses in this investigation. The lower bound value of 500Ω would represent a most conservative estimate of body resistance, allowing the greatest current through the body for a given voltage.

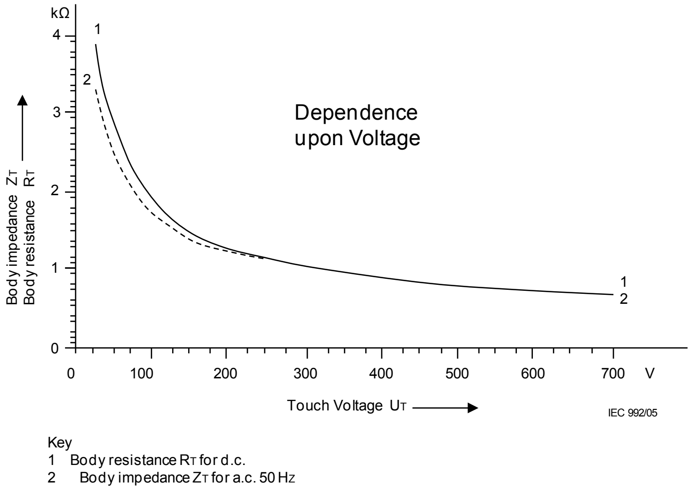
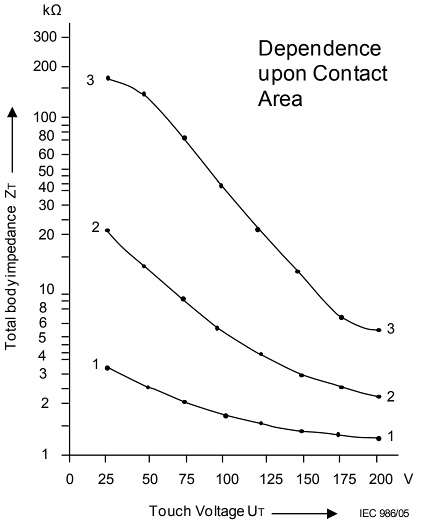
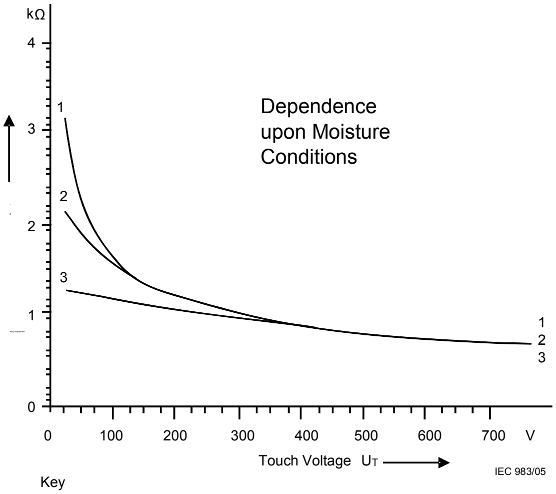


Figure 3. Statistical value of total body impedance Z_T and body resistances R_T for large surface areas of contact, dry conditions for touch voltages up to 700 V, for AC 50/60 Hz and DC (Figure 13 from IEC TS 60479-1).



Key
1 large surface areas of contact, electrodes type A (order of magnitude 10 000 mm²), according to table 1
2 Middle sized surface areas of contact, electrodes type B (order of magnitude 1000 mm²), according to table 5
3 Small surface areas of contact, electrodes type C (order of magnitude 100 mm²), according to table 8

Figure 4. Dependence of the total body impedance Z_T for large, medium and small surface areas of contact in dry conditions (Figure 7 from IEC TS 60479-1).



Key
1 Dry conditions (Table 1)
2 Water-wet conditions (Table 2)
3 Saltwater-wet conditions (Table 3)

Figure 5. Total body Impedances Z_T (50%) for large surface areas of contact in dry, water-wet and saltwater-wet conditions (Figure 4 from IEC TS 60479-1).

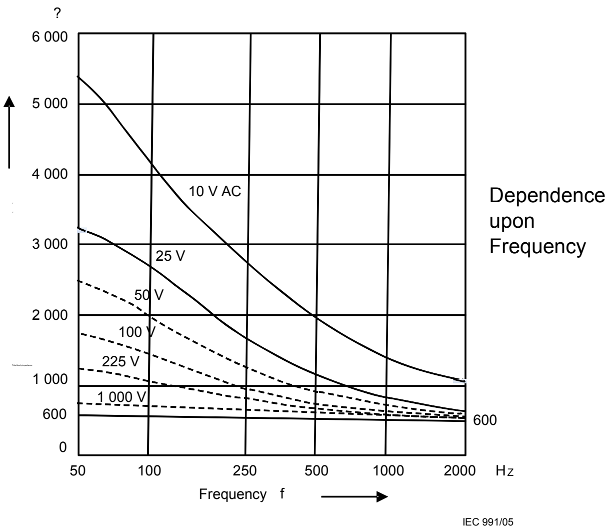
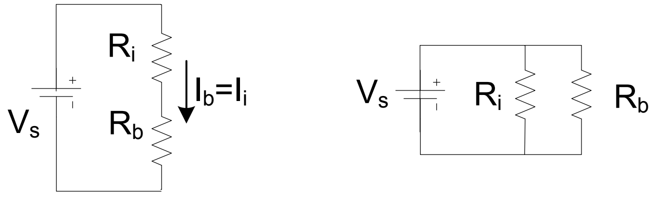


Figure 6. Frequency dependence of the total body impedance ZT for touch voltages from 10V to 1,000V and a frequency range from 50 Hz to 2kHz (Figure 12 from IEC TS 60479-1).

2.3 Electrical Isolation Resistance in Series and Parallel Circuits

Electrical isolation resistance plays an important role in subsequent analyses in this report. Electrical isolation resistance can limit the current flow through a body, providing electrical safety protection. However, the functionality depends upon whether the resistance is electrically in series or in parallel with the body. This behavior is illustrated in the simple circuits in Figure 7. This figure compares two examples of isolation resistance R_i, and body resistance R_b, the left in a series circuit and the right in a parallel circuit.



Isolation and Body Resistance in Series

Isolation and Body Resistance in Parallel

Figure 7. Illustration of isolation and body resistance in series and in parallel

For the isolation and body resistance in series, the current through the two resistors is the same such that

$$I_{series} = I_b = \frac{V_s}{R_i + R_b}$$

For the case where $V_s = 500V$, $R_i = 100\ \Omega/V = 50{,}000\Omega$ and $R_b = 500\Omega$, we observe that $R_i = 100R_b$ so that the isolation resistance is substantially greater than the body resistance. Consequently in this series circuit the isolation resistance limits the body current such that it can be no greater than 10 mA (500V/50,500Ω).

In the parallel case, the voltage across the two resistors is the same such that

$$I_{parallel} = \frac{V_s}{R_i} + \frac{V_s}{R_b}\ ;\ I_b = \frac{V_s}{R_b}$$

Hence, the isolation resistance does not limit the body current in this simple parallel case. For the case of $V_s = 500V$ and $R_b = 500\Omega$, we see that Ib = 1,000mA, well above the safe thresholds for body current.

This simple comparison of series and parallel circuits demonstrates that the location of the body in the vehicle electrical circuit plays a substantial role in the nature of the protection provided by isolation. This is explored in more depth in the failure modes described in Chapter 5 and analyses conducted in Chapter 6.

3. Summary of Relevant Standards Safety Requirements

As noted earlier, the AAM issued a letter on December 10, 2007, requesting a new option for electrical safety be added to FMVSS No. 305, the use of physical barriers to prevent contact with high-voltage sources. This additional option is driven by current hydrogen fuel cell vehicle design in which the high-voltage DC electrical bus is conductively connected to the AC bus through the DC/AC inverter. In the case where the electrical isolation of fuel cells is of the order of 100 Ω/VDC, this conductivity reduces the AC bus isolation below the 500 Ω/VAC safety threshold. The electrical protective barrier option is included in the ELSA 2010 Draft and the GTR HFV 2011 Draft.

This chapter summarizes the safety requirements from FMVSS No. 305, ELSA 2010 Draft and the GTR HFV 2011 Draft to set the stage for subsequent discussions and assessments. There has been substantial work and written discussions in the Federal Register and in the ELSA 2010 Draft 2010 Draft and HF GTR documents since 2007, with many details and nuances as the dialogue has evolved. They are all well summarized in the supplementary information provided by NHTSA in its rulemaking process. This section is not intended to provide a comprehensive overview of these discussions and changes in the standards. Rather this chapter summarizes the key requirements needed for comparisons and analysis in this report.

3.1 FMVSS No. 305 Electrical Safety Provisions

Prior to the 2007 Notice of Proposed Rule Making (NPRM) FMVSS No. 305 required 500 Ω/V electrical isolation between propulsion batteries and the vehicle's electrical conducting structure, following frontal, side, and rear crash tests. The standard has been updated and revised subsequently through the rule making process including the 2007 NPRM, 2010 Final Rule and the 2011 Final Rule, Response to Petitions for Reconsideration. The 2011 Response substantially revised definitions of the electrical system components illustrated in the schematic in Figure 8 to provide more clarity. In the 2011 Response schematic, NHTSA identifies two devices, an energy conversion device and an energy storage device, which, for the purposes of this investigation represent a fuel cell and battery, respectively. NHTSA also recognizes that each of these devices may be part of a "system" that also includes DC/DC converters to step up or step-down the voltage, as appropriate, to transfer energy over the high-voltage bus. Although not called out explicitly in the diagram, these systems transfer energy with each other and with the propulsion system over a high-voltage bus, assumed to be DC. Traction motors for the vehicle are assumed to be AC, and energy is transferred from and to the high-voltage DC bus through DC/AC inverters. More detailed schematic descriptions for fuel cell and battery electric vehicles are provided in Chapter 4 explaining the design and function of vehicle combined high-voltage DC and AC electrical systems.

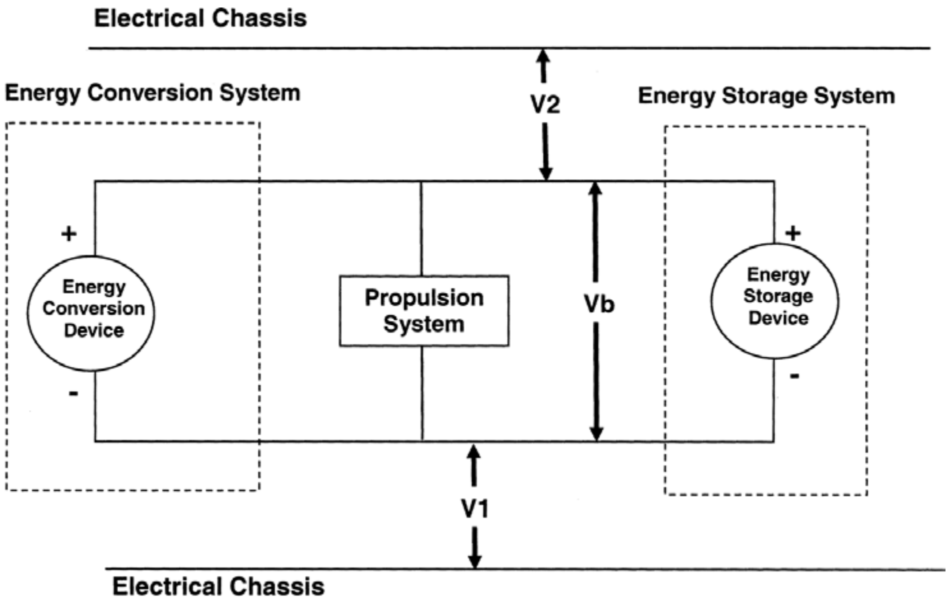


Figure 8. FMVSS No. 305 high-voltage system schematic (NHTSA 2011 Response).

NHTSA provides the following definitions for the terms used in this diagram and elsewhere.

- Automatic disconnect means a device that when triggered, conductively separates a high-voltage source from the electric power train or the rest of the electric power train.
- Electric energy storage device means a high-voltage source that stores energy for vehicle propulsion. This includes, but is not limited to, a high-voltage battery or battery pack, rechargeable energy storage device, and capacitor module.
- Electric energy storage/conversion device means a high-voltage source that stores or converts energy for vehicle propulsion. This includes, but is not limited to, a high-voltage battery or battery pack, fuel cell stack, rechargeable energy storage device, and capacitor module.
- Electric energy storage/conversion system means an assembly of electrical components that stores or converts electrical energy for vehicle propulsion. This includes, but is not limited to, high-voltage batteries or battery packs, fuel cell stacks, rechargeable energy storage systems, capacitor modules, inverters, interconnects, and venting systems.
- Electric power train means an assembly of electrically connected components that includes, but is not limited to, electric energy storage/conversion systems and propulsion systems.

- Electrical chassis means conductive parts of the vehicle whose electrical potential is taken as reference and that are: (1) conductively linked together, and (2) not high-voltage sources during normal vehicle operation.
- Electrical isolation of a high-voltage source in the vehicle means the electrical resistance between the high-voltage source and any of the vehicle's electrical chassis divided by the working voltage of the high-voltage source.
- High-voltage source means any electric component contained in the electric power train or conductively connected to the electric power train that has a working voltage greater than 30 VAC or 60 VDC.
- Propulsion system means an assembly of electric or electro-mechanical components or circuits that propel the vehicle using the energy that is supplied by a high-voltage source. This includes, but is not limited to, electric motors, inverters/converters, electronic controllers, and associated wire harnesses and connectors, and coupling systems for charging rechargeable energy storage systems.

Table 1 summarizes the key electrical safety requirements for this investigation resulting from the NHTSA 2011 Response. As understood in this investigation, following crash, each high-voltage source must meet either the requirement for absence of high voltage or for electrical isolation. Absence of high voltage here requires that $V \leq 60$ VDC and $V \leq 30$ VAC.

Electrical isolation for DC sources must be greater than or equal to 500 Ω/V for a DC high-voltage source without electrical isolation monitoring during vehicle operation or greater than or equal to 100 Ω/V for a DC high-voltage source with electrical isolation monitoring, during vehicle operation. Electrical isolation for AC sources must be greater than or equal to 500 Ω/V for an AC high-voltage source.

An important element of the revised FMVSS No. 305 to note is that the requirement is applied to all "high-voltage sources" defined as any electric component contained in the electric power train or conductively connected to the electric power train that has a working voltage greater than 30 VAC or 60 VDC. Other standards apply their requirements to the high-voltage bus, whose application may not be clear when considering complex interaction between AC and DC buses through electrical inverters and converters.

The revised FMVSS No. 305 also offers the option of complying with either absence of voltage or electrical isolation on a component by component basis, in contrast with other standards that appear to require one or the other for the entire connected AC and DC bus system.

Table 1. Summary of FMVSS No. 305 Electrical Safety Requirements (NHTSA 2011 Response).

	Absence of High Voltage		Electrical Isolation		
DC Sources	Vb, V1 & V2 ≤ 60 VDC	or	Ri ≥ 500 Ω/V for a DC high-voltage source without electrical isolation monitoring during vehicle operation	or	Ri ≥ 100 Ω/V for a DC high-voltage source with electrical isolation monitoring during vehicle operation
AC Sources	Vb, V1 & V2 ≤ 30 VAC	or	Ri ≥ 500 Ω/V		
Notes	Voltages measured according to the procedure specified in S7.7.		Isolation determined in accordance with the procedure specified in S7.6.		Isolation monitoring, in accordance with the requirements of S5.4.

Ri - isolation resistance of high-voltage source

3.2 ELSA 2010 Draft Electrical Safety Provisions

In comparison with Figure 8, Figure 9 shows the high-level system schematic from the ELSA 2010 Draft. The GTR HFV 2011 Draft uses the same diagram as the ELSA 2010 Draft. It is similar in layout to the FMVSS No. 305 schematic, with some differences in labels. ELSA and GTR uses "system" and "assembly" where FMVSS No. 305 uses "device" and "system,," respectively. ELSA and GTR also use the term Rechargeable Energy Storage System (RESS) where FMVSS No. 305 uses Energy Storage System. ELSA and GTR use traction system where FMVSS No. 305 uses propulsion system. ELSA and GTR specifically call out the high-voltage bus, but make no distinction whether it is DC or AC. The diagrams appear comparable, but there appear to be differences in requirement for isolation of the high-voltage bus, versus high-voltage sources, discussed below.

Table 2 below summarizes the key electrical safety requirements for this investigation from the ELSA 2010 Draft Post Crash Safety Provisions. There are three primary options identified in the ELSA 2010 Draft, Absence of High Voltage, Isolation Resistance, and Physical Protection. The Absence of High Voltage Option requires that $V \leq 60$ VDC and $V \leq 30$ VAC within 60 seconds. The third primary option is Physical Protection, which requires that the AC bus meet IPXXB protection for Direct Contact and that chassis resistance $R < 0.1\ \Omega$ or that chassis connection is by welding for indirect contact.

Under the Isolation Resistance Option, there is a single set of isolation resistance requirements for the case of conductively unconnected DC and AC buses. They are $R_i \geq 100\ \Omega$/VDC and $R_i \geq 500\ \Omega$/VAC. There are three options for isolation resistance under conductively connected DC and AC buses. In the first Combined Bus Option, $R_i \geq 500\ \Omega$/V for all sources and buses. In the second and third Combined Bus Option Options, $R_i \geq 100\ \Omega$/V for all sources and buses. The second option has the supplemental requirement that the AC bus meets IPXXB protection for Direct Contact and that chassis resistance $R < 0.1\ \Omega$ or connection by welding for Indirect contact. The third Combined Bus Option has the supplemental requirement that the AC bus meets $V \leq 30$ VAC.

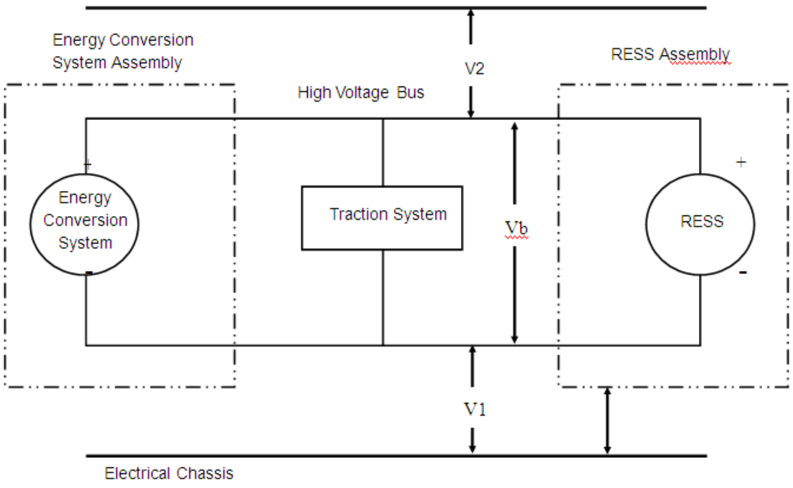


Figure 9. ELSA 2010 Draft and GTR HFV 2011 Draft high-voltage system schematic description.

This draft also includes an optional Low Electrical Energy criterion that may be adopted by contracting parties, that Total Energy < 2.0 Joules and Energy in Y capacitors TEy1, TEy2 < 2.0 Joules.

As described in the ELSA 2010 Draft document, the Physical Protection is a standalone option with no other requirements, just that IPXXB protection is provided for all sources and buses for direct contact safety and that the chassis resistance is below 0.1 Ω for indirect contact safety. There is no limitation on voltage and no requirement for isolation resistance of the sources.

Chapter 5 of this report reviews a series of failure modes for physical protection and isolation resistance identified in this investigation. Chapter 6 analyzes the protection measures to prevent or mitigate the failure modes and Chapter 7 summarizes the assessments, observations and considerations for physical protection and isolation resistance as outlined in Table 2.

3.3 GTR HFV 2011 Draft Safety Provisions

The GTR HFV 2011 Draft is similar to the predecessor ELSA 2010 Draft, but does have some differences. For comparison, Table 3 summarizes the key electrical safety requirements for this investigation from the GTR HFV 2011 Draft. One key difference is that it does not include the Optional Low Electrical Energy Criterion.

Appendix A of this document provides a review and discussion of the test procedure in section 6.3 or the GTR HFV 2011 Draft, along with some considerations for potential enhancement based upon testing conducted in this investigation.

Table 2. Summary of electrical safety provisions for vehicles post-crash, draft agreed during, 8th ELSA meeting, ELSA -8-05 Rev.01.

<table>
<tr><td colspan="14">3-2 Protection Against Electrical Shock General
– After impact at least one of the three criteria in 3-2-1 through 3-2-3 shall be met. 3-2-4 may be adopted by the ´98 Contracting Parties as an additional criteria
– If circuit is automatically disconnected or during driving conditions conductively divided, at least one criterion shall apply to disconnected or each divided circuit</td></tr>
<tr><td rowspan="2"></td><td rowspan="2">3-2-1 Absence of High Voltage</td><td rowspan="4">or</td><td colspan="7">3-2-2 Isolation Resistance
(3-2-2 shall not apply if more than a single potential is not protected under IPXXB)</td><td rowspan="4">or</td><td rowspan="2">3-2-3 Physical Protection</td><td rowspan="5">or</td><td rowspan="4">3-2-4 Low Electrical Energy
Total Energy < 2.0 Joules and
Energy in Y capacitors TEy1, TEy2 < 2.0 Joules</td></tr>
<tr><td>3-2-2-1 Separate DC- or AC- Buses</td><td rowspan="3">or</td><td colspan="5">3-2-2-2 Combined DC- and AC- Buses
Buses shall meet one of the following</td></tr>
<tr><td>DC Bus</td><td>Vb, V1 & V2 ≤ 60 VDC within 60 sec</td><td>Ri ≥ 100 Ω/V for DC buses</td><td>3-2-2-2a
Ri ≥ 500 Ω/V</td><td rowspan="2">or</td><td>3-2-2-2b
Ri ≥ 100 Ω/V</td><td rowspan="2">or</td><td>3-2-2-2c
Ri ≥ 100 Ω/V</td><td>IPXXB protection For Direct Contact and,
for Indirect Contact,
R < 0.1 Ω or
connection by welding</td></tr>
<tr><td>AC Bus</td><td>Vb, V1 & V2 ≤ 30 VAC within 60 sec</td><td>Ri ≥ 500 Ω/V for AC buses</td><td>Ri ≥ 500 Ω/V</td><td>AC Bus meets IPXXB protection For Direct Contact and,
for Indirect Contact,
R < 0.1 Ω or
connection by welding</td><td>AC Bus meets
Vb, V1 & V2 ≤ 30 VAC within 60 sec</td><td>IPXXB protection For Direct Contact and,
for Indirect Contact,
R < 0.1 Ω or
connection by welding</td></tr>
<tr><td>Notes</td><td>(5<measure<60 sec)
If part of the system is not energized during test, protection shall be by either 3-2-2 or 3-2-3</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
</table>

Table 3. Summary of GTR electrical safety provisions for vehicles post-crash.

5.3.2.2. Protection against electric shock (General Provisions)

– After the impact at least one of the three criteria specified in paragraphs 5.3.2.2.1. to 5.3.2.2.3. shall be met.
– If the vehicle has an automatic disconnect function, or devices that conductively divide the electric power train circuit during driving condition, at least one of the following criteria shall apply to the disconnected circuit or to each divided circuit individually after the disconnect function is activated.

	5.3.2.2.1 Absence of High Voltage	or	5.3.2.2.2 Isolation Resistance (5.3.2.2 shall not apply if more than a single potential is not protected under IPXXB)							or	5.3.2.2.2 Physical Protection
			5.3.2.2.2.1 Separate DC- and AC- Buses	or	5.3.2.2.2.1 Combined DC- and AC- Buses Buses shall meet one of the following						
DC Bus	Vb, V1 & V2 ≤ 60 VDC within 60 sec		Ri ≥ 100 Ω/V for DC buses		5.3.2.2.2.1 (a) Ri ≥ 500 Ω/V	or	5.3.2.2.2.1 (b) Ri ≥ 100 Ω/V	or	5.3.2.2.2.1 (c) Ri ≥ 100 Ω/V		IPXXB protection For Direct Contact and, for Indirect Contact, R < 0.1 Ω or connection by welding
AC Bus	Vb, V1 & V2 ≤ 30 VAC within 60 sec		Ri ≥ 500 Ω/V for AC buses		Ri ≥ 500 Ω/V		AC Bus meets IPXXB protection For Direct Contact and, for Indirect Contact, R < 0.1 Ω or connection by welding		AC Bus meets Vb, V1 & V2 ≤ 30 VAC within 60 sec		IPXXB protection For Direct Contact and, for Indirect Contact, R < 0.1 Ω or connection by welding
Notes	Within 60 seconds after the impact as specified in para. 6.3.5. and para. 6.3.5.2.2.		Measurement shall be conducted in accordance with paragraph 6.3.5.2.3. of paragraph 6.3.5.								

3.4 IPXXB Protection Against Direct Contact

Physical protection requirements in the ELSA 2010 Draft and GTR HFV 2011 Draft require IPXXB protection for Direct Contact and for, indirect contact, R < 0.1 Ω or connection by welding. Indirect contact is discussed in detail in Chapter 6 of this report.

IPXXB protection refers to application of a jointed finger test probe, shown in Figure 10, to openings in protective enclosures to determine if live parts may be contacted. The finger is placed in "every possible position" to assess the potential for contact. Verification of contact may be through an electrical signal circuit or visual means. Figure 11 shows a photograph of the finger probe in contact with a circuit board inside an enclosure that is part of the indirect contact Protection Demonstration Kit shown in Appendix C of this report.

IPXXB protection provides a standardized, consistent method for assessing the accessibility of energized components post-crash in cases where a protective barrier has openings by design or is breached.

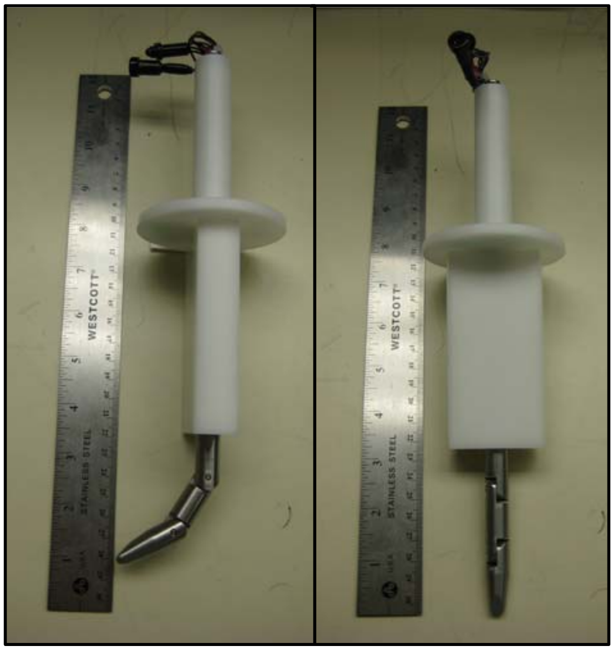


Figure 10. Side and front views of IPXXB finger probe

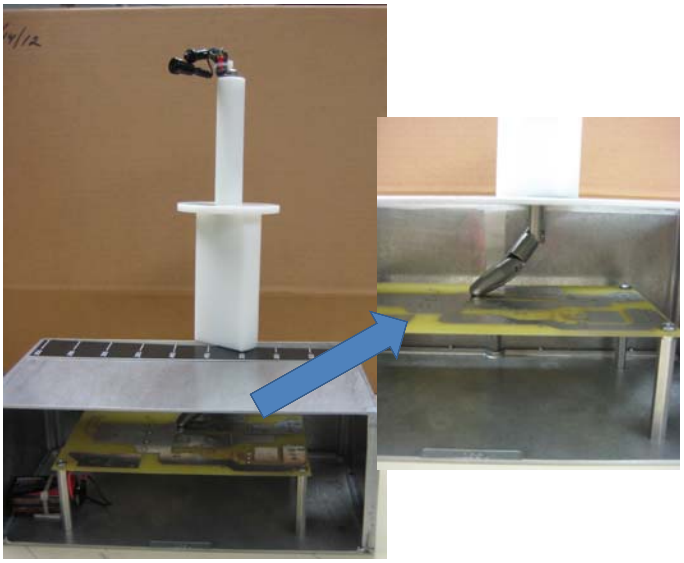


Figure 11. Benchtop demonstration of finger probe contacting energized circuit board through gap in simulated protective enclosure.

4. Fuel Cell and Battery Vehicle Electrical System Design Schematics

This section of the report summarizes electrical system schematics used as the basis for design, safety analysis and discussion in this investigation. This section introduces a high-level system schematic showing the major components and a detailed schematic with DC/DC Converter and DC/AC Inverter Details.

4.1 High-Level Fuel Cell and Electric Vehicle System Schematic

Figure 12 provides a schematic illustration of the electrical system under consideration in this investigation. Table 4 provides a summary description of each of the components in the schematic. This illustration expands upon the simple schematics used in FMVSS 305, ELSA 2010 Draft, and GTR HFV 2011 Draft standards to identify key components that may influence safety, although the major components remain as black boxes here.

High-voltage energy sources considered here include the fuel cell, the high-voltage battery (or batteries) and ultra capacitors. While not used universally, ultra capacitors are in some current systems and are expected to have widespread use in the future. These components are all understood to be DC and they each are expected to have high-voltage disconnects, activated by crash sensors or other external electronics. These DC components may generate current at a voltage different from that of the primary high-voltage electrical bus. Consequently high-voltage DC inverters are used to convert the DC voltage levels used individually to the common voltage level of the high-voltage DC bus used throughout the vehicle electrical system. More details on the design and function of inverters are provided in the next section.

Both the high-voltage battery and the fuel cell are expected to have liquid coolant loops for heating and possibly cooling. This is not generally an electrical issue for batteries because the coolant is isolated fully from the electrical systems, but it is an electrical issue for fuel cells. Isolation is a concern for fuel cell vehicles because the fuel cell coolant contacts conductive surfaces within the fuel cell as well as electrical chassis components in the heater, radiator and pump. While the fuel cell coolant is deionized and initially nonconductive, it accumulates conductive contaminants over time, becoming mildly conductive. As it does so, the coolant can provide a path for leakage currents. The work in the companion study by Kimmel et al on Electrical Isolation Test Procedure Development provides more extensive discussion and analysis of this subject. The limited isolation of a fuel cell and current loop is sufficient to achieve the minimum requirement of 100 Ω/V isolation required for the DC bus, but is not sufficient to support the 500 Ω/V isolation required for AC buses and conductively connected DC and AC buses.

The high-voltage bus is expected to provide power for low voltage components such as lights, audio, braking assist, and power steering assist through a low voltage regulator.

High-voltage electric motors on the vehicle are expected to all be AC. Power is delivered to them through DC/AC inverters. In the case of regenerative braking, traction motors may also deliver power back through the inverter to the high-voltage bus for use by other components and/or for temporary storage. More details on the design and function of DC/AC inverters (and DC/DC converters) is provided in the next section.

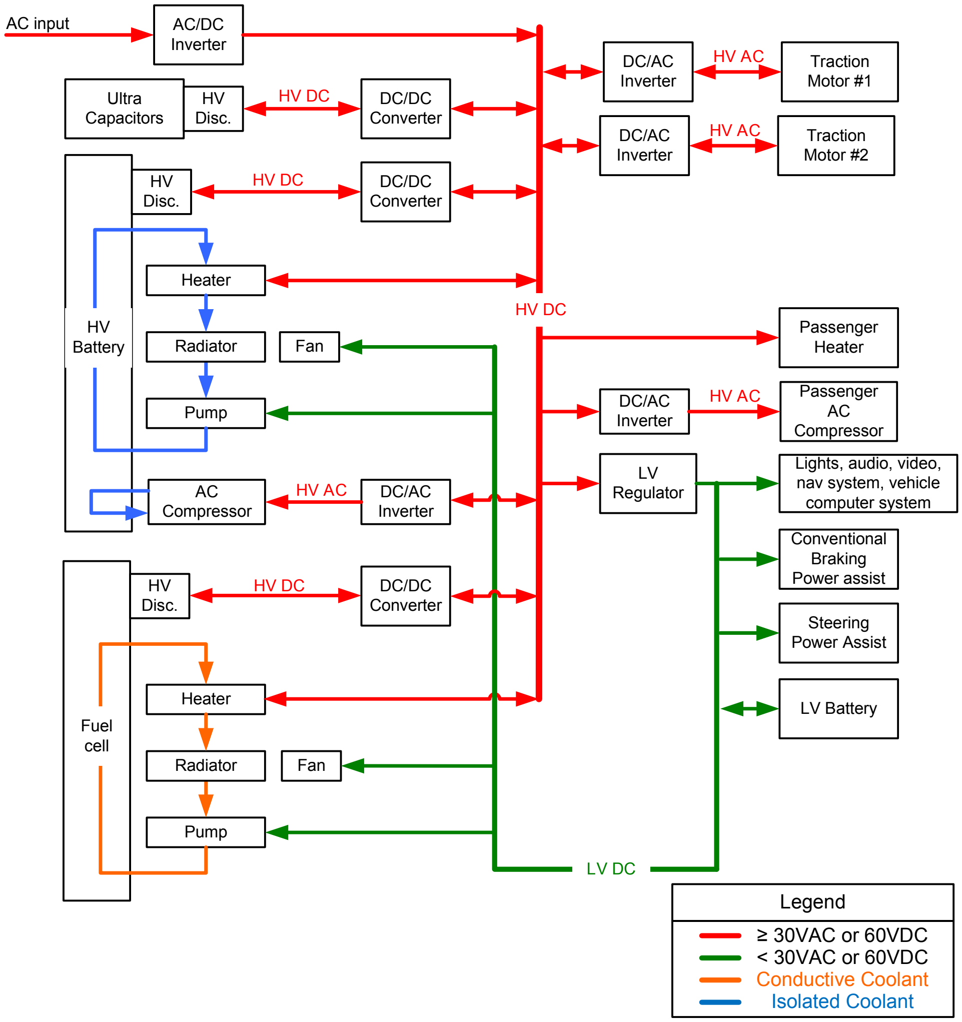


Figure 12. High-level fuel cell and battery vehicle electrical system schematic.

Table 4. Summary description of components in protective barrier assessment high-level system schematic.

Component	Applicable Vehicles	Function
HV Disconnects	All	The HV Disconnects are electrically controlled high-voltage switches that interrupt the high voltage supplied by voltage sources in the event of a vehicle crash.
AC/DC Inverter	Plug-in hybrid, electric	Converts AC main voltage to DC for charging of the high-voltage battery
DC/DC Converter	All	Converts the multiple DC voltage levels used individually by the battery, ultra capacitors, and fuel cell to the common voltage level of the high-voltage DC bus used throughout the vehicle electrical system
Ultra Capacitors	All	Part of the energy storage subsystem. Complements the battery by providing a means for storage and delivery of short, transient pulses of electrical energy during regenerative braking and rapid acceleration.
HV Battery	All	Provides the primary means of electrical energy storage. Provides all traction energy in an electric vehicle. Supplements both the ICE and the HFC, found in hybrid and HFC vehicles, by providing transient energy required during vehicle acceleration.
Fuel Cell	HFCV	Is the source of electrical energy in HFC vehicles. The output capacity of the HFC is designed to provide a continuous, nominal level of energy during vehicle operation. The battery and ultra capacitors supplement the fuel cell by providing additional energy required during transient conditions.
Heater	All	Provides the heating and cooling of the battery and fuel cell.
Radiator/Fan		
Pump		
AC Compressor	All	Provides cooling of the passenger compartment and also provides additional cooling for the high-voltage battery, above and beyond the cooling capacity of the Radiator/Fan.
DC/AC Inverter	All	Converts DC voltage from the high-voltage bus to the AC voltages required by electrical motors.
LV Regulator	All	Converts the high-level voltage of the high-voltage DC bus to a low voltage level used by the low voltage subsystems and accessories.

4.2 Fuel Cell and Electric Vehicle System Schematic With Converter and Inverter Details

Figure 13 provides a more detailed schematic of the system than Figure 12, showing design details added to illustrate the electrical safety concerns resulting from the specific performance characteristics at the inverter and converter component level. Auto manufacturers showed that a more detailed schematic, such as that shown in Figure 13, is needed to capture safety related issues associated with the Insulated Gate Bipolar Transistors (IGBTs) and Y capacitors commonly used in both the DC/DC converters and the DC/AC inverters. Table 5 summarizes the additional components shown in Figure 13.

IGBTs are semiconductor devices that function as electrically controlled switches. At certain points in their cycle, IGBTs provide direct electrical conductive paths between the DC and AC components. As discussed in the next chapter, this prevents separation of the AC and DC buses, further compounding the challenges of achieving adequate isolation resistance on AC buses. Y capacitors are used from the high-voltage bus-to-chassis to filter common mode EMI currents flowing on both the positive and negative rails of the high-voltage DC bus. They may retain energy following a crash event, resulting in a possible shock hazard. The potential contributions of IGBTs and Y capacitors to electrical safety hazards are discussed in Chapter 5.

Table 5. Summary description of components in detailed system schematic.

Component	Number on Figure	Function
Insulated Gate Bipolar Transistor (IGBT)	1	IGBTs are semiconductor devices that function as electrically controlled switches. IGBTs have no moving parts and therefore are capable of operating at high switching speeds. These devices are typically used in AC/DC inverters, DC/DC converters, and DC/AC inverters.
X Capacitor	2	X Capacitors are used from line-to-line to filter differential mode EMI currents flowing between the positive and negative rails of the high-voltage DC bus created during the high speed switching of the IGBTs operating in the voltage converters and inverters.
Y Capacitor	3	Y Capacitors are used from line-to-chassis to filter common mode EMI currents flowing on both the positive and negative rails of the high-voltage DC bus. These currents are created during the high speed switching of the IGBTs operating in the voltage converters and inverters, and they are shunted to chassis via the Y Capacitors.
Transformer	4	A transformer consists of two or more coils magnetically coupled together that provide a means of power transfer from one circuit to another while maintaining galvanic isolation. Galvanic isolation prevents current from one circuit from conducting to another circuit; therefore, the transformer used in the Low Voltage Regulator maintains electrical isolation of the low voltage DC components from the high-voltage DC bus.

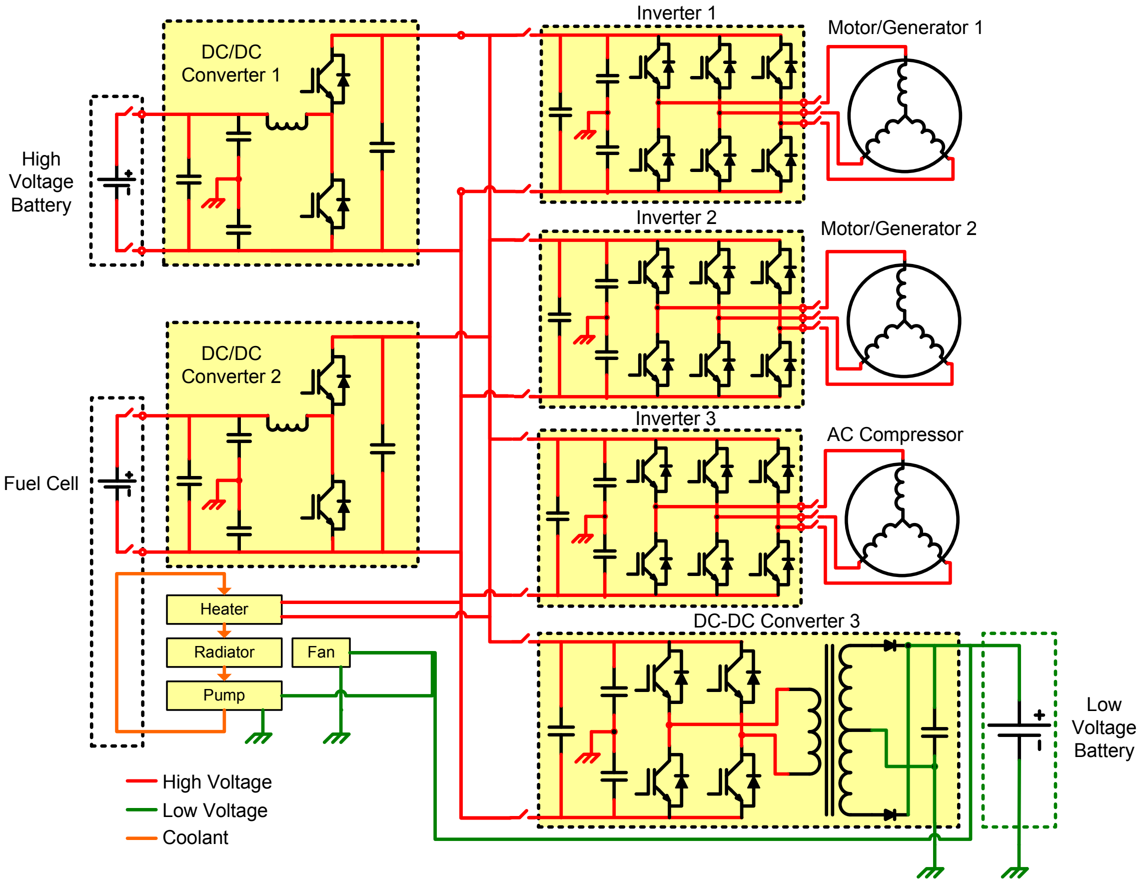


Figure 13. Fuel cell and battery vehicle electrical system schematic with inverter and converter details.

5. Potential Electrical System Safety Failure Modes

This chapter of the report summarizes the potential electrical system safety failure modes identified in this investigation. These are system level failures, involving failure or breakdown in some fashion of multiple components. Assessment of safety measures to prevent or mitigate these failure modes is discussed in Chapter 6. The following failure modes are considered.

- Electrical Disconnect Failure
- Protective Barrier Failure Modes
    - Protective Barrier Failure Modes illustration
    - Electrical Isolation Failure
    - Direct Contact Failure - Protective Barrier Breach or Penetration
    - Indirect Contact Failure – Loss of Internal Electrical Isolation
    - Loss of Chassis Electrical Bonds
- AC-DC Bus Conductive Connection
- Y capacitor Discharge on an Asymmetric HV Bus

5.1 Electrical Disconnect Failure

As illustrated in Figure 12, high-voltage systems have electrical disconnects that open and interrupt the high voltage supplied by sources in the event of a significant vehicle crash. These connects may be contained fully within the high-voltage source or may be exterior to it. High-voltage electrical disconnects are understood to be activated in vehicles by accelerometers similar to (or the same as) those that activate air bags in the event of a crash. These devices are expected to open in high speed crashes, but failure to do so should be considered. The speed and acceleration conditions in which they activate are determined by vehicle manufacturer and suppliers. Manufacturers calibrate electrical disconnects to open in crashes where the electrical system may be damaged, but crashes vary so widely, that consideration should be given to low-to-moderate speed impacts in which the disconnects remain closed.

5.2 Protective Barrier Failure Modes

As described earlier, electrical protective barriers have been proposed as a means to protect occupants, first responders and the public against direct and indirect contact with high-voltage electrical sources in the event of a crash. NHTSA desires to investigate the protective barrier as an option for ensuring electrical safety and to understand failure modes associated with direct and indirect contact.

Electrical protective barriers are a form of physical protection that prevents direct body contact with high-voltage sources or components. This can take the form of insulation on wires or enclosures that prevent occupants and first responders from directly contacting an energized wire or component in the event of a crash. Protective barriers include electrical enclosures that contain high-voltage controls and components such as capacitors and IGBTs. For illustration purposes, Figure 14 shows pictures of an electrical protective barrier and the electronics components contained from a prototype fuel cell vehicle.

Electrical protective barriers may be constructed of conductive or nonconductive material. Metallic enclosures are commonly used for this application to provide mechanical protection from impact, scratch and abrasion and overall durable protection over the life of the vehicle. A variety of electrically insulating materials may be used within the enclosures to prevent high-voltage components from contacting the enclosure.

Figure 14. Example of an electrical protective barrier and the electronics components contained within in a prototype fuel cell vehicle.

5.2.1 Protective Barrier Failure Modes Illustrations

Figure 15 shows the graphic used to illustrate protective barrier failure modes. In this case a high-voltage source is shown on the left, enclosed in a green box representing the protective barrier. For this discussion, the high-voltage source may be either DC or AC and may represent a variety of components such as a fuel cell, battery, traction motor or capacitor. The source delivers electrical current through insulated wires to various circuits contained within protective barriers, shown by the two green boxes on the right. The illustration shows the source and return wiring (positive and negative) lines necessary to complete a circuit. The illustration uses two boxes for illustration purposes, but the source and return may be in the same box. The body is shown contacting the two protective barriers. The electrical resistance or impedance of the body is represented by R_b. Surrounding the circuit illustration is the conductive electrical chassis and vehicle body. The protective barriers are electrically bonded to the electrical chassis, as illustrated by the green “cables.” While small, the chassis has resistance, denoted by R_{ChH}, R_{Ch}, and R_{ChL}. Important additions to this graphic not included by other authors, are the isolation resistances shown as R_{iH} and R_{iL}, connected from the source and return lines from within the source enclosure. These two resistances represent the path of electric current from the source through imperfections in the electrical isolation to the electrical chassis. These represent the isolation resistances measured between the high-voltage sources and the chassis according to FMVSS and other standards. As shown in discussions below, they are critical in understanding and illustrating the functionality and potential failure modes of protective barriers.

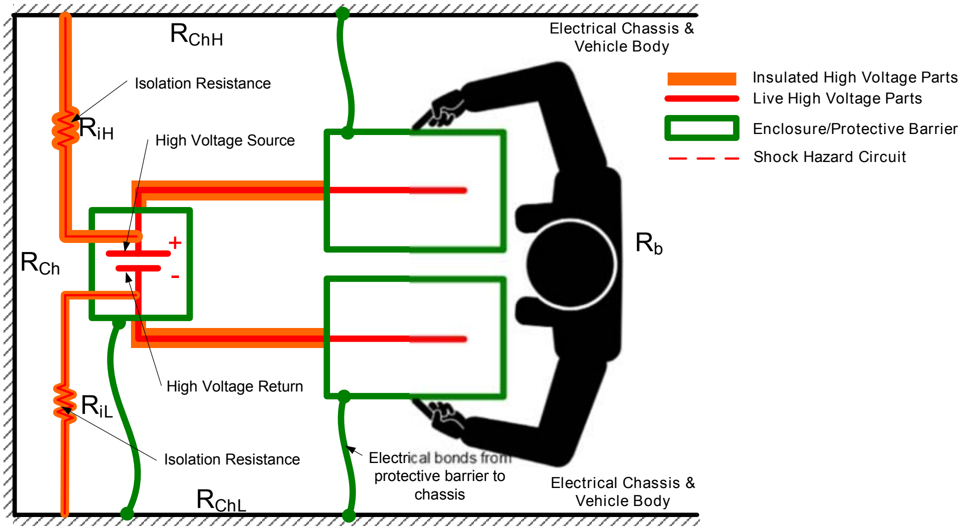


Figure 15. Graphic illustration of body contact with protective barriers.

5.2.2 Electrical Isolation Failure

The first class of failure modes to be considered is electrical isolation failure, illustrated in Table 6. Case 1a in the table shows candidate electrical paths for electrical current as dashed red lines on the graphic from Figure 15 as well as an equivalent electric circuit for a body contacting two protective barriers[2]. Note here that we show a current path through the isolation resistors, the body and the electrical bonds from the barriers to the chassis. Other analyses have assumed that there is no body current in this case, but inclusion of the isolation resistance illustrates that there is a path for current flow through the body. As illustrated by the equivalent circuit, the body is in series with the isolation resistance, and the body and chassis resistances are much less than isolation resistance. In this case the isolation resistances (R_{iH} and R_{iL}) limit the body current. Hence, if total isolation resistance $R_i \geq 100\ \Omega/\text{VDC}$, then $I_b \leq 10$ mA DC and if $R_i \geq 500\ \Omega/\text{VAC}$ then $I_b \leq 2$ mA AC.

Case 1b and 1c in the table examine the cases when electrical isolation, R_{iH} and R_{iL} are lost. In Case 1b, the isolation is lost on either the source or the return. The body still remains in series with electrical isolation on at least one leg of the circuit, limiting the body current. However, in Case 1c, isolation is lost on both legs. As the chassis resistance is low in this case, there is nothing to limit the current through the body.

Case 1c demonstrates that adequate isolation resistance increases the likelihood protective barriers will be effective, even when the barrier is intact internally and externally and connected to the electrical chassis. This example suggests that protective barriers may not be effective unless there is adequate complementary isolation resistance.

For illustration purposes, Case 1c also applies to the case where isolation is present, but does not meet the 500 Ω/V requirement for AC current ($500\ \Omega/\text{VAC} \geq R_i \geq 100\ \Omega/\text{VAC}$). The equivalent

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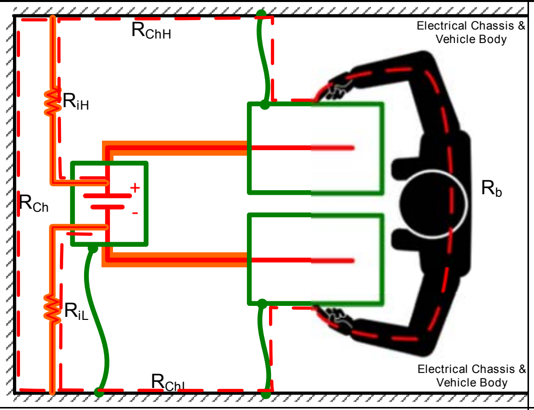
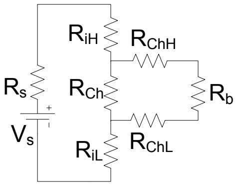
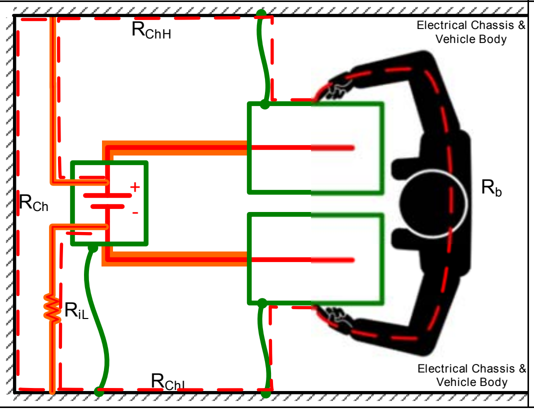
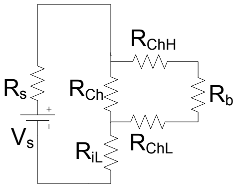
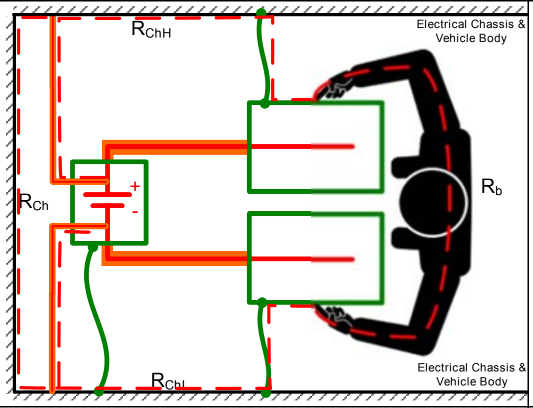
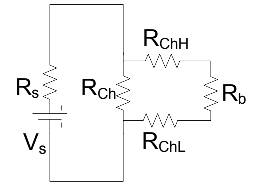
[2] The equivalent circuit includes the source voltage V_s and internal resistance R_s.

circuit for Case 1c suggests that if the available isolation resistance does not satisfy the 500 Ω/V criterion, there is nothing else to prevent the body current from exceeding the 2 mA AC criterion.

Table 6. Illustrations of electrical isolation failure modes.

Case Number and Description	Graphic Illustration	Equivalent Circuit
1a. Contact with Protective Barrier Exteriors and intact Electrical Isolation		 Current through the body is below safety threshold levels if R_{iH} or R_{iL} ≥ 500 Ω/VAC or R_{iH} or R_{iL} ≥ 100 Ω/VDC
1b. Contact with Protective Barrier Exteriors and Lost Isolation on Source or Return		 Current through the body is below safety threshold levels if R_{iL} ≥ 500 Ω/VAC or R_{iL} ≥ 100 Ω/VDC

Case Number and Description	Graphic Illustration	Equivalent Circuit
1c. Contact with Protective Barrier Exteriors and Lost Isolation on Both Source and Return		 Current through the body is not limited by isolation resistance
Assumptions	$R_{iH} \neq R_{iL}$ $R_{iH} >> R_b >> (R_{Ch}, R_{ChH}$ & $R_{ChL})$ $R_{iL} >> R_b >> (R_{Ch}, R_{ChH}$ & $R_{ChL})$	

5.2.3 Direct Contact Failure - Protective Barrier Breach or Penetration

Table 7 illustrates three failure modes in which the protective barrier is breached or penetrated. Certainly protective barrier failure modes in the event of a crash include mechanical failure or penetration of electrical insulation that would allow direct contact with high-voltage sources and returns. This could include fracture and opening of barriers, allowing direct contact by fingers, hands or conductive tools, as well as barrier penetration by conductive elements such as vehicle structural members. As illustrated by the equivalent circuit, the body is in parallel with the isolation resistance, R_i (the lower value of R_{iH} and R_{iL}). Each of these cases assumes that electrical disconnects and other protections within the battery have not activated, either because of insufficient speed or failure of the disconnects. These cases assume the source and return lines are energized and that the body and chassis resistance are much less than the isolation resistance.

Case 2a illustrates direct contact with both a high-voltage source and return. As illustrated by the equivalent circuit, the body is in parallel with the isolation resistance, R_{iH} and R_{iL}. This requires breaching or penetration of a protective barrier, allowing direct electrical contact with each. While the illustration shows finger penetration through the protective barrier, this failure mode could also occur if conductive rods or structural members penetrate protective barriers. Clearly in this case, the body provides the shortest and least resistance path to close the circuit. Here $R_b << R_i$, such that greater current will flow through the body.

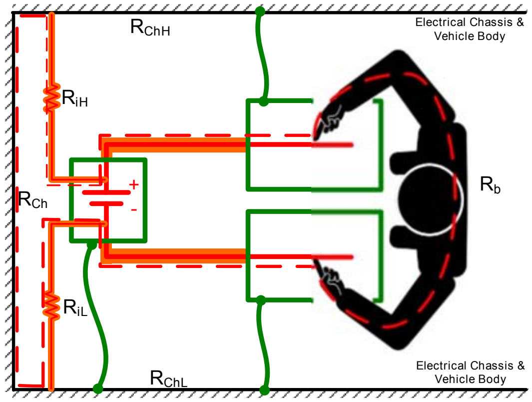
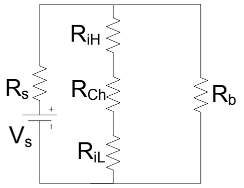
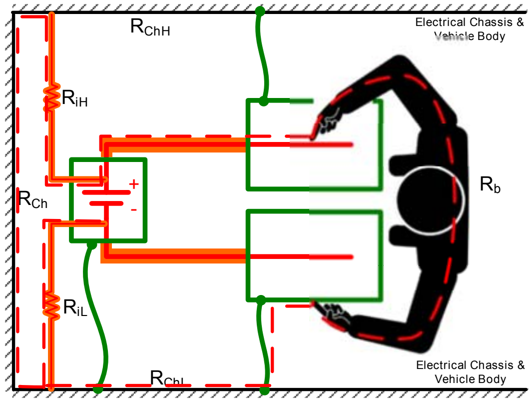
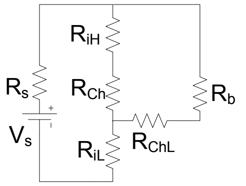
Case 2b illustrates direct contact with high-voltage source or return only. In this case, the source or return is exposed and accessible by a body, but not both. Here the body contacts the source or return and the protective barrier. A simplistic model might suggest that no current flows in this case, but the illustration shows that a current can flow through the isolation resistance, completing a circuit. As illustrated by the equivalent circuit, the body is in series with the isolation resistance, and the body and chassis resistances are much less than isolation resistance.

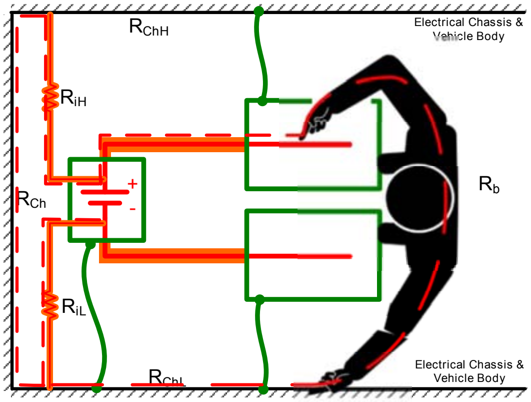
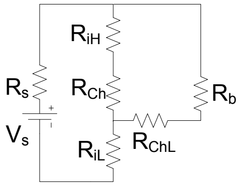
In this case the isolation resistance limits the body current. Hence, if isolation resistance $R_i \geq 100$ Ω/VDC, then $I_b \leq 10$ mA DC and if $R_i \geq 500$ Ω/VAC then $I_b \leq 2$ mA AC.

Case 2c is similar to 2b, but with the body contacting the chassis, rather than the protective barriers. Because the barriers are electrically bonded to the chassis, this is essentially equivalent to Case 2b where protection is provided by electrical isolation. While not shown here, this case can be extended further to the case of the electrical chassis in contact with earth ground and a person contacts the earth and a live wire. Shock protection is provided again by the electrical isolation requirements.

These cases further illustrate that electrical isolation provides protection in conjunction with protective barriers, even when body contacts either the source or the return.

Table 7. Illustrations of protective barrier breach direct contact failure modes.

Case Number and Description	Graphic Illustration	Equivalent Circuit
2a. Direct Contact with High-voltage Source and Return		 Current through the body is not limited by isolation resistance
2b. Direct Contact with High-voltage Source or Return Only and With Protective Barrier Exterior		 Current through the body is below safety threshold levels if $R_{iL} \geq$ 500 Ω/VAC or $R_{iL} \geq$ 100 Ω/VDC

Case Number and Description	Graphic Illustration	Equivalent Circuit
2c. Direct Contact with High-voltage Source or Return Only and With the Electrical Chassis		 Current through the body is below safety threshold levels if $R_{iL} \geq 500\ \Omega/VAC$ or $R_{iL} \geq 100\ \Omega/VDC$

5.2.4 Indirect Contact Failure – Loss of Internal Electrical Isolation

The next series of failure modes in Table 8 below examine modes in which electrical isolation is lost within the protective barrier and the surface of the barrier becomes energized by either the high-voltage source or the return. This analysis assumes that electrical isolation within the high-voltage source itself is maintained, but isolation of high-voltage components within the protective barriers is lost. This series of illustrations shows that failure of isolation within a barrier could be detected through electrical isolation tests.

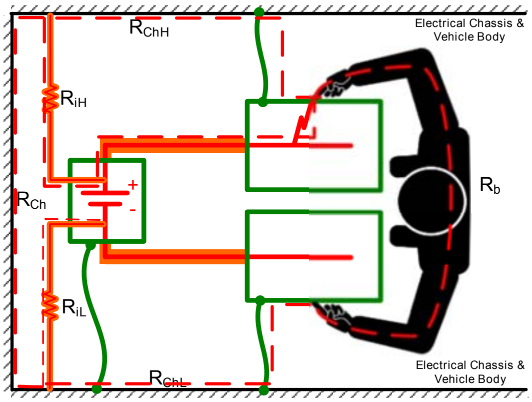
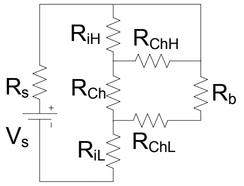
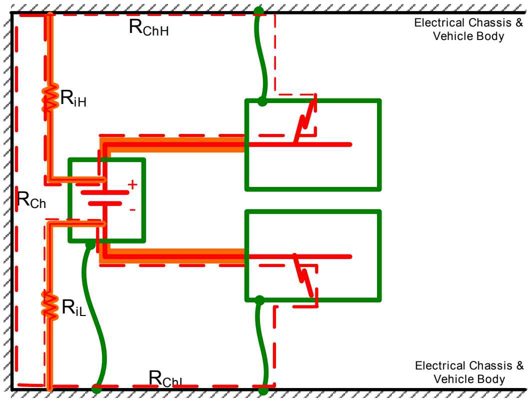
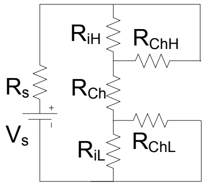
Case 3a is an example in which a body contacts a barrier in which isolation is lost and one in which it is not lost. Similar to Case 2b, a current may flow through the isolation resistance, completing a circuit. As illustrated by the equivalent circuit, the body is in series with the isolation resistance, and the body and chassis resistances are much less than isolation resistance. In this case the isolation resistance limits the body current. Hence, if isolation resistance $R_i \geq 100\ \Omega/VDC$, then $I_b \leq 10$ mA DC and if $R_i \geq 500\ \Omega/VAC$ then $I_b \leq 2$ mA AC.

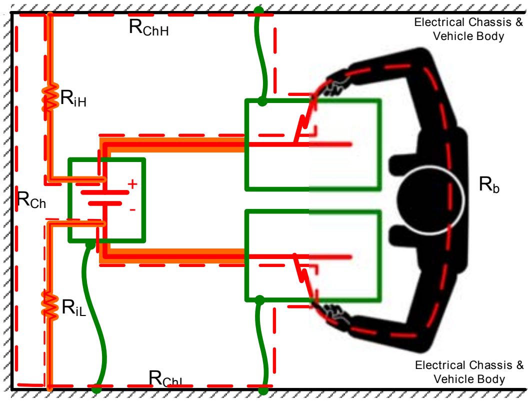
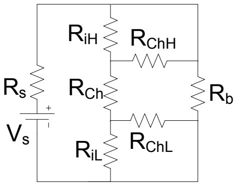
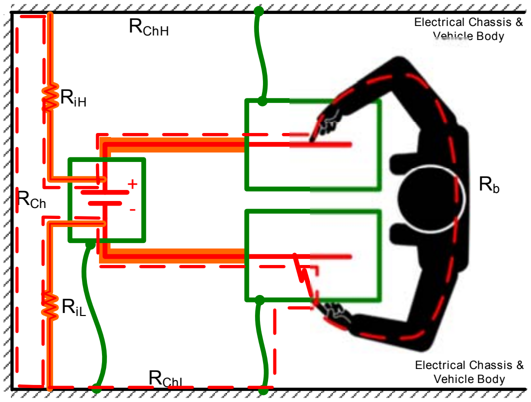
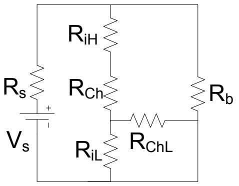
Case 3b1 is the case in which isolation is lost in two protective barriers. Recognizing that R_{Ch}, R_{ChH} and R_{ChL} are all very low values, the graphic illustration and equivalent circuit illustrate that there may be a short circuit condition that would activate and open a fuse, if one were present. Clearly failure of a fuse is a failure mode for consideration. Furthermore, Chapter 6 discusses this circuit in more detail and demonstrates that there are combinations of source resistance and other resistances in the circuit that may prevent the current from reaching levels sufficient to activate a fuse.

Case 3b2 is the variation of Case 3b1 in which a fuse does not activate and a body contacts two energized barriers, one energized by a source and one energized by a return. Here the body is in parallel with the isolation resistance, rather than in series with it. Consequently, the isolation does not limit the current flow through the body. The body current depends upon the relationship between the chassis resistance and the body resistance. This case is considered and analyzed in more detail in Chapter 6.

Case 3c is the combination of direct and indirect contact. Here again, the body is in parallel with the isolation resistance, rather than in series with it and the isolation does not limit the current flow through the body. Again, the body current depends upon the relationship between the chassis resistance and the body resistance. In this case the chassis is in series with the isolation resistance, so the chassis does not experience a current sufficient to activate a fuse.

Table 8. Illustrations of protective barrier isolation failure modes.

Case Number and Description	Graphic Illustration	Equivalent Circuit
3a. Indirect Contact with Source or Return and with Protective Barrier Exterior (isolation failed in one protective barrier)		 Current through the body is below safety threshold levels if $R_{iL} \geq 500\ \Omega$/VAC or $R_{iL} \geq 100\ \Omega$/VDC
3b1. Isolation Failure in Two Protective Barriers Resulting in Short Circuit and Fuse Activation		 Short circuit condition if if R_{ChH} and R_{ChL} are very low.

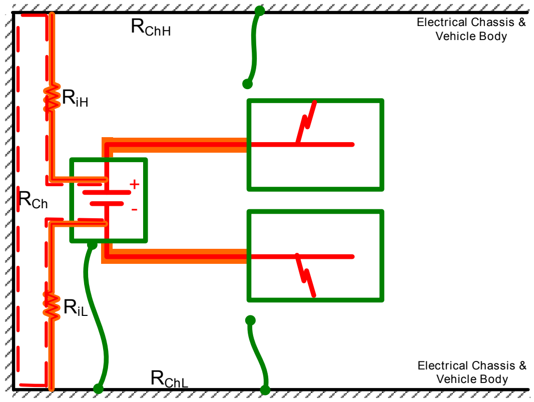
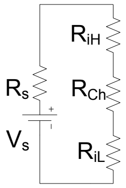
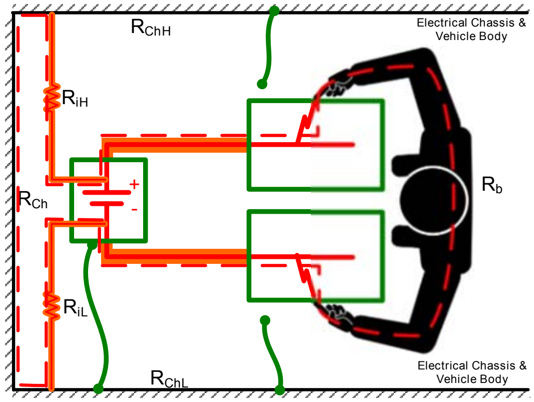
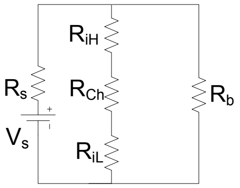
Case Number and Description	Graphic Illustration	Equivalent Circuit
3b2. Indirect Contact with Source and Return (isolation failed in two protective barriers, no fuse)		 Current through the body is not limited by isolation resistance
3c. Direct Contact with source or return and indirect contact with the other (breach of one barrier and isolation failure in other barrier)		 Current through the body is not limited by isolation resistance

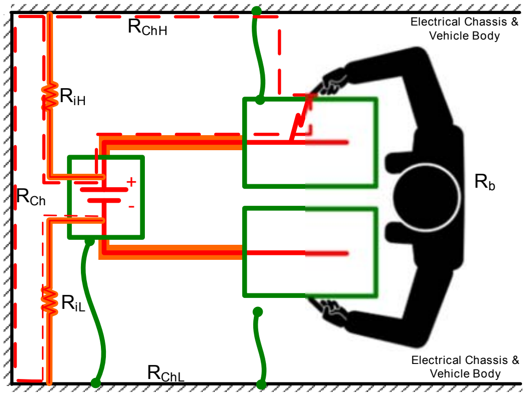
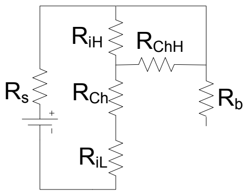
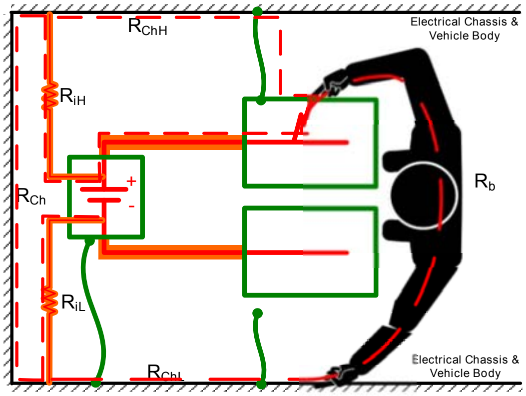
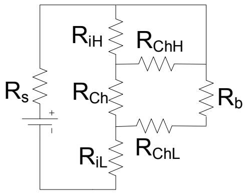
5.2.5 Loss of Chassis Electrical Bonds

Examining the failure mode illustrations above, there is a current path to the body through the electrical bond between the chassis and protective barrier. One might suppose that this suggests that deleting the chassis bond or removing the chassis bond would reduce the likelihood of shock hazard. Table 9 considers Cases 4a1 and 4a2 when chassis bond failures are lost at the same time that isolation is lost within protective barriers (Cases 3b1 and 3b2). In comparing 4a1 and 3b2, there is no short circuit condition that would activate and open a fuse, if one were present. Hence the chassis bond supports other protective measures such as fuses and bond loss prevents the proper functioning of those measures. Comparison of 4a2 and 3b2 shows that, without the chassis bonds, the body is in parallel with the isolation resistances, essentially without any protection from the full voltage of the source. These graphics illustrate that the chassis bond may result in serious hazard in conjunction with loss of isolation. Comparison of Cases 4b1, 4b2 and

3a illustrate the case of isolation loss on one protective barrier and bond loss on the other. While contacting the two protective barriers does not complete a circuit through the body, contact with the chassis become equivalent to contacting a barrier with an intact chassis bond. The current through the body is within safe levels if the chassis isolation resistance remains above the specific levels. If the chassis isolation resistance is not above the specified level, then there can be a shock hazard. The figure suggests that loss of isolation of both the source and return (two failures), whether it is isolation of the protective barriers or isolation of the chassis, can result in a shock hazard.

Table 9. Illustrations of chassis bond failure modes.

Case Number and Description	Graphic Illustration	Equivalent Circuit
4a1. Loss of electrical chassis bonds		 Hazard from loss of electrical isolation and chassis bonds
4a2. Indirect Contact with source and return with loss of electrical chassis bonds		 Current through the body is not limited by isolation resistance

Case Number and Description	Graphic Illustration	Equivalent Circuit
4b1. Indirect Contact with source only with loss of electrical chassis bonds		 Loss of Chassis bond prevents completion of circuit through the body.
4b2. Indirect Contact with source and with chassis		 Current through the body is below safety threshold levels if $R_{iL} \geq 500\ \Omega$/VAC or $R_{iL} \geq 100\ \Omega$/VDC

5.3 Y-Capacitor Discharge on an Asymmetric HV Bus

The high-voltage DC bus in vehicle systems generally refers to the bus across which the inverter is connected. The inverter switches current to the motor to control the speed of the vehicle in electric drive mode. Several capacitors are usually located at the input of the inverter.

The inverter requires a large energy storage capacitor, C_X, that serves as a low impedance source at the input of the inverter. This capacitor is known throughout the industry as the X capacitor. The X capacitor may also serve as the output filter capacitor for the boost converter connected between the battery and the high-voltage DC bus. The terms DC bus filter capacitor and X capacitor are used interchangeably. In addition to the X capacitor, there are two capacitors, C_{Y1} and C_{Y2}, that connect each polarity of the DC bus to chassis. These capacitors are known throughout the industry as Y capacitors. Figure 16 shows the location of the X and Y capacitors.

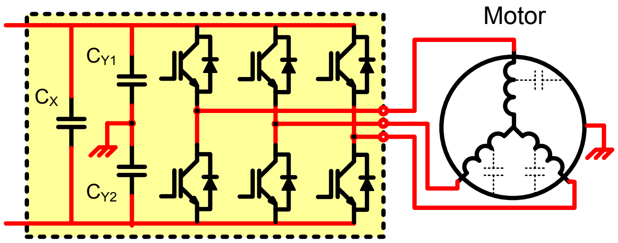


Figure 16. Schematic of the inverter and motor showing respective location of X and Y capacitors[3].

The primary purpose of the Y capacitors is to provide a return path for parasitic AC currents that are generated by the switching transients of the inverter and the parasitic capacitance between the motor windings and the motor housing. These capacitors are shown with dotted lines in the motor portion of Figure 16. By design, the chassis is isolated from the DC bus on the vehicle, but the insertion of the Y capacitors provides an AC connection to the chassis.

The vehicle chassis potential "floats" with respect to the DC bus voltage, meaning that the chassis voltage magnitude is somewhere between the maximum DC voltage and zero volts ($V_{source} \geq V_{chassis} \geq 0$). The voltage on the chassis with respect to each polarity of the DC bus is dependent on the isolation resistance between each leg of the circuit and the chassis. Consequently, the two Y capacitors will be charged to different voltages. Following a crash or other shutdown these capacitors discharge through the isolation resistance. Consider the illustration and equivalent circuit for Y capacitor discharge shown in Table 10. Here we have replaced the source in Case 1a with the Y capacitors (which are a high-voltage source). If $R_{iH} = R_{iL}$, then $V_{chassis} = 0$ and the capacitors are equally charged, meaning $V_{Cy1} = V_{Cy2}$. However, it is more likely that $R_{iH} \neq R_{iL}$ and that $V_{Cy1} \neq V_{Cy2}$. In this case the capacitors must discharge through the isolation resistance and chassis and will discharge through a body in contact with protective barriers as shown. The equivalent circuit shows that, as in Case 1a, the body is in series with the isolation resistance, limiting the current through the body. It is noted that the discharge in this case is DC, suggesting that 100 Ω/VDC isolation resistance criterion would apply.

When considering shock hazards from Y capacitors, they may be considered similar to other high-voltage sources as shown in Table 6, Table 7, and Table 8. The high isolation resistance may limit the discharge rate of Y capacitors. However, the analysis shown here indicates that current through the body is limited by isolation resistance in series.

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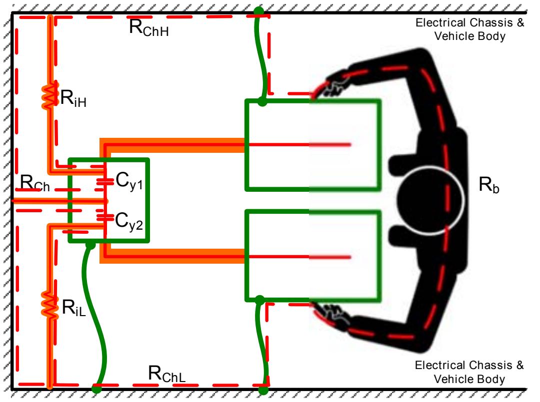
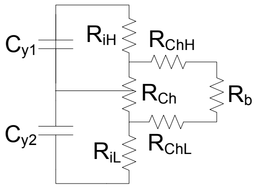
[3] The dotted line capacitors shown in the figure are not Y capacitors, but are a byproduct inherent to the construction of the motor. The capacitance results from the proximity of the windings to the housing.

Table 10. Illustration of Y Capacitor Discharge Paths and Equivalent Circuit

Case Number and Description	Graphic Illustration	Equivalent Circuit
5a. Contact with Protective Barrier Exteriors with Electrical Isolation in the case of Y capacitor Discharge		

5.4 AC-DC Bus Conductive Connection

A conductive connection between the DC and AC buses is an artifact of efficient system design, rather than a failure mode. It is included in this section of the report because it has important implications for electrical isolation of the DC and AC buses.

Electric vehicle propulsion systems rely on inverters to generate variable frequency AC voltage waveforms to control the motor that propels the vehicle. An inverter generally uses several insulated gate bipolar junction transistors (IGBTs) to pulse width modulate (PWM) the DC bus voltage. The IGBTs switch in a sequence that generates a bi-polar PWM voltage, and the current into the motor is filtered by the inherent motor inductance. The inverter electronics are also capable of transferring energy back to the battery if the vehicle has a regenerative braking capability. The circuit topology found in most three-phase inverters is depicted in Figure 17. The current path illustrated by the solid red line shows how the inverter switches DC voltage to the motor. There are six switch configurations that provide DC voltage to the motor. The switches are capable of inverting the voltage from the DC bus with respect to the reference of the motor thereby generating an AC signal. In the circuit in Figure 17, only Switch 1 (S1) and Switch 6 (S6) are gated on, the remainder of the switches are off. It is assumed, that at least one of these circuits is conductive even when the switches are stopped and no AC current is generated, thereby establishing a conductive connection between the DC and AC circuits.

A typical inverter switches the six switches in unique pairs many thousand times a second. This attribute of the inverter is known as the switching frequency. Each time a pair of transistors is switched on, the DC bus is momentarily connected to the AC connections to the motor. This lack of electrical isolation between the DC bus and AC lines is an example of AC to DC impingement.

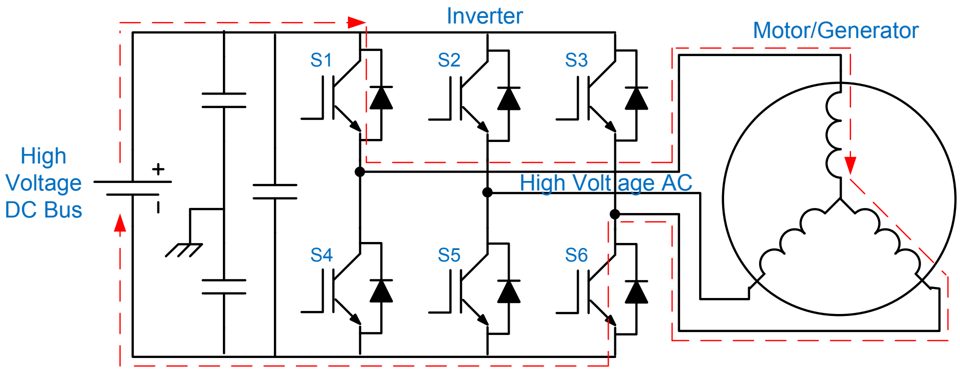


Figure 17. Typical three-phase inverter/motor schematic illustrating bus impingement.

The impingement of one bus onto another is important because AC and DC bus voltages are treated differently with respect to the standard of safety enforced on each bus; however, if there is impingement then it is sensible to assume that each bus must conform to the highest level of safety for either bus. The consequence of this "impingement" is that, if the DC bus cannot achieve 500 Ω/V electrical isolation, such as the case with a fuel cell coolant loop, then the AC bus cannot achieve the necessary 500 Ω/V electrical isolation either.

Another impingement scenario occurs during regenerative braking. During regenerative breaking the energy required to stop the car is transferred by the motor back into the vehicle electrical system. This is accomplished by turning the energy from the moving vehicle into electromagnetic energy via the motor. In essence, the motor becomes a generator that develops a voltage (back electromotor force, emf) from the rotation of the high strength magnets at its core. The voltage pushes current back into the inverter. The inverter then transfers the energy back to the DC bus where it is used to partially recharge the battery. The current path for this regenerated energy depends on the rotor position inside the stator of the motor. As the rotor spins inside the stator of the motor, the same switch pairs that the inverter energizes to connect the DC bus to the motor are in effect turned on via the anti-parallel diode in the IGBT module[4]. This allows current to flow from the motor to the DC bus as illustrated in Figure 18.

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[4] The anti-parallel diode is the term used for the diode intentionally designed into the package with the IGBT. The diode is in parallel with the collector and emitter of the IGB. The term anti-parallel refers to the fact that the polarity of the diode is backwards with respect to the normal flow of current through the IGBT. So normally the IGBT is gated on, current flows from C to E through the device. The diode allows currents developed from the back emf to flow back to the bus as shown in the Figure.

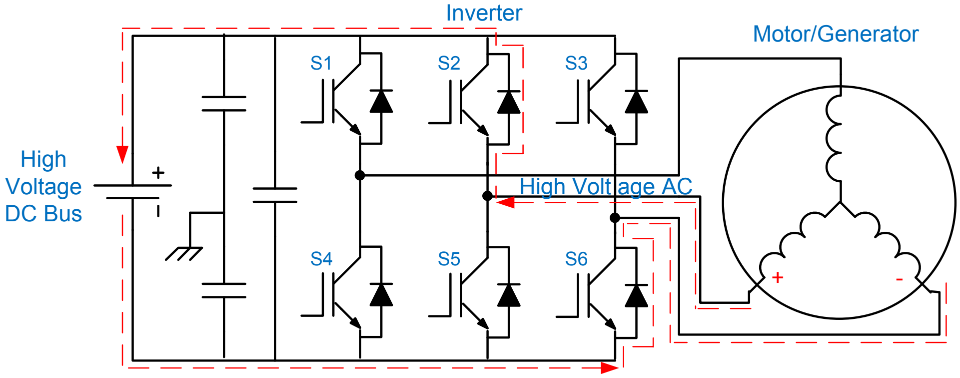


Figure 18. Bus impingement due to regenerative breaking.

5.5 AC Ripple Waveforms on DC Bus

Appendix D summarizes an analysis of DC/DC converters and DC/AC inverters inducing small AC ripple voltages on DC circuits, whose voltage range may be from 1 to 5 percent of the DC voltage, depending upon design. The analysis shows that for very large voltages, up to 1,500 VDC, the AC ripple waveform range could approach 75 V, exceeding the 30V low voltage limit for AC. The energies from these ripple voltages are spread over a range of frequencies. If isolation resistance for 1,500 VDC circuit is 100 Ω/VDC, then the total isolation resistance would be 150,000 Ω. This would then be equivalent to 2,000 Ω/VDC, well above the isolation threshold for AC currents. While a detailed examination of this topic in the technical literature was beyond the scope of this investigation, no evidence was found that ripple waveforms create an incremental safety hazard if the isolation resistance requirements for DC circuits are met.

6. Analysis of Failure Modes and Protection Measures

This chapter compares protection measures from FMVSS No. 305, ELSA 2010 Draft and GTR HFV 2011 Draft identified in Chapter 3 to failure modes identified in Chapter 5. The topics addressed here include

- protection by absence of high voltage,
- electrical isolation,
- protective barriers and direct contact protection, and
- protective barriers and indirect contact protection.

6.1 Protection by Absence of High Voltage

One of the fundamental protection measures to prevent electrical shock is to disconnect or isolate high-voltage sources from the electrical bus. This takes the form of the "Absence of High Voltage" option found in all standards, with the requirement that, for each voltage source, the potential between the source and return, between the source and chassis, and between the return and chassis be less than 30 VAC or 60 VDC. The high-voltage source in this case is defined in FMVSS No. 305 as any electric component contained in the power train or conductively connected to the electric power train that has a working voltage greater than 30 VAC and 60 VDC. This requirement is consistent with the definition of voltage class A in ISO 6469-3.

Absence of high voltage is typically accomplished through electrical disconnects. These disconnects are activated by an external circuit, sensing an external stimuli, such as an accelerometer detecting that a crash impact has exceeded a specific threshold. Electrical disconnects are indirect, in that they don't specifically sense an electrical failure. Rather they sense another stimulus that may or may not cause failure, such as decelerations during a crash event. Their performance depends upon the correlation between stimuli, sensors and actual safety events. These devices are expected to activate in high-speed crashes, but they can fail or may not activate in low- to moderate-speed impacts. While it is expected that higher speed impacts are more likely to damage the onboard electrical system and induce more severe damage, the uncontrolled and unpredictable nature of vehicle crash events prevents ruling out electrical system damage in low-to-moderate speed impacts.

Electrical disconnects are not effective in cases where, either there are no electrical disconnects in the high-voltage source, or if disconnects do not activate. While large energy sources such as batteries and fuel cells are expected to have disconnects, energy storage devices such as X and Y capacitors are examples of devices that do not have electrical disconnects. It is noted that S capacitors discharge very quickly. Y capacitors discharge more slowly, but are lower voltage.

Electrical disconnects are considered to be a good design practice. However, available information discussed above suggests they may not be sufficient by themselves to prevent contact with energized sources in all cases. Hence, additional safety precautions may be considered in when disconnects are not present on all sources, in event of electrical disconnect failure, or in the case that electrical disconnects do not activate.

6.2 Electrical Isolation Protection

Electrical isolation resistance is the composite isolation resistance of all components in the complex vehicle electrical system between high-voltage sources and the chassis and between high-voltage returns and the chassis. Electrical insulation is not perfect and some current does flow through their imperfections, resulting in a measureable isolation resistance. For the electrical contact cases discussed in Chapter 5, electrical isolation is shown as a simple resistance in series with the body, such that the current through the "isolation resistor" is the same as the current through the body. As long as the isolation resistance is sufficiently high (500 Ω/VAC or 100 Ω/VDC according to standards), the current through the body (in series) will be within the acceptable thresholds for body current (2mA AC or 10mA DC).

The failure modes analysis in Chapter 5 demonstrate that electrical isolation resistance is the most fundamental and critical protection that limits current flow through the body in most of the cases of direct and indirect contact. In those cases where the body is in series with and protected by sufficient isolation resistance, then isolation resistance is sufficient by itself to ensure body currents are within acceptable thresholds. Isolation resistance also augments other protection measures, providing redundancy. Isolation resistance may also provide protection in cases where there are gaps, such as the case of low- to moderate-speed impacts when electrical disconnects may not activate.

6.3 Protective Barriers and Direct Contact Protection

Protective barriers are proposed in the ELSA 2010 Draft and the GTR HFV 2011 Draft as standalone electrical protection and as protection for AC bus and sources when electrical isolation is not sufficient. Protective barriers are a form of physical protection that prevents direct body contact with high-voltage sources or components. This can take the form of insulation on wires or enclosures that protect occupants and first responders from directly contacting energized wires or components in the event of a crash. Protective barriers include electrical enclosures that enclose high-voltage controls and components such as capacitors and IGBTs.

Direct contact barrier enclosures may be constructed of conductive or nonconductive material. Metallic enclosures are commonly used for this application to provide mechanical protection from impact, scratch and abrasion and overall durable protection over the life of the vehicle. Insulation is used within the enclosures to prevent high-voltage components from contacting the enclosure. It is considered good design practice in high-voltage systems to electrically bond metallic enclosures to the vehicle electrical chassis to ensure that the chassis and all exposed components are at the same potential.

6.3.1 Direct Contact with Protective Barrier Enclosure Surfaces

One of the basic arguments for safety through protective barriers is that, if all exposed surfaces are at the same potential, no current will flow through a contacting body and there is no potential shock hazard. However, as discussed in Section 5.2.1, this is overly simplified for the case where the isolation resistance is measurable due to myriad imperfections in system isolation. Case 1a in Table 6 illustrates current paths and an equivalent circuit for the more realistic case of small currents through "electrical isolation resistors." Here, the resistance of the chassis, R_{chH} and R_{chL} are lower that the body resistance, R_b. The isolation resistances R_{iH} and R_{iL} are not equal, and are much greater than the body and chassis resistances. In this case, the electrical isolation resistance ensures that the current through the body are within acceptable thresholds.

Case 1c in Table 6 illustrates the case of direct contact with barrier enclosures when isolation resistance is lost or below acceptable criteria. In this case, there is no large resistance in the circuit to limit the current flow through the body. This is an important observation. The direct contact barrier protection may require electrical isolation to limit currents through the body and may not be sufficient by itself to ensure body currents are within acceptable thresholds. This applies to contact with external conductive surfaces of the barriers. The external surfaces of conductive barriers do not provide electrical safety protection without complimentary electrical isolation.

Case 1c also applies to the AC case in which 500 Ω/VAC ≥ R_i ≥ 100 Ω/VAC. If the available isolation resistance does not satisfy the requirement for AC such that R_i ≥ 500 Ω/VAC, then protective barriers do not have a means for limiting the body current to I_b ≤ 2 mA AC.

This assessment suggests that protective barriers may not be an alternative protection measure for AC sources when R_i is below the 500 Ω/VAC threshold.

It is recognized that multiple events are required in order for Case 1c to occur, that is the high-voltage disconnect would have to either fail or not engage, the isolation resistance of the high-voltage source would either have to be lost on both ends or below acceptable criteria on either end, and contact must be made to both body must make contact with both barriers. Considering the unpredictability of events in a crash, the probability of these events occurring simultaneously may be considered acceptable; however, estimating such probabilities was beyond the scope of the current study and cannot be addressed here.

6.3.2 Direct Contact through Breach and Penetration of Protective Barriers

Cases 2a, 2b and 2c in Table 7 illustrate the case of direct contact through protective barriers that are breached or penetrated, allowing direct contact with the source and/or return voltage. These illustrations and equivalent circuits indicate that, as long as only one high-voltage component is contacted, the electrical isolation resistance ensures that the current through the body is limited to acceptable thresholds, if the isolation resistance is sufficient. When both a high-voltage source and return are contacted, the body becomes the path of least resistance and there are no protections to prevent a high body current.

Physical protection requirements in the ELSA 2010 Draft and GTR HFV 2011 Draft require IPXXB protection for Direct Contact. IPXXB protection refers to application of a jointed finger test probe, shown in Figure 10, to openings in protective enclosures to determine if live parts may be contacted. IPXXB protection provides a standardized, consistent method for assessing the accessibility of energized components post-crash in cases where a protective barrier has openings or is breached.

This assessment indicates that electrical isolation may be needed with protective barriers to provide protection in the event of direct contact with either the source or return voltage. Direct contact with both the source and return voltage cannot be mitigated with electrical isolation.

6.3.3 Loss of Isolation within the Enclosures

Cases 3a, 3b1, 3b2 and 3c in Table 8 illustrate the cases wherein electrical isolation is lost within at least one of the protective barriers, allowing the barrier surface to become energized. It is noted that loss of isolation within a barrier also means that the source would fail requirements for electrical isolation.

In Case 3a, electrical bonding to the chassis ensures exposed surfaces are at the same potential, and electrical isolation ensures any currents are within allowable thresholds, if the isolation is sufficient. Even though an enclosure is at the potential of either the source or return, electrical isolation limits the current.

Cases 3b1 and 3b2, represent the protective barrier failure mode of failure of internal insulation in two protective enclosures. This case is the problem of "indirect contact" analyzed in more detail in the next section of the report. Here the isolation resistances are "short-circuited" by the low chassis resistance. If the resistance of the chassis is substantially less than the body resistance, then the body current may be within acceptable thresholds. However, if the chassis resistance is not low enough, there is potential for electrical shock.

Case 3c in Table 8 is the combination of direct and indirect contact. Here the body is in parallel with the isolation resistance, rather than in series with it, and current can flow through the body without being limited by the isolation resistance. This case does not have the low resistance chassis path for current in parallel with the body that exists in Cases 3b1 and 3b2. The chassis currents are limited by the isolation resistance, thereby shifting the current flow through the body.

This assessment indicates that electrical isolation may be needed with protective barriers to provide protection in the event of loss of isolation within one barrier and in the event of indirect contact with either the source or return voltage.

6.4 Protective Barriers and Indirect Contact Protection

This section considers a more detailed examination of the indirect contact problem in which the body is in contact with two protective barriers with lost internal isolation, resulting in a parallel equivalent circuit. The assumption here is that, as long as the chassis resistance is sufficiently lower than the body resistance, the body current will be "safe." A more detailed electrical circuit analysis is needed to understand if this assumption can be confirmed.

The hazard of electric shock through indirect contact occurs through inadvertent contact of a positive high-voltage source to a protective barrier and the inadvertent contact of the negative high-voltage source to a separate, electrically isolated, protective barrier. This scenario is illustrated in the image in Figure 19.

Figure 19 illustrates a person touching two different protective barriers that are electrically isolated from each another. The barrier at the top of the image is shorted to the positive terminal of the power source and barrier on the bottom is shorted to the negative terminal of the power source. The body in this image simultaneously touches each barrier and thereby completes the circuit, causing a shock hazard.

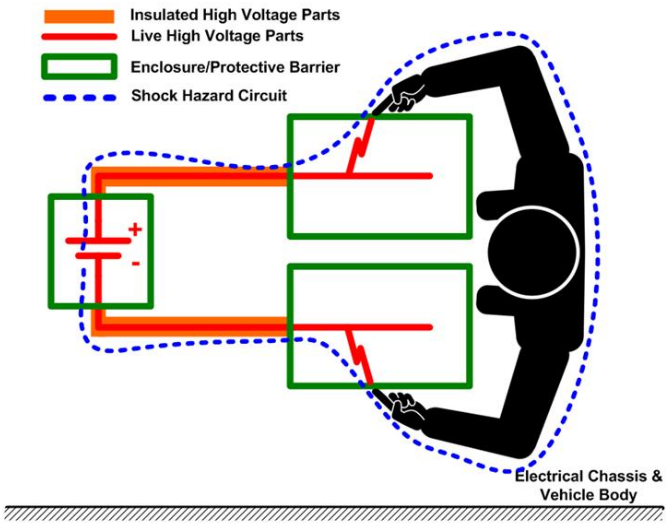


Figure 19. Illustration of indirect contact scenario with no shock protection.

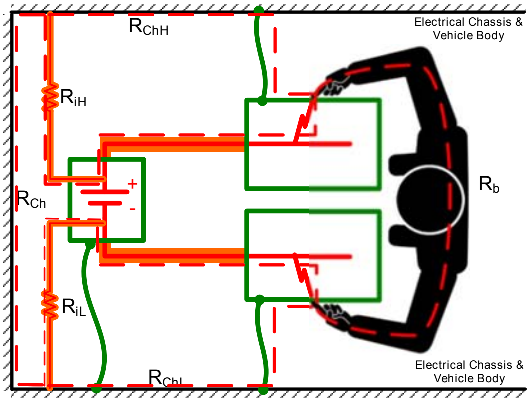
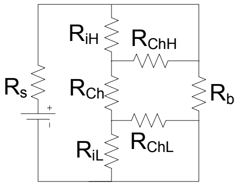
3b2. Indirect Contact with Source and Return (isolation failed in two protective barriers, no fuse)		

Figure 20. Illustration of indirect contact where chassis connection provides shock protection.

For both engineering and safety reasons, protective barriers are typically bonded electrically to a common electrical chassis, along with the vehicle body, as illustrated in Figure 20. This figure illustrates a person touching the same locations as the person in Figure 19. The difference is that little current is expected to flow through the body of the person because the chassis has a much lower resistance than that of the body.

It is assumed that the battery includes protective components such as fuses or a contactor that opens in the presence of high current through the electrical chassis. The low resistance chassis connection provides a means for the protection equipment to quickly detect the short and remove the source from the circuit, thereby protecting the body. In the event that this protection equipment fails or the protection circuit design is inadequate, current may still flow through the person. As discussed further below, however, the current may or may not be sufficient to cause harm, depending upon the vehicle and circumstances.

The current through the body in Figure 20 depends upon a number of factors, particularly the chassis resistance. Depending on the location and type of equipment, vehicle manufacturers bond the protective enclosures to the chassis of the vehicle using contact methods such as:

- Bolts and shared conductive surfaces,
- Bonding straps, and
- Welded joints.

Failure of any of these bonds during a crash would defeat this method of protection.

6.4.1 Equivalent Circuit Analysis for Indirect Contact

The image in Figure 20 can be recast as a simple parallel circuit diagram for use in validating and analyzing this concept further. The circuit diagram is a simplified model that assumes steady state (no transient analysis) in which all circuit elements can be represented using only a resistor (no inductance or capacitance). This circuit is shown in Figure 21.

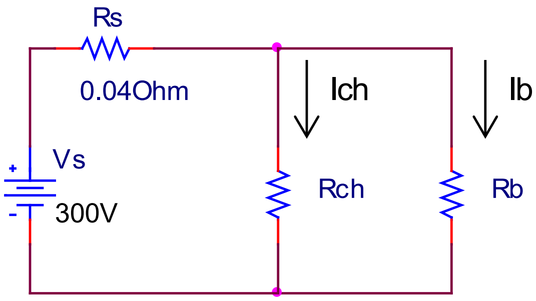


Figure 21. Model of indirect contact with chassis bonding protection.

The “Vs” element in this circuit represents any high-voltage potential that is present in the vehicle, such as a battery or fuel cell. The “Rs” element represents the internal source resistance. The “Rch” element represents the chassis resistance between the points at which the person is touching the chassis. The “Rb” element is the resistance of the body. Ich and Ib represent the current through the chassis and body, respectively. The values of these circuit elements depend on a variety of conditions such as the source type, the locations on the chassis being touched, the environmental and moisture conditions, and the contact area of the skin touching the chassis. Each parameter in the circuit varies depending on these conditions, but, as discussed further below, it is possible to place reasonable limits on the values over which each parameter varies and draw useful observations.

Elementary circuit theory suggests that the body current Ib is not zero. It may be negligible if Rch is significantly lower than Rb, but nevertheless, it is dependent on the parameters:

1. Source Voltage Magnitude, Vs
2. Source Resistance, Rs
3. Chassis Resistance, Rch
4. Body Resistance, Rb

The next section discusses appropriate values for these parameters and is followed by parametric analyses.

6.4.2 Range of Suitable Parameter Values for Analysis

The voltage source Vs is bounded by the definition for high-voltage sources found in ISO 6469-3. As noted earlier, the ranges are 60 to 1,500 DC Volts and 30 to 1,000 AC Volts. The source resistance Rs is dependent on the source type, that is, whether it is a battery or a fuel cell, and the specific design of the source (chemistry, cell configuration, etc.). For the remainder of this section, we assume a battery for the voltage source for illustration purposes. Generally, different battery types are used for different applications such that the source resistance will differ with application. For example, an all-electric vehicle may use a high energy density battery whereas a hybrid might use one that has a high power density. Battery chemistries with a higher discharge capability and power density inherently have lower internal resistance. Conversely batteries with higher energy density and lower power density have a higher internal resistance. Web searches revealed that battery pack internal resistance is typically not a published number. For the purposes of this effort, the source resistance value was estimated for an electric vehicle and that estimation was used to generate a viable range for this resistance.

Values for the other resistances for the parallel circuit model were quantified from the literature. ISO 6469-3 and ELSA 2010 Draft Electrical Safety Provisions specify that the maximum resistance between any two exposed conductive parts that can be touched by a person should not exceed 0.1Ω. IEC TS 60479-1 plots for impedance of bodies demonstrating that body impedance can range between 500Ω and 500kΩ. The plots in IEC TS 60479-1 suggest that body resistance approaches approximately 500Ω for the conditions of interest in this investigation. Lower body resistances are also more conservative for this analysis than higher resistances.

6.4.3 Preliminary Safety Assessment

The equation for body current Ib in the simple parallel circuit in Figure 21 can be expressed as

$$Ib = \frac{Ibatt * Rch}{Rch + Rb}$$

Or as

$$Ib = \frac{Vs * Rch}{Rs * Rch + Rs * Rb + Rch * Rb}$$

Using the aforementioned ranges for each parameter, plots can be developed that show the body current magnitude for a variety of model conditions. Figure 22, a parametric sweep, shows the body current as a function of chassis resistance while the voltage and source resistance are held constant and the body resistance is varied in steps. This results in a family of curves that depict the shock potential for a 300V, 0.04 Ω source.

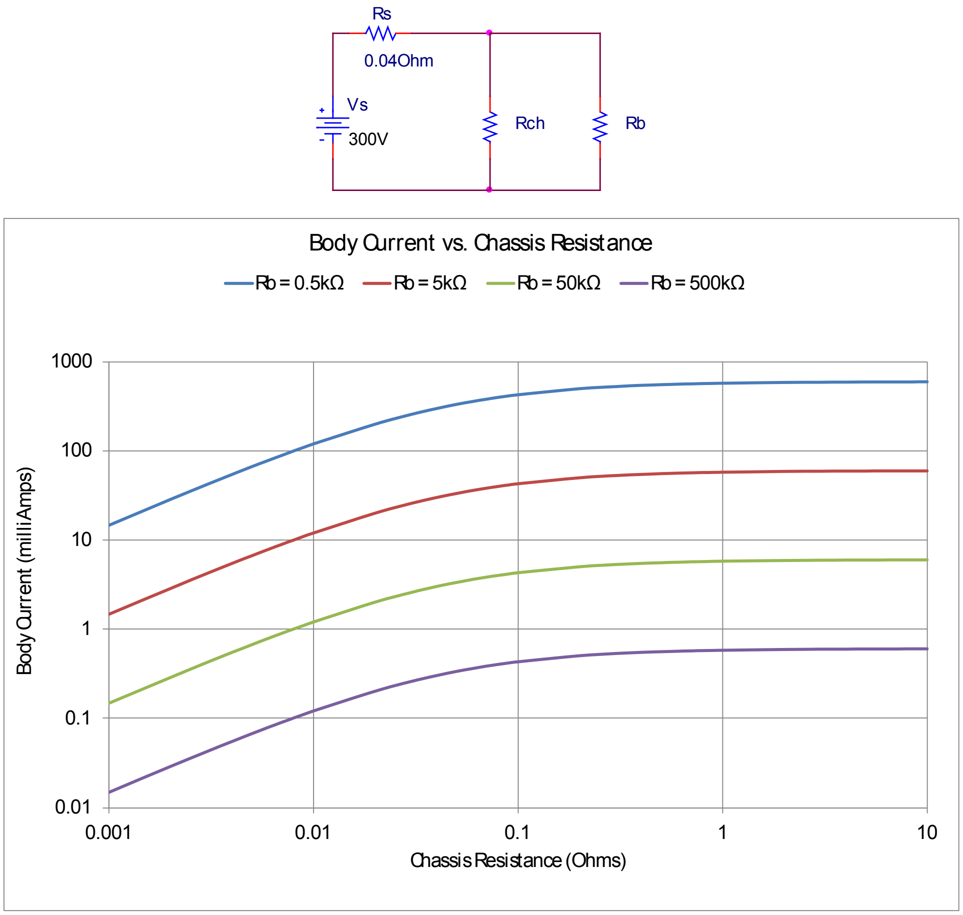


Figure 22. Example plot of body current vs. chassis resistance and the accompanying circuit diagram.

Two key observations may be made from this initial example.

- Body current (and therefore shock potential) increases as body resistance decreases
- Body current (and therefore shock potential) increases as chassis resistance increases

Figure 23 compares the results in Figure 22 to allowable AC and DC body currents and the maximum allowable chassis resistance of 0.1Ω from ISO 6469-3 and ELSA 2010 Draft. The range of the X axis on the plot is 1mΩ to 10Ω with 0.1Ω as the center point. This shows two logarithmic decades of resistance below and above the maximum allowed resistance.

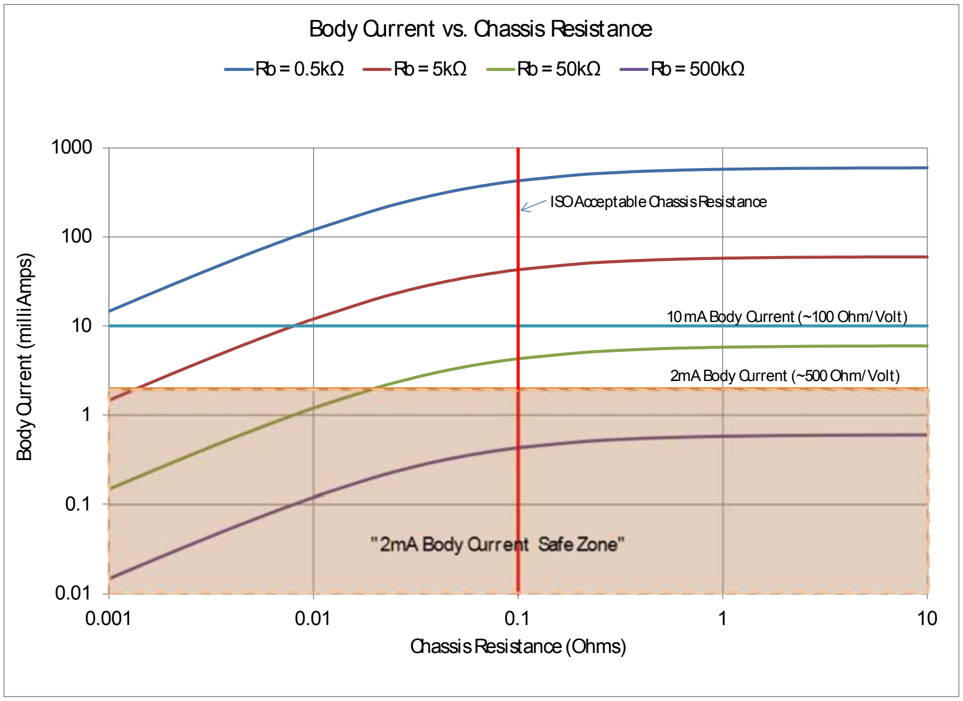


Figure 23. Example plot of body current vs. chassis resistance with 2mA and 10mA limits.

The results in Figure 23 indicate that, for the model and parameters selected, low body resistances may result in body currents well above the acceptable 2mA and 10mA levels. For the values chosen in this model, the body current for a conservative 500Ω body resistance is fully outside the “safe zone.”

The results in Figure 23 also indicate that the chassis resistance requirement of 0.1Ω is orthogonal to the safety requirements of 2mA and 10mA. For the conditions shown here, a chassis resistance requirement of 0.1Ω does not appear sufficient to ensure that body currents remain within acceptable ranges.

The analysis above is a single example for a specific voltage source and set of conditions. Following is a more detailed and broader parametric analysis, as well as an example based upon a specific vehicle battery design intended to explore the veracity of this model and observations that may be drawn from it.

6.4.4 Assessment of Chassis Currents

Next we consider the magnitude of current that flows from the battery through the chassis in the event of the condition illustrated in Figures 20 and 21. The chassis current, Ich, is given by elementary circuit theory by the expression

$$Ich = \frac{Vs * Rb}{Rs * Rch + Rs * Rb + Rch * Rb}$$

Figure 24 shows the chassis current predicted by the model over the same four decades of chassis resistance considered in Figure 22.

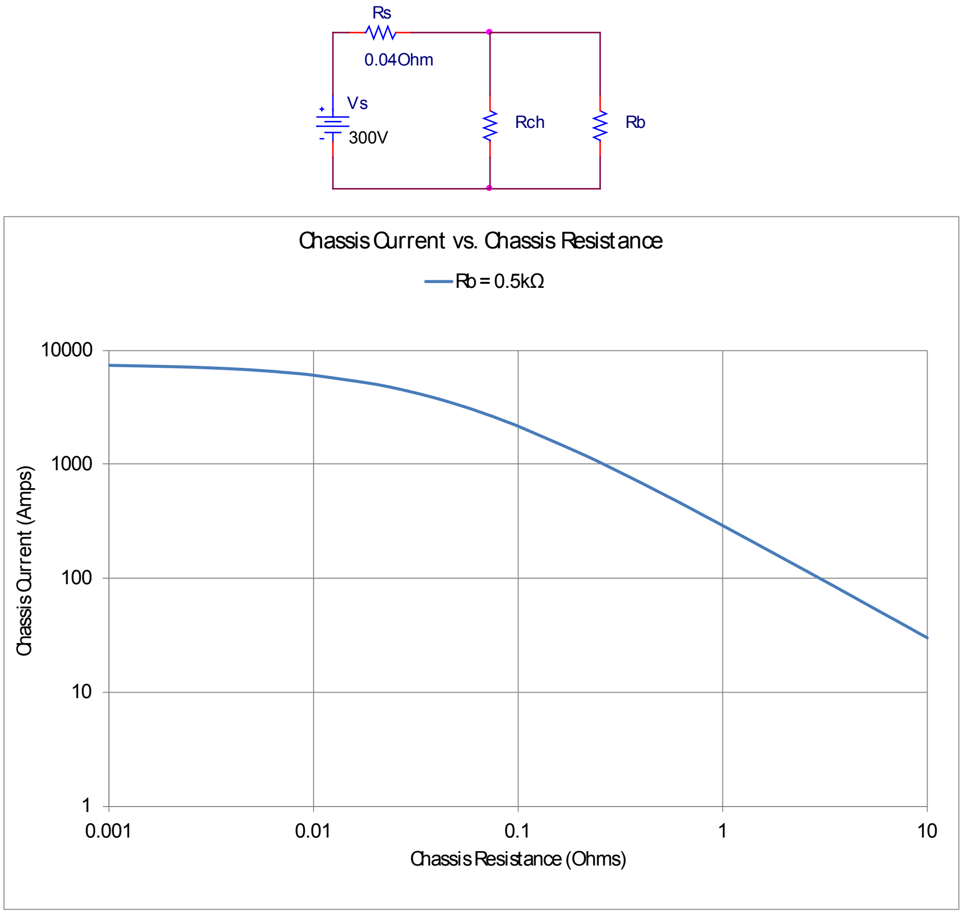


Figure 24. Plot of chassis current and chassis resistance and the accompanying circuit diagram.

Note that the body resistance is much larger than either the source resistance or the chassis resistance. As a consequence, the chassis current is primarily dependent mathematically upon the source and chassis resistances and negligibly dependent upon body resistance. For example, using a chassis resistance of 1mΩ, the chassis current when the body resistance is 500Ω and 500kΩ is as follows.

$$Ich_{500\Omega} = 7317.06A$$

$$Ich_{500k\Omega} = 7317.07A$$

If the chassis resistance is changed to 10 Ω, the following results are obtained.

$$Ich_{500\Omega} = 29.878A$$

$$Ich_{500k\Omega} = 29.880A$$

Consequently, we only consider a single value of body resistance in the figure.

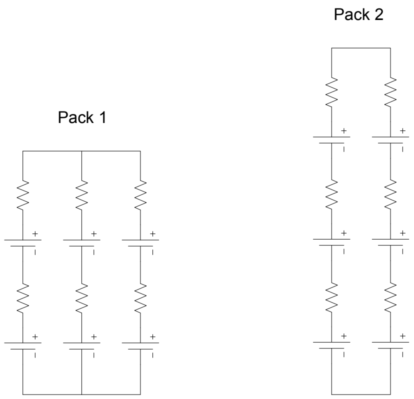
The modeling results in Figure 24 suggest theoretically that thousands of amps could flow through the vehicle chassis for chassis resistances of 0.1Ω and lower. These high currents depend upon the values chosen for this particular circuit. While a few hundred amps may be expected in service, in practice the battery and chassis wiring would fail, possibly catastrophically, before achieving thousands of amps as suggested here.

The situation shown here is a preliminary illustration, which suggests that further consideration of the chassis current is warranted. As shown by the equation, it depends upon the battery source resistance, Rch, which will be examined next.

6.4.5 Potential Influence of Source Voltage and Resistance

The circuit schematic and data plots in prior examples demonstrated the electric shock potential during the indirect contact scenario shown in Figure 20. In that analysis, the voltage source and source resistance were constant, but these values also may have a significant impact on the shock hazard.

The source voltage and resistance can be varied in the equations in order to observe the effects of these values on body current, but it is important to note that the source voltage and internal resistance are interdependent. The voltage and resistance should not vary independently without consideration of their ratio to one another. This can be demonstrated through an example using a battery pack as the vehicle power source. For a given pack type (made of the same cell level building blocks) and overall size, if the voltage is increased then the internal resistance must also increase because more cells are added in series to increase the voltage. If more cells are added in series, fewer cells can be placed in parallel for the overall pack volume to remain the same. This concept is illustrated in Figure 25.



Number of Cells: 6
Cell Voltage: 3.6V
Cell Resistance: 0.012Ω
Stack Voltage: 7.2V
Pack Resistance: 0.008Ω
V/R: 900

Number of Cells: 6
Cell Voltage: 3.6V
Cell Resistance: 0.012Ω
Stack Voltage: 10.8V
Pack Resistance: 0.018Ω
V/R: 600

Figure 25. Source voltage/resistance relationship example.

This suggests that the source voltage and resistance must be considered simultaneously in analyzing the shock potential for a given vehicle system and that the ratio of source voltage and source resistance should be a reasonable number. If the V/R ratio is calculated for the source in Figure 22, the result is V/R = 7500. It is unlikely that a battery for a present day electric vehicle application could achieve this high a ratio, because the internal cell resistance in combination with the limited car volume would inherently limit its magnitude. A similar argument can be made for a fuel cell power source, because they generally have an even higher internal resistance than a battery. It is possible that a hybrid source using ultra capacitors could achieve a source resistance this low.

The illustrations, plots and data above have been generalized examples that show how to construct the evaluation of a shock hazard for this indirect contact condition. In order to more accurately define the results and expand the analysis, more realistic values from actual vehicle power sources must be considered.

For this analysis, data were gathered from various sources on the Web for the battery design of a Chevy Volt. The data collected suggest a battery pack voltage of approximately 360V and a pack consisting of 288 cells where each cell has a resistance of 4.2mΩ and an assumed nominal voltage of 3.75V. Using this information and assuming that the point-to-point wiring and contact resistance is negligible, the resultant pack resistance is approximately 0.134Ω and the V/R ratio is approximately 2,687. This calculation is performed as follows.

$$Number\ of\ cells\ in\ string = \frac{360V}{3.75V} = 96$$

In this case, the number of cells in the pack must add up to 288 and they must be organized into series and parallel configurations to match the voltage and number of cells. It is assumed that they are split evenly into parallel strings, which means three strings with 96 cells per string. Using an internal resistance of 4.2mΩ, the total internal resistance of the pack is calculated:

$$Internal\ Pack\ Resistance = \frac{96 * 0.0042}{3} = 0.134\Omega$$

The assumption that the contact resistance and cable resistance is negligible may not be a fully valid, but there is no practical means by which this information can be obtained and categorized at the present time, so this assumption is used in the generation of plots in this document. In addition, the internal resistance of a cell varies depending on cycle life, temperature, and other parameters. The value of the source resistance is varied in later examples to show how an increase in this number affects the shock potential.

Figure 26 and Figure 27 show body current and chassis current as a function of chassis resistance using the computed values determined for the battery pack in the Chevy Volt. The figures show that the battery pack is theoretically capable of delivering a maximum of approximately 2600 amps. The likelihood that given a failure in the protection circuitry this battery can provide this much current would have to be verified by the manufacturer. The magnitude of this current is likely large enough to cause other failures before presenting a shock hazard.

The results in Figure 27 suggest that, if the chassis resistance is higher than 0.1Ω such as may be the case if an electrical bond fails, then it may be possible for the chassis to carry hundreds of amps.

The estimated data for the Chevy Volt can be used to evaluate different battery pack configurations using the same cell type. For example, if the battery pack were reconfigured using the same number of cells for a higher voltage resulting in two strings of 144 cells the result is a pack voltage of 540V, a pack internal resistance of 0.302Ω, and a V/R ratio of 1788. Figures 28 and 29 compare results for a 360V battery pack and a postulated 540V battery pack with the same number of cells with suitable source resistances. The comparisons are very enlightening in that they suggest that the body currents are comparable for the two cases, suggesting similar shock potential. This indicates that there is not a direct relationship between voltage and body current and that higher voltages are not automatically more or less safe than lower voltages. However, these values are still well above acceptable body currents. Figure 28 shows that chassis currents are also comparable on a log-log plot, although the voltages are significantly different.

Figures 30 and 31 examine the effects of source resistance, comparing body current and chassis current for a 360V source with source resistances of 0.134Ω, 0.5Ω and 1Ω. Figure 30 shows that increasing the source resistance can reduce the body current, although not sufficiently to achieve acceptable levels. Figure 31 suggests that chassis current is also reduced for increasing source resistance. In the case of 1Ω source resistance, the theoretical chassis currents are of the order of hundreds of amps, which are plausible levels in high-voltage systems.

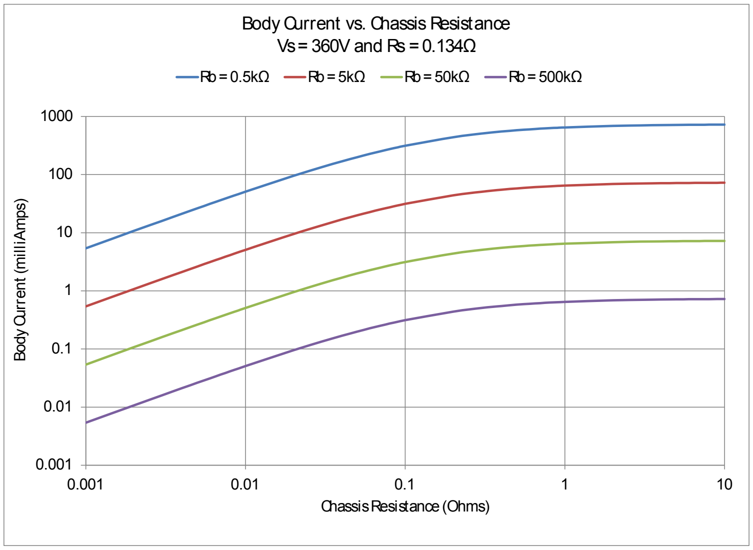


Figure 26. Plots of body current vs chassis resistance for a Chevy Volt battery pack.

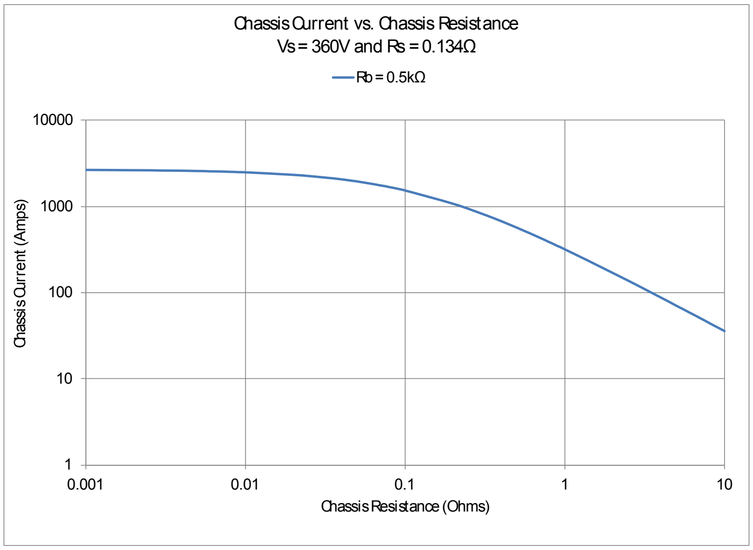


Figure 27. Plot of chassis current vs chassis resistance for a Chevy Volt battery pack.

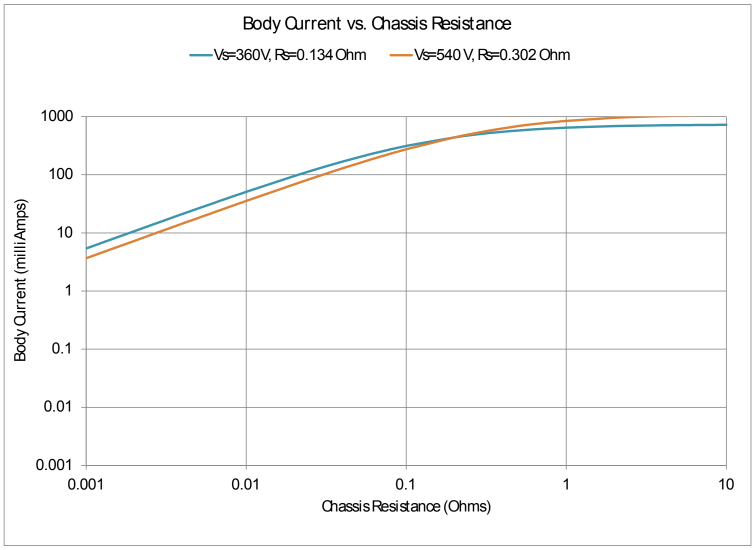


Figure 28. Comparison of body current for 360V and 540V batteries with the same number of cells.

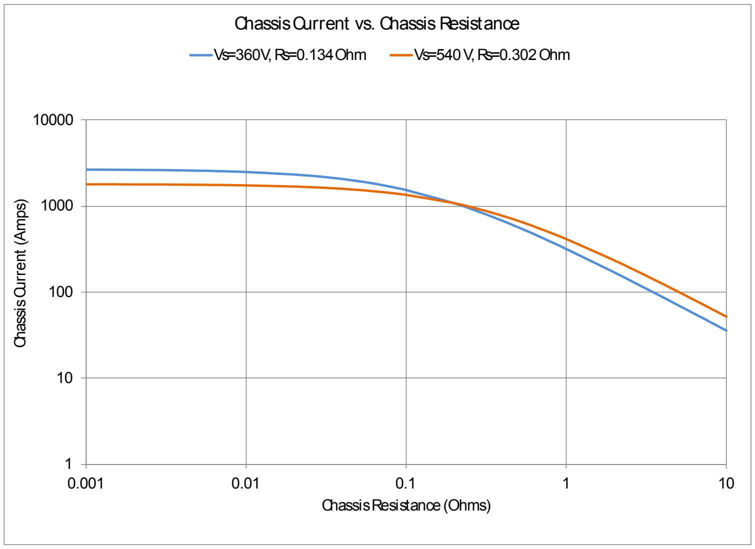


Figure 29. Comparison of chassis current for 360V and 540V batteries with the same number of cells.

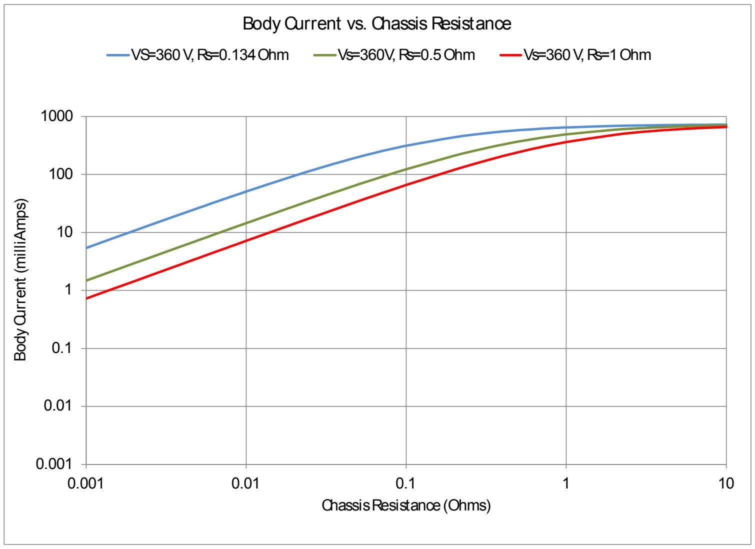


Figure 30. Comparison of body current for three different source resistances.

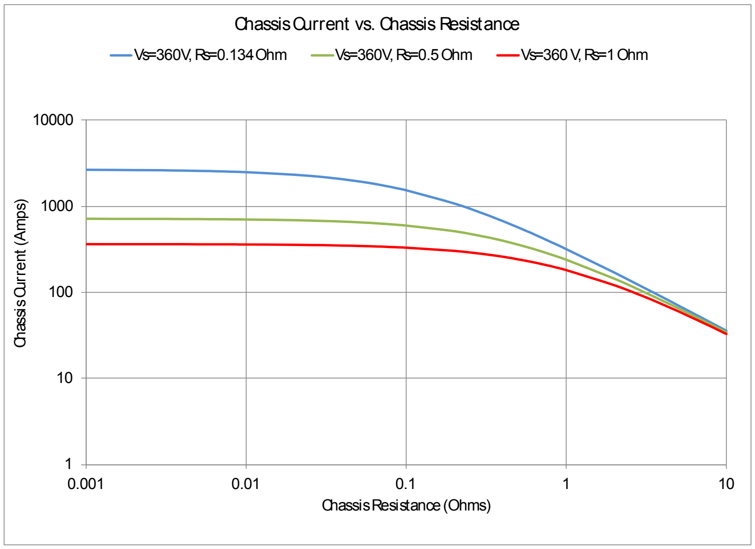


Figure 31. Comparison of chassis current for three different source resistances.

6.4.6 Indirect Contact Observations and Considerations

The analysis shown here was undertaken with the intent of demonstrating that electrically bonding protective barriers to the electrical chassis provides a substantial margin of safety for the indirect contact problem. However, a plausible simple parallel circuit model suggests that this may not be the case. Analyses based upon plausible ranges of battery and vehicle resistance values could not rule out potentially unsafe currents through the body. Further, analyses based upon data from the literature for a specific vehicle model could also not rule out potentially unsafe currents through the body. The analyses and results shown here need review and discussion with vehicle battery system designers and experts to assess their validity. Experimental testing and verification of this proposed safety feature may be warranted.

The analyses performed here indicate that

- Body current, and therefore shock potential, increases as body resistance decreases,
- Body current, and therefore shock potential, increases as chassis resistance increases, and
- Body current, and therefore shock potential, does not necessarily increase with vehicle voltage, but is dependent upon vehicle electrical system design.

Analyses performed here suggest that, if fuse and/or contactor circuit protections fail, and a battery "short circuits" through the chassis, the body current could readily exceed the 2mA and 10mA acceptable levels specified in vehicle electrical system safety standards.

The analysis performed here could not confirm the requirement that a chassis resistance less than or equal to 0.1Ω is sufficient to ensure that body currents are within acceptable levels in the event of an indirect contact exposure. More information concerning the rationale for this requirement is needed.

The results developed here indicate that the body current is dependent on source resistance and source voltage, which are unique for each vehicle design. Consequently, the necessary chassis resistances to achieve acceptable body currents for indirect contact are different for each vehicle system design.

The results of the modeling shown here illustrate that hundreds of amps of current may be flowing through the vehicle electrical chassis in the case of indirect contact exposure. The results also suggest that currents generated in the chassis may be sufficient to damage or melt wiring and cause hazardous failures.

It would be expected that battery systems would contain fuses, current limiters, and/or contact interrupts that would prevent the level of currents suggested here, and that this type of protection would only be necessary when all other safety measures have failed.

Shock protection of protective barriers by bonding to the electrical chassis is a redundant safety measure that is needed when there are multiple point failures (two separate protective barriers must be in contact with high-voltage sources) and when other safety precautions (such as fuses and electrical contactors) have failed.

Electrical bonding of protective barriers to the chassis may not provide a comprehensive solution for the indirect contact problem, but may be a supporting and complementary solution in combination with other requirements. Electrical bonding of enclosures to the electrical chassis is considered good engineering practice, particularly for high-voltage systems. No evidence was found here to suggest that it should not be implemented.

The analysis shown here does not suggest that electric vehicles are unsafe in a crash or other events. This is an engineering analysis of a specific set of circumstances in order to understand how hazardous failures may be better prevented or mitigated.

7. Summary of Assessments, Observations and Considerations

Following is a summary of the key observations and considerations resulting from this investigation as well as gaps identified.

7.1 Absence of High Voltage

The most fundamental protection measure to prevent electrical shock is to disconnect or isolate high-voltage sources from the electrical bus and chassis. This is commonly achieved through electrical disconnects. Electrical disconnects are indirect safety devices, in that they don't specifically sense an electrical failure, but sense other stimuli that may or may not cause failure, such as decelerations during a crash event. These devices are expected to activate in high speed crashes, but may fail or may not activate due to insufficient deceleration in low-to-moderate speed impacts. While it is expected that high speed impacts are more likely to damage the onboard electrical system and induce more severe damage than low speed impacts, the uncontrolled and unpredictable nature of vehicle crash events prevents ruling out electrical system damage in low-to-moderate speed impacts. Hence, electrical disconnects may not be sufficient by themselves to prevent contact with energized components in all crash conditions. Hence, additional safety precautions, such as electrical isolation, appear prudent to provide redundant protection in the case disconnects are not present on all sources, in event of electrical disconnect failure, or in the case that electrical disconnects do not activate.

7.2 Electrical Isolation

Electrical isolation resistance is the composite resistance of all components in the complex vehicle electrical system between high-voltage sources and the chassis and between high-voltage returns and the chassis. The failure modes analysis in Chapter 5 demonstrate that electrical isolation resistance is a fundamental and critical protection that limits current flow through the body in most of the cases of direct and indirect contact. In those cases where the body is in series with and protected by sufficient isolation resistance, then isolation resistance is sufficient by itself to ensure body currents are within acceptable thresholds. Isolation resistance also augments and addresses gaps in other protection measures, providing redundancy.

7.3 Protective Barriers

While not specifically required in industry standards, electrical protective barriers are a fundamental and necessary component of all high-voltage vehicle systems, preventing direct body contact with high-voltage sources and returns during routine service, maintenance, as well as during and after crash.

Protective barrier enclosures commonly contain multiple high-voltage components. This report suggests the components should be electrically isolated from conductive enclosures and barriers. This isolation resistance should be sufficient to ensure currents in contacting bodies are within acceptable thresholds for safety.

Electrical bonding of conductive protective barriers to the vehicle electrical chassis is also an important component of high-voltage system, ensuring the potential of exposed surfaces are equal to the vehicle electrical chassis, and providing low resistance path for current in the case of isolation resistance is lost for both voltage source and return.

7.4 Need for Electrical Isolation of Protective Barriers

The analysis performed here indicates that protective barriers may not limit currents through a contacting body to acceptable levels without complementary electrical isolation. This applies during service as well as post-crash. Electrical isolation can be used in conjunction with conductive barriers to limit currents through the contacting body.

The analysis performed here suggests that various imperfections in electrical isolation may allow current to flow through a body in contact with conductive protective barriers and the chassis and that they may exceed acceptable thresholds without sufficient electrical isolation. The analysis conducted here indicates that conductive protective barriers do not limit body currents to acceptable thresholds in all cases even when bonded to the chassis.

Requirements for electrical isolation should also limit isolation loss within a conductive protective barrier to acceptable thresholds, thereby providing protection for indirect contact.

7.5 IPXXB Protection

IPXXB protection defines a consistent, repeatable criterion for gaps and breaches in protective barriers. Gaps and breaches are permitted as long as the articulated finger cannot contact an energized high-voltage source or return. It augments requirements for physical protection, providing a standardized tool and method for verification of physical protection adequacy in preventing direct contact.

IPXXB does not verify the electrical isolation of a protective barrier surface or that current flowing through a body in contact with barrier surfaces are within acceptable levels.

7.6 Electrical Chassis Bonding of Protective Barriers for Indirect Contact Protection

In the event of isolation loss within multiple protective barriers such that they become energized, a low resistance electrical path from the barriers through the chassis may activate electrical fuses or current limiting devices, if present, thereby preventing a shock hazard. If isolation is lost within multiple protective barriers and fuses do not activate, the low resistance electrical path from the barriers through the chassis may reduce the current flow through a contacting body, but will not limit current flow through the body in all cases.

In the indirect contact case of isolation loss within multiple protective barriers, the body is electrically in parallel with the isolation resistance of the source. As discussed in Chapter 6, the current through the body is not limited in the parallel case as it is by isolation resistance in series circuit and does not provide the same level of protection. The body current in a parallel circuit depends upon a number of factors, including the source voltage, the source resistance, the chassis resistance and the body resistance. These factors may be sufficient in some cases to control body current to acceptable thresholds, but may not be in others.

The analysis shown in Chapter 6 could not confirm the requirement that a chassis resistance less than or equal to 0.1 Ω is sufficient to ensure that body currents are within acceptable levels in the event of an indirect contact exposure. More information is needed concerning the engineering rationale and basis for this requirement in the standards.

7.7 Physical Protection as a Standalone Option

ELSA 2010 Draft and GTR HFV 2011 Draft offer physical protection from direct contact and indirect contact as a standalone option for electrical safety without need for either absence of high voltage or electrical isolation. The analyses performed here cannot confirm that standalone physical protection is sufficient to limit body currents to acceptable thresholds for safety. The analysis indicates that protective barriers do not provide protection equivalent to electrical isolation requirements of 100 Ω/V for DC sources, and 500 Ω/V for AC sources or 500 Ω/V for conductively connected AD-DC buses. This observation applies before crash or damage is induced, as well as post-crash.

Requirements for electrical isolation should limit isolation loss within a conductive barrier to acceptable threshold, whereas standalone physical protection requirements may not.

7.8 Physical Protection as an Alternative for AC Isolation

In the case of conductively connected AC-DC bus, ELSA 2010 Draft and GTR HFV 2011 Draft propose 100 Ω/V isolation on the connected bus plus physical protection for AC sources as an alternative to 500 Ω/V isolation for the connected bus. The results of this investigation suggest that a barrier protecting an AC source does not limit AC current through a contacting body to the 2mA threshold unless the source has at least 500 Ω/VAC isolation.

7.9 Absence of Voltage as an Alternative for AC Isolation

In the case of conductively connected AC-DC bus, ELSA 2010 Draft and GTR HFV 2011 Draft propose 100 Ω/V isolation on the connected bus plus absence of high voltage from AC sources as an alternative to 500 Ω/VAC isolation for the connected bus. Absence of voltage from an AC source and/or an AC bus is expected to prevent AC current flow through a body in contact with the source and associated barriers, thereby supporting safety. However, absence of voltage is commonly achieved through electrical disconnects that are expected to activate in high speed crashes. However, they may not be sufficient by themselves to prevent contact with energized components in all cases, such as failure to activate in low-to-moderate speed impacts.

7.10 Y Capacitor Discharge

The vehicle chassis potential floats with respect to the DC bus voltage, meaning that the chassis voltage magnitude is somewhere between the maximum DC voltage and zero volts (Vsource ≥ Vchassis ≥ 0). The voltage on the chassis with respect to each polarity of the DC bus is dependent on the isolation resistance between each leg of the circuit and the chassis. Consequently, the two Y capacitors will be charged unequally. Following a crash or other shutdown these capacitors discharge through the isolation resistance. The analysis shown here indicates that current through the body is limited and protection may be provided by isolation resistance. Y capacitors may be considered similar to other sources for consideration of failure modes in Table 6, Table 7, and Table 8. Similar conclusions with regard to safety protection apply.

Further investigation and analysis would be needed to determine if the low energy option proposed in the ELSA 2010 Draft is sufficient to ensure body currents are within acceptable thresholds.

8. References

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Appendix A. Review and Comment on GTR HFV 2011 DRAFT Test Procedures

A part of this investigation was to assess and discuss test procedures associated with the electrical protective barrier option. This appendix addresses the test procedure section of the December 2011 ECE/TRANS/WP.29/GRSP/2011/33 UNECE Working Party document as it relates to electrical isolation and protective barriers. The specifications in the December 2011 revision are reviewed section by section and the overall procedure is assessed for completeness.

Section 6.2.1.3.1.3. Measurement method

This section states,

> "An insulator isolation resistance test instrument is connected between the live parts and the electrical chassis. The isolation resistance is subsequently measured by applying a DC voltage at least half of the working voltage of the high voltage bus. If the system has several voltage ranges (e.g. because of boost converter) in conductive connected circuit and some of the components cannot withstand the working voltage of the entire circuit, the isolation resistance between those components and the electrical chassis can be measured separately by applying their own working voltage with those components disconnected."

The Working Party may consider expanding the first sentence in this section to state that two isolation resistance measurements are needed for each DC voltage in the electrical system. The measurement device should be used to measure the isolation resistance from the positive polarity to the chassis and the negative polarity to the chassis. The lower of the two resistances is then used to calculate the ohms/volt value for that voltage in the vehicle. If there are multiple voltage magnitudes within the vehicle then isolation resistance for each voltage should be tested. The lowest overall ohms/volt value is the isolation resistance per volt for that vehicle.

In situations where multiple voltage magnitudes are present in the vehicle electrical system, all the electronic equipment that the system is composed of should remain intact (un-removed) for the isolation resistance measurement because the measurement is dependent on all paths to chassis. If a component within the electrical system is removed and tested independently, it will likely yield a higher isolation resistance. If the concern is that a component within the electrical system will be damaged due to overvoltage stress, the measurement voltage should be tailored to the ratings of the components under test. For example, if 360VDC and a 600VDC exists in the same vehicle, then the 360VDC bus should be tested with a minimum voltage of 180VDC and the 600VDC should tested with a minimum voltage of 300VDC. No components should be removed for this test.

Section 6.3.1.2.2.1 Test vehicle conditions

> "The high voltage-bus is energized by the vehicle's own RESS and/or energy conversion system and the voltage level of the RESS and/or energy conversion system throughout the test shall be at least the nominal operating voltage as specified by the vehicle manufacturer."

The Working Party may consider revising this section to be more specific about the operating conditions of the vehicle. For example, the method should take into consideration the operating condition of the boost converter in the vehicle, if present. Likewise, the inverter may be enabled, but not operating.

Section 6.3.1.2.2.3.2. Second step

> "The voltage (V1) between the negative side of the high voltage bus and the electrical chassis is measured and recorded (see Figure 9)."

Section 6.3.1.2.2.3.3. Third step

> "The voltage (V2) between the positive side of the high voltage bus and the electrical chassis is measured and recorded (see Figure 9)."

A polarity should be specified in taking these measurements, or it should state that the magnitude of the voltage should be measured.

6.3.1.2.2.3.4. Fourth step

> "If V1 is greater than or equal to V2, a standard known resistance (Ro) is inserted between the negative side of the high voltage bus and the electrical chassis. With Ro installed, the voltage (V1') between the negative side of the high voltage bus and the electrical chassis is measured (see Figure 2). The electrical isolation (Ri) is calculated according to the following formula:
>
> $$Ri = Ro^*(Vb/V1' - Vb/V1) \text{ or } Ri = Ro^*Vb^*(1/V1' - 1/V1)$$
>
> The resulting Ri, which is the electrical isolation resistance value (in Ω), is divided by the working voltage of the high voltage bus in volt (V):
>
> $$Ri\ \Omega / V = Ri\ \Omega / \text{Working voltage } (V)$$
>
> If V2 is greater than V1, a standard known resistance (Ro) is inserted between the positive side of the high voltage bus and the electrical chassis. With Ro installed, the voltage (V2') between the positive side of the high voltage bus and the electrical chassis is measured. (See Figure 10). The electrical isolation (Ri) is calculated according to the formula shown below. This electrical isolation value (in ohms) is divided by the nominal operating voltage of the high voltage bus (in volts). The electrical isolation (Ri) is calculated according to the following formula:
>
> $$Ri = Ro^*(Vb/V2' - Vb/V2) \text{ or } Ri = Ro^*Vb^*(1/V2' - 1/V2)$$
>
> The resulting Ri, which is the electrical isolation resistance value (in Ω), is divided by the working voltage of the high voltage bus in volts (V).
>
> $$Ri\ \Omega / V = Ri\ \Omega / \text{Working voltage } (V)$$"

6.3.1.2.2.3.5. Fifth step

> "The electrical isolation value Ri (in ohms) divided by the working voltage of the high voltage bus (in volts) results in the isolation resistance (in ohms/volt).
>
> (Note: The standard known resistance Ro (in ohms) is the value of the minimum required isolation resistance (in ohms/V) multiplied by the working voltage of the vehicle plus/minus 20 per cent (in volts). Ro is not required to be precisely this value since the equations are valid for any Ro; however, a Ro value in this range should provide good resolution for the voltage measurements.)"

In the previous two underlined sections, there is a conflict in terms. The term "isolation resistance" is used both to represent the resistance measured via this test and the calculated ohms/volt value. The Working Party may want to clarify that isolation resistance refers only to resistance and ohms/volt is a separate expression, unless there is another technical term that is has been defined specifically for this work.

Both test methods for measuring isolation resistance only measure resistance. The presence of AC components from switch power electronics on the DC bus cannot be measured with DC isolation resistance meter. However, the resistor insertion method could be used to measure the AC isolation resistance of the DC. If the same test was performed and the meter measured AC voltage instead of DC voltage, this result could be used along with a measurement of the ripple voltage on the DC bus to determine the AC isolation resistance.

6.3.3.2 Test Conditions

> "The access probe is pushed against any openings of the enclosure with the force specified in Table 1. If it partly or fully penetrates, it is placed in every possible position, but in no case shall the stop face fully penetrate through the opening.
>
> Internal electrical protection barriers are considered part of the enclosure.
>
> A low-voltage supply (of not less than 40 V and not more than 50 V) in series with a suitable lamp is connected, if necessary, between the probe and live parts inside the electrical protection barrier or enclosure.
>
> The signal-circuit method is also applied to the moving live parts of high voltage equipment.
>
> Internal moving parts may be operated slowly, where this is possible."

The Working Party may consider expanding the practical guidance on the application of force and include Table 1 in the test method document. The specific method for measuring the force exerted with the probe should be provided in the document.

The rationale for the requirement that the low voltage supply for the lamp be a minimum of 40V is not given, and the Working Party may consider reducing the minimum. If the voltage could be decreased, the probe could be made to use a small battery and LED pair and the probe could be modified such that the battery and LED were part of the probe. This would eliminate the need for additional external equipment. However, the same problem exists for either approach, namely that access to the live parts of the circuit under test must be provided so that the side the test voltage that powers the lamp can be connected. This would require OEMs to provide access to all points in the vehicle, which is what stakeholders desire to avoid. Another alternative would be to temporarily gain access to a vehicle voltage with the understanding that it is only for the purposes of this test. It is possible that the finger probe could be outfitted with other onboard electronics or an optical camera that would alert the user if the probe touches live parts inside an enclosure. This would eliminate the need for access to live parts for the lamp.

6.3.4 Test Method for Measuring Electric Resistance

> "Test method using a resistance tester.
>
> The resistance tester is connected to the measuring points (typically, electrical chassis and electro conductive enclosure/electrical protection barrier) and the resistance is measured using a resistance tester that meets the specification that follows.
>
> Resistance tester: Measurement current at least 0.2 A
>
> Resolution 0.01 Ω or less
>
> The resistance R shall be less than 0.1 ohm.
>
> Test method using DC power supply, voltmeter and ammeter.
>
> Example of the test method using DC power supply, voltmeter and ammeter is shown below.

> Test Procedure
>
> The DC power supply, voltmeter and ammeter are connected to the measuring points (Typically, electrical chassis and electro conductive enclosure/electrical protection barrier).
>
> The voltage of the DC power supply is adjusted so that the current flow becomes more than 0.2 A.
>
> The current “I” and the voltage “V” are measured.
>
> The resistance "R" is calculated according to the following formula:
>
> R = V / I
>
> The resistance R shall be less than 0.1 ohm”

A resolution for the tester of 0.01Ω may not be sufficient, because chassis resistances are often less than 10mΩ. The data for chassis resistance measurements between various locations on the Chevy Volt is shown in Appendix B. Also, the Working Party should consider requiring a resistance tester with a 4 wire measurement method.

The second test method that uses a power supply and separate voltmeter specifies a minimum test current of 0.2A. This current is not sufficient to produce repeatable accurate results. The document should specify a higher but still practical test current.

Experimental Assessment of Test Current

Two tests were conducted on vehicles at Battelle to further examine the specification of this test current. The first vehicle was a 2012 Honda Civic Hybrid and the second was a circa 2002 Nissan Sentra SER. The tests were conducted using the method in which a current is injected into the chassis and resultant voltage is measured. The test setup for the Honda Civic is shown in Figure A-1. Two points on the chassis were selected to take this measurement. These locations were selected such that they spanned across the hood of the vehicle so that a reasonable distance of chassis resistance could be measured. A standard handheld digital multi-meter, Fluke 87V, was used to measure the resistance between these two points to ensure that a low resistance connection was present. This particular meter does not have the resolution to measure very low resistances, and it indicates a resistance of 0.2 when reading a short circuit. A reading of 0.3 (as shown in Figure A-1) indicates that these two points have good bonds to the chassis and that this connection is nearly a short circuit. These test points were carefully selected, as much of the chassis had a non-conductive coating over it. Only certain screws and brackets were exposed and had a conductive path to the chassis.

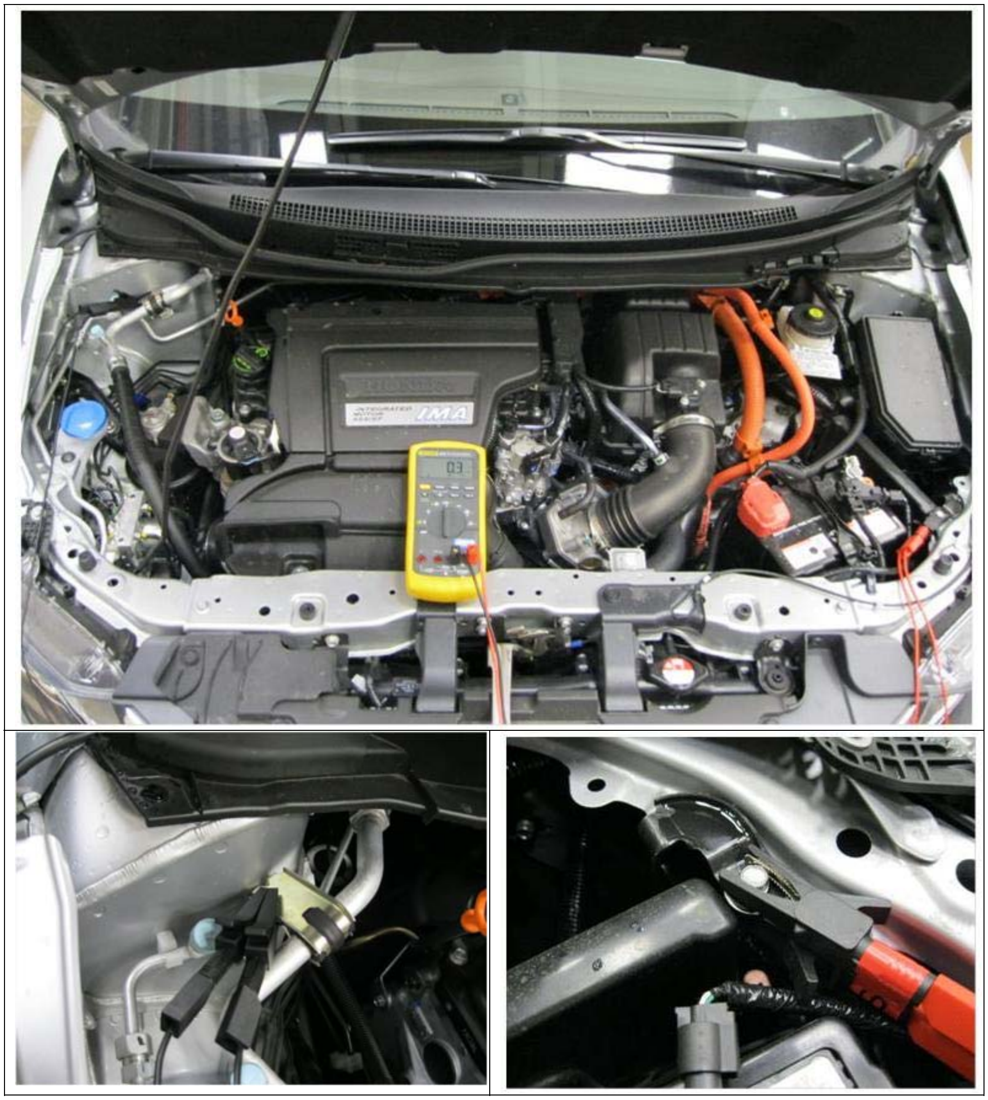

Figure A-1. Pictures of test point locations for the 2012 Honda Civic.

Alligator clips are used to attach the test points to the vehicle. There are 4 clips, 2 positive and 2 negative. The alligator clips of the same polarity need to be placed in close proximity to one another, preferably attached to the same mechanical component on the vehicle. The positive are connected to red wires and have red tape at the base of the clip. The negative are all black and connected to black wires. Two of the clips (one red, one black) connect back to the power supply and the other two connect back to the multi-meter. This setup is identical to the setup depicted in Figure A-2.

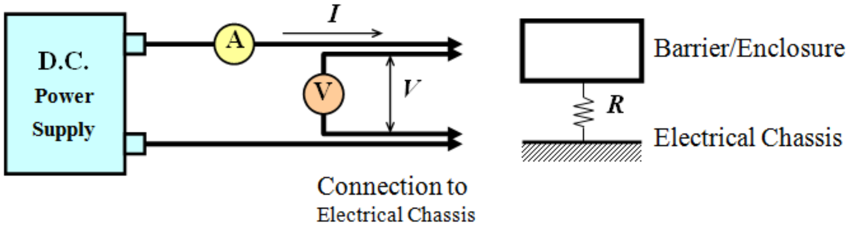

Figure A-2. Test setup diagram (Figure 13 from ECE/TRANS/WP.29/GRSP/2011/33).

The test was conducted using two multi-meters. The first was a handheld meter with a precision down to 0.1mV. The second was a benchtop meter with precision of 1µV. The same test points were used for each test and the current was swept over the "Desired Current" test intervals. The actual measured current and voltage are recorded below along with the calculated resistance for at each current for each meter. These results are shown in Table A-1 and plotted in Figure A-3.

Table A-1. 2012 Honda Civic chassis resistance measurements.

	Handheld DMM			Benchtop DMM		
Desired Current (A)	Measured Current (A)	Measured Voltage (mV)	Calculated Resistance (Ω)	Measured Current (A)	Measured Voltage (mV)	Calculated Resistance (Ω)
0.2	0.202	0.4	0.001980	0.201	0.38	0.001891
0.4	0.401	0.8	0.001995	0.401	0.716	0.001786
0.6	0.604	1.1	0.001821	0.603	1.056	0.001751
0.8	0.804	1.5	0.001866	0.8	1.386	0.001733
1	1.009	1.8	0.001784	1.002	1.728	0.001725
2	2.011	3.5	0.001740	2.001	3.41	0.001704
3	3.003	5.2	0.001732	3.001	5.096	0.001698
4	4.007	6.9	0.001722	4.001	6.781	0.001695
5	5.008	8.5	0.001697	5	8.466	0.001693
6	6.006	10.2	0.001698	6	10.158	0.001693
7	7	11.9	0.001700	7	11.843	0.001692
8	8	13.6	0.001700	8	13.531	0.001691
9	9	15.3	0.001700	9	15.218	0.001691

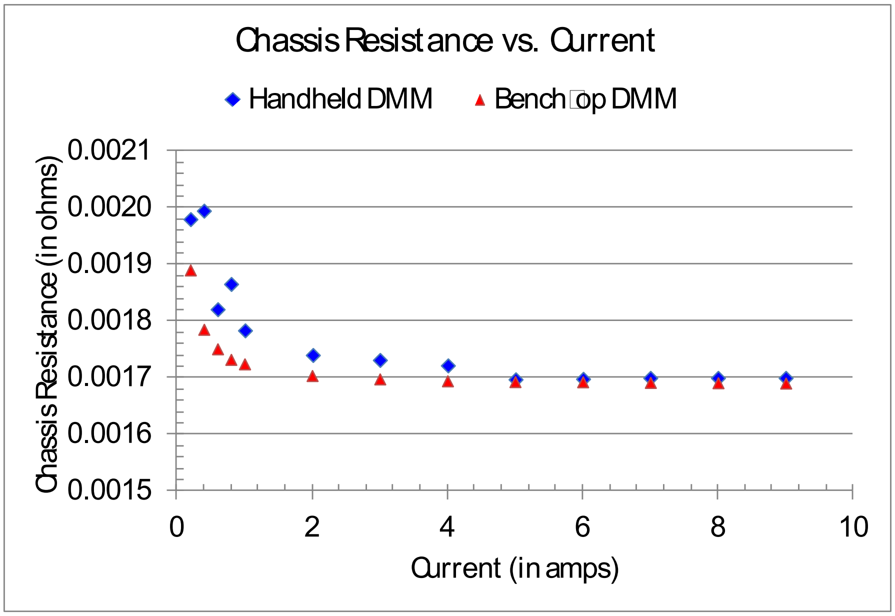

Figure A-3. Chassis resistance testing on a 2012 Honda Civic Hybrid using two digital multi-meters.

Several conclusions can be drawn from this data:

1. A test current of at least 5A is required to obtain accurate results when measuring chassis resistance if the expected resistance is in the 1mΩ range
2. Either meter can be used to take this measurement if the test current is between 5A and 9A
3. The test current does not need to be higher than 9A as the value of the calculated resistance has stabilized by this current
4. A meter with at least a 0.1mV precision is required to obtain accurate results when measuring resistances this low.

Another consideration in selecting the test current is the maximum allowable test current for the wires, the alligator clips (if they are used in place of bolting terminals to the vehicle), and the instrument used to measure the current. For this test, a second handheld meter was used to measure the current. Most handheld meters have a maximum measurable current of 10A.

A second vehicle was tested in order determine the effects of vehicle age on the ability to measure chassis resistance. The second car was not an electric vehicle. The measurements were taken at two locations spanning across the vehicle under the hood. As shown in Figure A-4, the bolts to which the clips are attached are corroded. There were no locations under the hood on this vehicle that provided a solid bond to the chassis. All exposed metal was corroded or painted such that the alligator clips could not make good contact with the chassis.

Figure A-4. Pictures of test point locations for the Nissan Sentra circa 2002.

The handheld digital multi-meter was the only meter used for this testing. The results in Table A-2 show that the resistance was dependent on the test current. A detailed explanation of the results is beyond the scope of this effort, but the corrosion on the bolt clearly has an effect on the chassis resistance and the ability to measure the chassis resistance. The current in this test was increased to the maximum current capability of the power supply, 16 amps. Even at 16 amps, the resistance did not reach a stable value.

Table A-2. c2002 Nissan Sentra chassis resistance measurements.

	Handheld DMM		
Desired Current (A)	Measured Current (A)	Measured Voltage (mV)	Calculated Resistance (Ω)
0.2	0.206	157.5	0.764563
0.4	0.404	357.7	0.885396
0.6	0.6	432	0.720000
0.8	0.8	441.4	0.551750
1	1.001	442.5	0.442058
2	2.005	550	0.274314
3	3.004	587	0.195406
4	4.002	612	0.152924
5	5.002	602	0.120352
6	6.002	629	0.104798
7	6.99	650	0.092990
8	8	674	0.084250
10	10	674	0.067400
12	12	702	0.058500
14	14	710	0.050714
16	16	705	0.044063

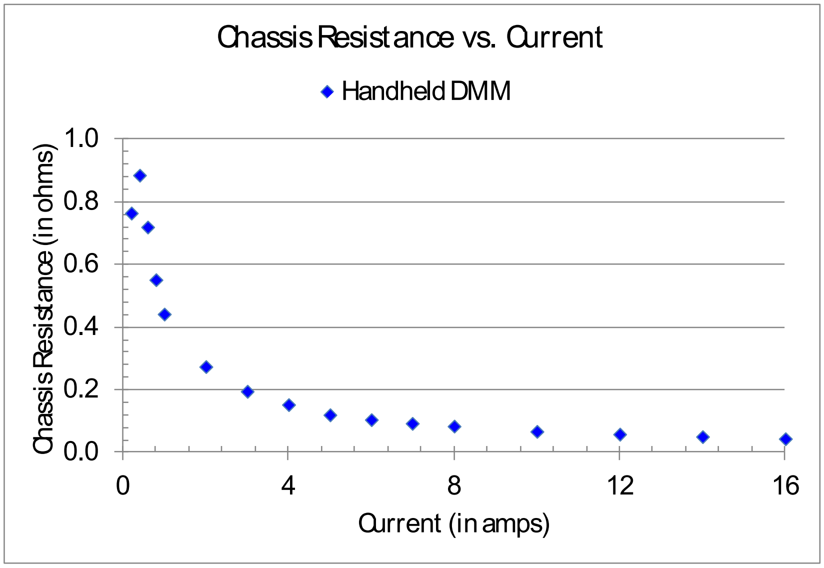

Figure A-5. Chassis resistance testing on a c2002 Nissan Sentra.

These test results show that the age of a vehicle and the resulting corrosion may impede the ability to measure the chassis resistance. If these same effects were present on an electric vehicle, the same problems could exist. In addition, many of the enclosures, including the high-voltage battery, can be bonded to the chassis via metal straps. If the points at which the straps connect one enclosure to another corrode, the possibility for a significant increase in chassis resistance exists. Lastly, another step when measuring this resistance may be required to obtain realistic measurements of the chassis resistance. In other words, the corrosion may need to be removed to gain access to points at which the test can be conducted successfully.

An attempt was made to bolt the test points to the chassis by removing two bolts on the frame of the chassis. Test cables with fork terminal ends were clamped between the head of the bolt and chassis. This attempt was unsuccessful as the bolts had corroded on both sides. This vehicle may not be exactly representative of the materials and coatings used in newer electric and hybrid electric vehicles.

6.3.6.2.3 Isolation Resistance

> “See para. 6.3.1.2 ‘Measurement method’
>
> All measurements for calculating voltage(s) and electrical isolation are made after a minimum of 5 seconds after the impact.
>
> For example, megohmmeter or oscilloscope measurements are an appropriate alternative to the procedure described above for measuring isolation resistance. In this case it may be necessary to deactivate the on-board isolation resistance monitoring system.”

This is the first place in this document that an oscilloscope is mentioned specifically. The Working Party may consider expanding on the choice of an oscilloscope to take these measurements.

Appendix B. Electric Vehicle Isolation and Chassis Resistances of Testing

Three crash-tested Chevy Volts located at the Vehicle Research Test Center were tested on February 7, 2012. The purpose of this testing was to measure isolation resistances and chassis resistances in various locations on each vehicle. These vehicles were selected for this test because of their availability and relevance to the topic of protective barriers for high-voltage sources on automobiles.

B-1 Vehicles Tested

Three vehicles were evaluated during this testing. Table B-1 is a list of the vehicles and Figure B-1. shows a picture of each.

Table B-1. VRTC Chevy Volt test list.

Battelle ID #	VIN#	Vehicle Status
1	1G1RD6E44BU102111	Side Impact Crash, Electronics Removed
2	1G1RC6E43BU100899	Front Impact Crash, Electronics under Hood
3	1G1RC6E47BU101294	Side Impact Pole Crash, Electronics under Hood

Vehicle 1, Side Impact

Vehicle 2, Front Impact

Vehicle 3, Side Pole Impact

Figure B-1. VRTC Chevy Volt vehicle pictures.

B-2 Vehicle Tests

Four tests were planned for each vehicle. The tests were developed to measure the isolation resistance and chassis resistance for each vehicle. The first test used a megohmmeter to measure the isolation resistance at various locations on the vehicle. The second and third tests were intended to measure the DC Chassis Resistance between different locations on the chassis. There were two tests that measured the same parameter in order evaluate the performance of each test method. Lastly an AC Chassis Impedance was measured using an LCR Meter.

The lithium ion battery in each vehicle was removed prior to this testing, which is why the isolation resistance was measured with a megohmmeter. Section 6.3.1.2.1.1. of the document ECE/TRANS/WP.29/GRSP/2011/33 suggests using an isolation test instrument capable of applying a DC voltage higher than the working voltage of the high-voltage bus. The lithium ion battery in the Volt has a nominal voltage of 360V, which is why a test voltage of 500V was used on the megohmmeter. The first DC resistance test used the low ohmic measurement feature on the same megohmmeter instrument. The second DC resistance test used a current injection test method to measure the chassis resistance. The AC impedance was measured using an LCR meter capable of testing at several frequencies ranging from 100Hz to 100kHz. This type of meter is generally used to measure network impedances, inductors, capacitors, and change in resistance or reactance as a function of frequency.

B-3 Test Equipment

The test equipment list is shown in Table B-2.

Table B-2. VRTC test equipment.

Instrument Type	Manufacturer	Model Number	Serial Number	Cal Date	Cal Due Date
MegOhmmeter	Fluke	1520	83910035	3/29/2011	3/29/2012
LCR Meter	Hewlett Packard	4263B	JP1KD02437	6/24/2011	6/24/2012
LCR Meter Coax Cable Ext Kit	Agilent	16048A	1122815*	NA	NA
Power Supply	Chroma	XPD 33-16	E00153580	5/17/2011	5/17/2012
Digital Multimeter	Fluke	87V	99380211	1/19/2012	1/19/2013
Digital Multimeter	Hewlett Packard	973A	JP34000167	6/7/2011	6/7/2012

* TRS Rentelco Asset Number

B-4 Test Setup

The test probe locations on each vehicle were maintained to the extent possible and were arbitrarily named based on engineering deduction of the purpose of the vehicle parts. As a result, the nomenclature may not match that of any Chevy Volt documentation. The accuracy of the names is not critical for the purposes of this testing. The names simply provide a reference for a specific location inside the vehicle. This provides clarity for tables in the results section of this appendix. The test locations inside the car are shown in Figure B-3, Figure B-4, and Figure B-5.

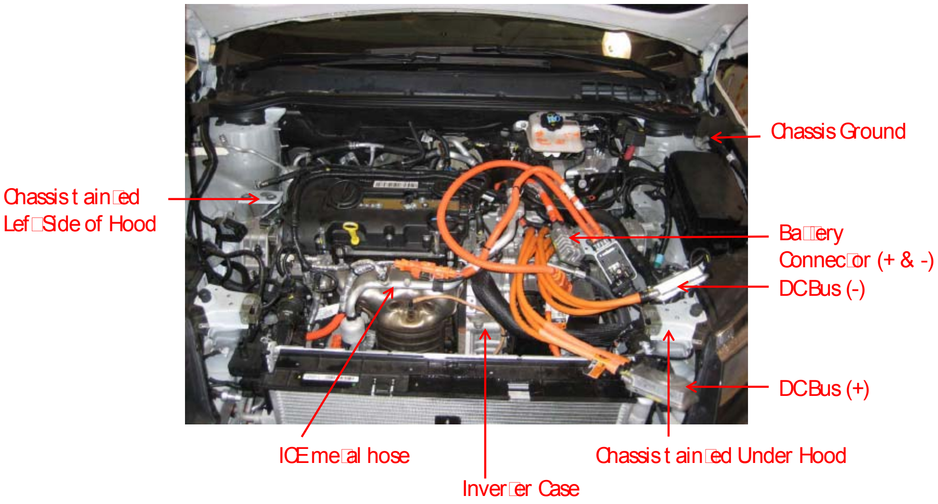

Figure B-2. Test point locations underneath the hood, no electronics module.

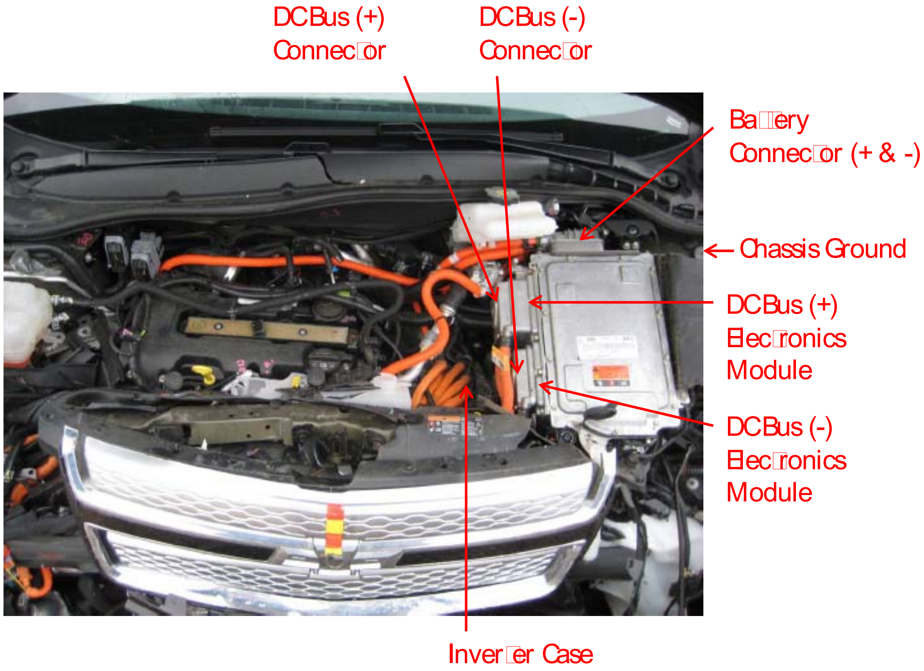

Figure B-3. Test point locations underneath the hood with electronics module.

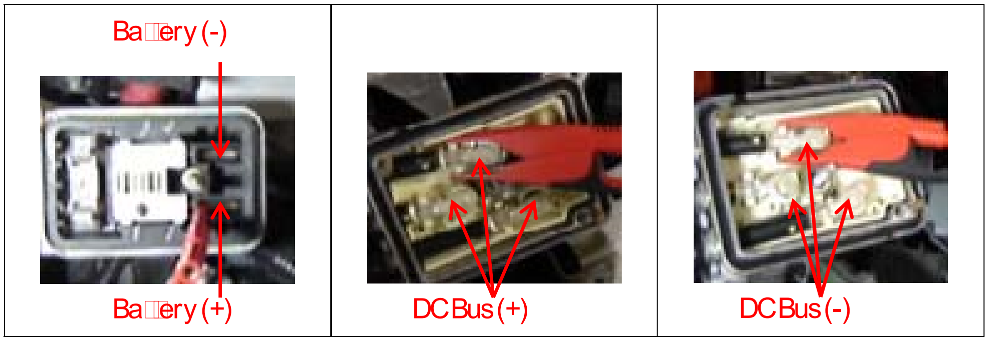

Figure B-4. Connector test point locations.

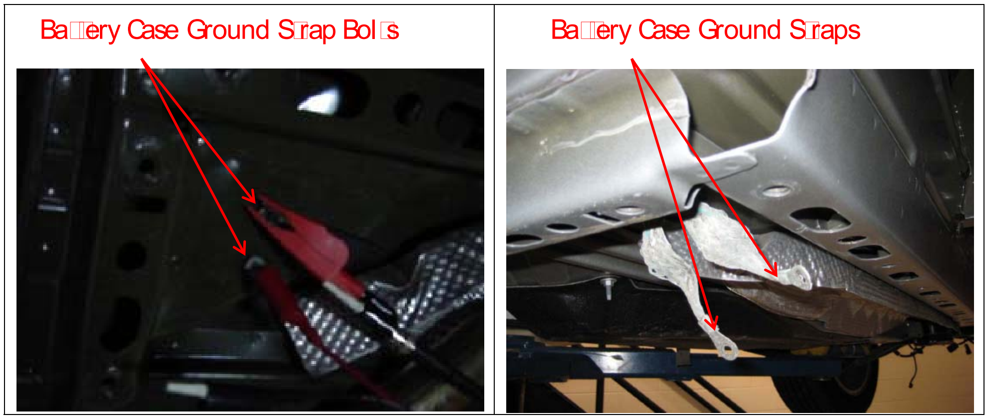

Figure B-5. Vehicle underbody test point locations.

B-5 Test Notes and Observations

The vehicle without an electronics module produced very high isolation resistances (generally greater than 2GΩ). This is to be expected as there were no apparent leakage paths to chassis. The lowest measured isolation resistance for the two vehicles with an electronics module was 1MΩ. These two vehicles had similar results for this test when probed in generally the same location on each vehicle. Assuming a voltage of 360V, a result of 2,778Ω/V is obtained. None of the vehicles contained a battery and it is possible that the presence of the battery could affect these results. The expectation is that the presence of a battery would lower the isolation resistance, but not by a significant amount.

DC Chassis Resistance Test 1 used the low ohmic capability of the megOhmmeter. This test was only performed on Vehicle 1. The meter provided unreliable measurements that also seemed to be unrealistic. As a result these measurements were taken only on Vehicle 1. If an instrument is to be used to measure DC resistance of the chassis, it is recommended that the instrument be validated against another method prior to acceptance of the results provided by that meter.

DC Chassis Resistance Test 2 used a power supply with constant current limit in combination with a digital multimeter to measure the voltage drop across two parts of the chassis. The measured voltage in combination with the measured current from the power supply was used to calculate the resistance. An 8 amp test current was used in order to stay under the 10 amp limit of the multimeter and at the same time provide enough current to produce a measureable voltage drop. The calculated chassis resistance for Vehicle 1 (29mΩ) was noticeably higher than those for vehicles 2 and 3 (0.3 to 1.2mΩ). It is possible that because more of the internal components and metal enclosures had been removed from Vehicle 1, the chassis resistance was affected. The crashed state of each vehicle possibly caused differences as well. The test clips were placed in similar locations but these clips do not necessarily guarantee a perfect bond with the test surface as they are not bolted on.

The AC Chassis Impedance Test was designed to measure the chassis impedance at several frequencies. The inverters and switching power converters required for electric vehicle propulsion produce significant AC voltage waveforms. These high frequency AC signals may potentially couple onto the chassis of the vehicle. If the AC signals were large enough in magnitude, this could present a shock potential. In order to determine the effect of these currents and the voltage developed across different points in the chassis, an LCR meter was used to measure the impedance. The LCR meter was programmed to display the measurements in terms of magnitude and angle, Z<Θ[5]. The meter is generally very precise but it is recognized that this method for measuring impedance may not be viable because of the inherently low test voltage of the meter, 1Vrms. The test results show that the impedance measurement was generally higher than the DC resistance, and that the impedance increased with frequency. These results seemed reasonable and an increase in impedance with frequency was expected. Tests were also performed between the chassis and the non-conductive door handle. The impedance was always large, as it should be, and the instrument did not produce steady measurements for these tests. The test data for all the vehicle testing is detailed in Table B-3 through B-12.

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[5] Here impedance is a vector where Z is the magnitude of impedance, Θ is the angle between the real imaginary components, and < is the symbol for angle.

B-6 Test Results

Table B-3. Vehicle 1 isolation resistance.

Test #	Probe Location (+)	Probe Location (-)	Test Voltage (V)	Res (MΩ)	Notes
1	Battery (+)	Chassis ground under hood	500	>2,000	Measured from terminal with 3 large wires terminated in it with a dot marking on each terminal
2	Battery (+)	Chassis painted under hood	500	>2,000	
3	Battery (+)	Car door handle	500	>2,000	
4	Chassis ground under hood	Battery (+)	500	>2,000	
5	Chassis painted under hood	Battery (+)	500	>2,000	
6	Car door handle	Battery (+)	500	>2,000	
7	Battery (-)	Chassis ground under hood	500	>2,000	
8	Battery (-)	Chassis painted under hood	500	>2,000	
9	Battery (-)	Car door handle	500	>2,000	
10	Chassis ground under hood	Battery (-)	500	>2,000	
11	Chassis painted under hood	Battery (-)	500	>2,000	
12	Car door handle	Battery (-)	500	>2,000	
13	DC bus (+)	Chassis ground under hood	500	>2,000	
14	DC bus (+)	Chassis painted under hood	500	>2,000	
15	DC bus (+)	Car door handle	500	>2,000	
16	Chassis ground under hood	DC bus (+)	500	>2,000	
17	Chassis painted under hood	DC bus (+)	500	>2,000	
18	Car door handle	DC bus (+)	500	>2,000	
19	DC bus (-)	Chassis ground under hood	500	>2,000	Reading started at 100M-300M and charged up to >2,000M as though there was a capacitor across the two points.
20	DC bus (-)	Chassis painted under hood	500	>2,000	Reading started at 100M-300M and charged up to >2,000M as though there was a capacitor across the two points.
21	DC bus (-)	Car door handle	500	>2,000	

Table B-3. Vehicle 1 isolation resistance. (Continued)

Test #	Probe Location (+)	Probe Location (-)	Test Voltage (V)	Res (MΩ)	Notes
22	Chassis ground under hood	DC bus (-)	500	>2,000	Reading started at 100M-300M and charged up to >2,000M as though there was a capacitor across the two points.
23	Chassis painted under hood	DC bus (-)	500	>2,000	Reading started at 100M-300M and charged up to >2,000M as though there was a capacitor across the two points.
24	Car door handle	DC bus (-)	500	>2,000	
25	Motor Phase A	Chassis under hood	500		Did not have access to motor phases as they appeared to be enclosed inside the housing for the motor and ICE drive train
26	Motor Phase A	Car door handle	500		Did not have access to motor phases as they appeared to be enclosed inside the housing for the motor and ICE drive train
27	Chassis under hood	Motor Phase A	500		Did not have access to motor phases as they appeared to be enclosed inside the housing for the motor and ICE drive train
28	Car door handle	Motor Phase A	500		Did not have access to motor phases as they appeared to be enclosed inside the housing for the motor and ICE drive train

Table B-4. Vehicle 1 DC chassis resistance test 1.

Test #	Probe Location (+)	Probe Location (-)	Res (Ω)	Notes
1	Chassis ground	ICE Engine metal hose	2.33	
2	Chassis ground	Chassis painted left side of hood	0.37	
3	Chassis ground	Inverter case	3.03	
4	Chassis ground	Battery case ground	0.35	
5	Chassis ground painted right side	Battery case ground	0.36	
6	Inverter case	Battery case ground	3.2	

Table B-5. Vehicle 1 DC chassis resistance test 2.

Test #	Probe Location (+)	Probe Location (-)	Current (A)	Voltage (V)	Notes
1	Battery case ground	Inverter case	8.04	0.23	Res = 0.02861
2	Battery case ground	Chassis ground	8.04	0.0076	Res = 0.00095
3	Chassis ground	Inverter case	8.04	0.1135	Res = 0.01412
4	Chassis ground	DC Bus (+) conn	8.04	0.1738	Res = 0.02162

Table B-6. Vehicle 1 AC chassis resistance.

Test #	Probe Location (+)	Probe Location (-)	Test Voltage (V)	Z (100Hz) (Ω)	Z (1kHz) (Ω)	Z (10kHz) (Ω)	Z (100kHz) (Ω)	Notes
1	Inverter case pipe	Chassis ground	1	34.2m<1.4	230m<1.5	72.13m<48.8	381m<87.4	
2	Door handle	Chassis ground	1	2.5M<70	30M<-90	3.1M<-86	324k<-84	Readings were not steady
3	Battery case ground	Chassis ground	1	1.42m<43.2	8.0m<74.75	63.3m<83.13	557.2m<101	

Table B-7. Vehicle 2 isolation resistance.

Test #	Probe Location (+)	Probe Location (-)	Test Voltage (V)	Res (MΩ)	Notes
1	Battery (+)	Chassis ground under hood	500	1	
2	Battery (+)	Car door handle	500	>2,000	
3	Chassis ground under hood	Battery (+)	500	1.02	
4	Car door handle	Battery (+)	500	>2,000	
5	Battery (-)	Chassis ground under hood	500	1.07	
6	Battery (-)	Car door handle	500	>2,000	
7	Chassis ground under hood	Battery (-)	500	1.06	
8	Car door handle	Battery (-)	500	>2,000	
9	DC bus (+)	Chassis ground under hood	500	1,500	Took a long time to charge; was still charging after 30 sec.
10	DC bus (+)	Car door handle	500	>2,000	
11	Chassis ground under hood	DC bus (+)	500	1,500	Took a long time to charge; was still charging after 30 sec.
12	Car door handle	DC bus (+)	500	>2,000	
13	DC bus (-)	Chassis ground under hood	500	>2,000	
14	DC bus (-)	Car door handle	500	>2,000	
15	Chassis ground under hood	DC bus (-)	500	>2,000	
16	Car door handle	DC bus (-)	500	>2,000	
17	DC bus (+) elec. mod.	Chassis ground under hood	500	1.15	
18	DC bus (+) elec. mod.	Car door handle	500	>2,000	
19	Chassis ground under hood	DC bus (+) elec. mod.	500	1.15	
20	Car door handle	DC bus (+) elec. mod.	500	>2,000	
21	DC bus (-) elec. mod.	Chassis ground under hood	500	1.15	
22	DC Bus (-) elec. mod.	Car door handle	500	>2,000	
23	Chassis ground under hood	DC bus (-) elec. mod.	500	1.15	
24	Car door handle	DC bus (-) elec. mod.	500	>2,000	

Table B-8. Vehicle 2 DC chassis resistance test 2.

Test #	Probe Location (+)	Probe Location (-)	Current (A)	Voltage (V)	Notes
1	Battery case ground	Inverter case	8	0.0026	Res = 0.00033
2	Battery case ground	Chassis ground	8	0.0109	Res = 0.00136
3	Inverter case	Chassis ground	8	0.0118	Res = 0.00146
4	DC bus (+) case	Chassis ground	8	0.0436	Res = 0.00545
5	DC/DC case	Chassis ground	8	0.0118	Res = 0.00148

Table B-9. Vehicle 2 AC chassis resistance.

Test #	Probe Location (+)	Probe Location (-)	Test Voltage (V)	Z (100Hz) (Ω)	Z (1kHz) (Ω)	Z (10kHz) (Ω)	Z (100kHz) (Ω)	Notes
1	Inverter case pipe	Chassis ground	1	17.5m<1.49	18.75m<7.4	28.2<22.6	73m<5	
2	Door handle	Chassis ground	1	800<70	25k<-140	40k<-80	5k<-88	Readings were not steady
3	Battery case ground	Chassis ground	1	1.69m<25.2	5.16m<55.5	26.6m<68.2	136m<111	

Table B-10. Vehicle 3 isolation resistance.

Test #	Probe Location (+)	Probe Location (-)	Test Voltage (V)	Res (MΩ)	Notes
1	Battery (+)	Chassis ground under hood	500	1.197	Connected to A terminal (assumed to be battery +) in connector
2	Battery (+)	Chassis painted under hood	500		Could not access test point
3	Battery (+)	Car door handle	500	1.19	Door handle destroyed went to edge of door by handle
4	Chassis ground under hood	Battery (+)	500	1.19	
5	Chassis painted under hood	Battery (+)	500		Could not access test point
6	Car door handle	Battery (+)	500	1.19	Door handle destroyed went to edge of door by handle
7	Battery (-)	Chassis ground under hood	500	1.19	
8	Battery (-)	Chassis painted under hood	500		Could not access test point
9	Battery (-)	Car door handle	500	1.19	Door handle destroyed went to edge of door by handle
10	Chassis ground under hood	Battery (-)	500	1.2	
11	Chassis painted under hood	Battery (-)	500		Could not access test point
12	Car door handle	Battery (-)	500	1.19	Door handle destroyed went to edge of door by handle
13	DC bus (+)	Chassis ground under hood	500	>2,000	
14	DC bus (+)	Chassis painted under hood	500		Could not access test point
15	DC bus (+)	Car door handle	500	>2,000	Door handle destroyed went to edge of door by handle
16	Chassis ground under hood	DC bus (+)	500	>2,000	
17	Chassis painted under hood	DC bus (+)	500		
18	Car door handle	DC bus (+)	500	>2,000	Door handle destroyed went to edge of door by handle
19	DC bus (-)	Chassis ground under hood	500	>2,000	
20	DC bus (-)	Chassis painted under hood	500		Could not access test point
21	DC bus (-)	Car door handle	500	>2,000	Door handle destroyed went to edge of door by handle
22	Chassis ground under hood	DC bus (-)	500	>2,000	
23	Chassis painted under hood	DC bus (-)	500		Could not access test point
24	Car door handle	DC bus (-)	500	>2,000	Door handle destroyed went to edge of door by handle
25	Motor Phase A	Chassis under hood	500		Did not have access to motor phases as they appeared to be enclosed inside the housing for the motor and ICE drive train

Test #	Probe Location (+)	Probe Location (-)	Test Voltage (V)	Res (MΩ)	Notes
26	Motor Phase A	Car door handle	500		Did not have access to motor phases as they appeared to be enclosed inside the housing for the motor and ICE drive train
27	Chassis under hood	Motor Phase A	500		Did not have access to motor phases as they appeared to be enclosed inside the housing for the motor and ICE drive train
28	Car door handle	Motor Phase A	500		Did not have access to motor phases as they appeared to be enclosed inside the housing for the motor and ICE drive train
31	DC bus (+) elec. mod.	Chassis ground under hood	500	1.19	
32	DC bus (+) elec. mod.	Car door handle	500	1.2	Door handle destroyed went to edge of door by handle
33	Chassis ground under hood	DC bus (+) elec. mod.	500	1.2	
34	Car door handle	DC bus (+) elec. mod.	500	1.2	Door handle destroyed went to edge of door by handle
35	DC bus (-) elec. mod.	Chassis ground under hood	500	1.2	
36	DC bus (-) elec. mod.	Car door handle	500	1.2	Door handle destroyed went to edge of door by handle
37	Chassis ground under hood	DC bus (-) elec. mod.	500	1.2	
38	Car door handle	DC bus (-) elec. mod.	500	1.2	Door handle destroyed went to edge of door by handle

Table B-11. Vehicle 3 DC chassis resistance test 2.

Test #	Probe Location (+)	Probe Location (-)	Current (A)	Voltage (V)	Notes
1	Battery case ground	Inverter case	8.04	0.01	Res = 0.00124
2	Battery case ground	Chassis ground	8.04	0.003	Res = 0.000373
3	Inverter case	Chassis ground	8.04	0.0105	Res = 0.00131
4	Chassis ground	DC bus (+) case	8.04	0.0167	Res = 0.002008
5	Chassis ground	DC/DC case	8.04	0.0042	Res = 0.000522

Table B-12. Vehicle 3 AC chassis resistance.

Test #	Probe Location (+)	Probe Location (-)	Test Voltage (V)	Z (100Hz) (Ω)	Z (1kHz) (Ω)	Z (10kHz) (Ω)	Z (100kHz) (Ω)	Notes
1	Inverter case pipe	Chassis ground	1	13.2<2.64	15.8m<12.8	30m<47.7	167m<82.1	
2	Door edge by handle	Chassis ground	1	24.95<0	25<-0.17	24.88<-1.06	23.99<-6.13	The door handle was destroyed from the crash and appears to be plastic. Attached to the door edge by the handle instead
3	Battery case ground	Chassis ground	1	0.87m<55.3	5.2m<71.7	35m<77.38	266.3m<94.8	The ground straps to the battery were not there so the clip was attached directly to the chassis ground screws

Appendix C. Indirect Contact Protection Demonstration Kit

A portable demonstration kit was constructed to facilitate the understanding of various indirect contact scenarios with respect to the electric shock potential in high-voltage electric vehicles and to allow for the demonstration of direct contact method testing with the IPXXB Finger Probe. This kit is designed to provide the user with interactive hardware that safely demonstrates abstract concepts.

The demonstration kit consists of the following items. Some items are used in both the direct and indirect contact simulations.

- (1) Model car with onboard electronics
- (2) Indirect contact breakout cables (one is a spare)
- (1) LiIon battery charger
- (1) Aluminum electronic enclosure
- (1) Aluminum electronic enclosure with measured slot and circuit card
- (1) IPXXB finger probe
- (2) Red alligator probe clips
- (2) Black alligator probe clips
- (1) Bag of wires and test cables

Figure C-1. Demonstration kit car, test cables, test clips and battery charger.

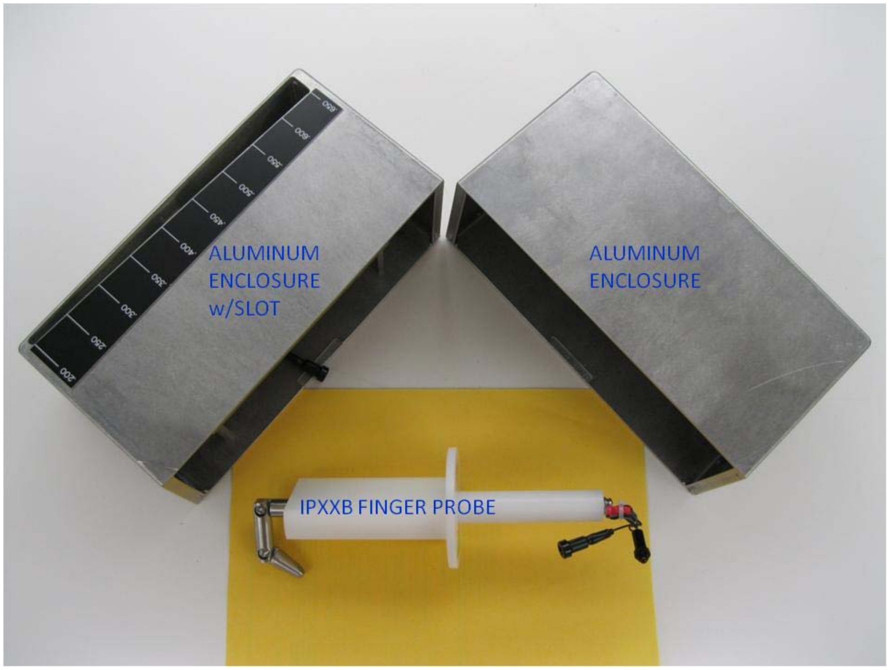


Figure C-2. Demonstration kit enclosure boxes and IPXXB finger probe.

C-1 Indirect Contact Demonstration

Indirect contact scenarios can be emulated using the model car along with the aluminum enclosure boxes and interconnecting cables. The model car contains electronics and indicators that provide feedback to the user during testing. The car contains a rechargeable lithium ion battery, a vibration motor, and two circuit card assemblies (CCA), one under the hood and the other in the back storage area. There is an on/off switch and two light emitting diodes (LED) on the vehicle. The LED under the hood illuminates to alert the user of a simulated electric shock. The LED in the back storage area informs the user that the lithium ion battery needs to be recharged.

How it Works

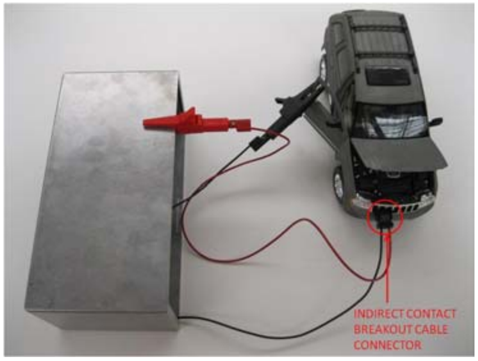
The indirect contact demonstration circuit inside the car puts out a low voltage, low current (10VDC max, 50uADC max) test signal that is used to measure the resistance across the Battery Test Probes. Based on the value of the resistance across these probes, an indicator LED and vibration motor are simultaneously energized to alert the user of a simulated electric shock.

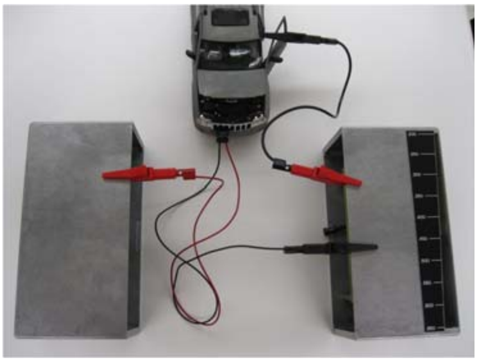
The resistance of the human body varies greatly and is dependent on several factors such as skin contact area, environmental conditions, moisture level on skin, etc. The circuit in the car detects the difference between an open circuit, a short circuit, and a resistance that is typical for the human body. If an open or short circuit is detected, the LED and motor will remain off. If the car detects a resistance in the range of approximately 500Ω to 1MΩ, (typical of the human body) the LED and motor will switch on. The vibration motor is intended to indicate when a shock might be experienced by a body contacting a vehicle with an impaired high-voltage system. If the test setup is such that the user is not directly touching the vehicle and no vibration is felt, the LED under the hood provides the necessary feedback.

How to Set Up the Indirect Contact Simulator

The setup for the indirect contact simulator is fairly simple. It requires the use of the model car, (1) battery probe cable, (1) red alligator clip probe, (1) black alligator clip probe, and (2) aluminum enclosure boxes. Follow these steps to configure and connect the setup.

1. Flip the switch under the hood of the model car to the ON position
2. Arrange the model car and one of the aluminum enclosure boxes in close proximity to the hood of the car
3. Attach the alligator probe clips to the red and black ends of the indirect contact breakout cables respectively
4. Clip the red alligator probe to the aluminum enclosure box
5. Clip the black alligator probe to any metal part of the model car
6. Connect the other end of the indirect contact breakout cable to the connector in the front grill of the car (the writing on the connector should face up from the table; a picture of the setup is shown in step 7)

7. 

8. With one hand touch the aluminum box and with the other hand touch the model car. The LED under the hood should illuminate and the car should begin to vibrate
9. Move the black alligator clip from the car to the same aluminum enclosure box as the red alligator clip
10. With one hand touch the aluminum box and with the other hand touch the model car; the LED under the hood should remain off
11. Add the second enclosure with slot to the setup by connecting the black alligator clip of the indirect contact breakout cable to the second enclosure
12. Attach the red and black alligator clips to one of the test cables
13. Connect the test cable between one of the aluminum enclosures and the car. A picture of the setup is shown in step 14
14. 
15. Touch between the following locations:
    a. Car and enclosure with no slot – LED should illuminate
    b. Car and enclosure with slot – LED should remain OFF
    c. Enclosure with no slot and enclosure with slot – LED should illuminate.

The steps listed above demonstrate the concept of a failure of the protective barrier. The setup can be configured in additional ways to illustrate the concept. The steps here serve to present the initial concept. In step 9, this scenario represents the battery terminals shorting to a protective barrier that is isolated from the chassis causing a shock potential if a person touches the barrier (aluminum enclosure box) and the chassis of the car (model car). In step 11, this scenario represents the battery terminals shorting together over a sufficiently low resistance to protect the user from shock, which is why the LED does not illuminate. Step 15 is a different configuration that represents the same concept as step 9.

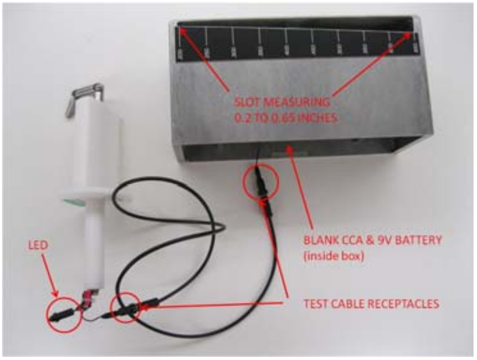
C-2 Direct Contact Demonstration

The direct contact demonstration uses the IPXXB jointed finger probe. The probe is used to simulate the reach and range of motion of the average person's finger. It is used to determine the accessibility to dangerous voltage levels in situations where live parts are intentionally or circumstantially accessible. The finger probe is used in conjunction with the aluminum enclosure box that has a measured slot cut into one side. The slot in the box has a measurement gauge that corresponds to the width of the opening at that point. Inside the box a bare circuit card and a 9V battery are mechanically attached to the base of the enclosure. The jointed finger probe has an LED on the handle that illuminates if the probe touches the energized portion of the circuit card.

How it Works

The positive terminal of the 9V battery inside the enclosure is connected to the circuit card and the negative terminal is connected to a female banana receptacle. If a test wire is connected between the receptacle on the box and the probe, the probe can be used to detect the minimum slot width and finger positions required to contact the circuit card inside the box. When the finger probe contacts the section of the circuit that is energized by the battery, the circuit is completed through the LED, and the LED illuminates.

How to Set Up the Direct Contact Simulator

1. Use a black banana to banana test cable to connect the LED on the probe to the battery terminal in the aluminum enclosure as shown in step 2.
2. 

3. Insert the jointed test probe finger into the slot of the aluminum box and manipulate the finger so that it contacts various sections of the circuit card. When the finger contacts a section that is energized by the battery, the LED will illuminate.
4. Try different configurations with the finger and touch different metal areas of the circuit card (not all are energized)

The steps listed above demonstrate the use of the IPXXB finger probe in assessing direct contact hazards. The probe can only be inserted through part of the slot in the top of the box. The amount of the probe that protrudes through the slot can be observed from the side opening in the box.

Appendix D: AC Waveforms Induced on a DC Bus by Inverters and Converters

The high-voltage DC bus on an electric vehicle refers to any portion of the circuit that has a measured voltage of greater than 60VDC and less than 1,500VDC. It is common for manufacturers to use a battery that produces several hundreds of volts and a DC/DC converter to boost that voltage to a higher, better regulated value that is then used by the inverter to control the propulsion motor. A schematic of this concept is shown in Figure D-1.

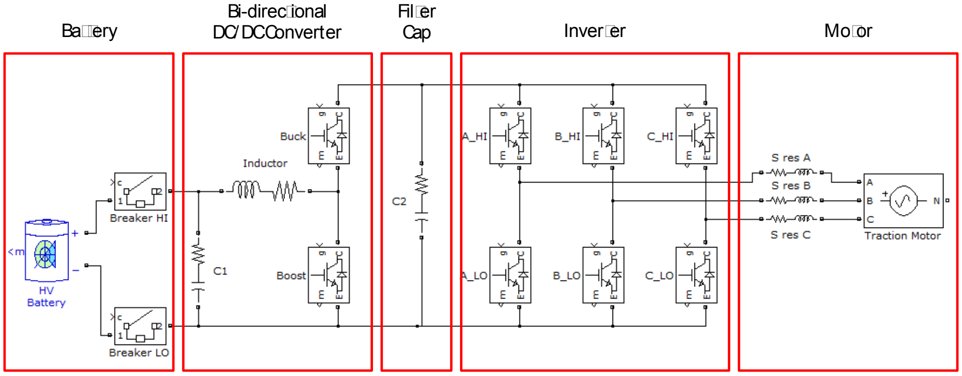


Figure D-1. Representative vehicle schematic showing sections of the circuit.

DC-DC Inverters

The inverter circuit in Figure D-1 works by sequentially switching the six transistors in specific pairs. The inverter generates an AC waveform by switching the transistors to provide both the full positive and negative DC bus voltage to the motor terminals. This pulse width modulated (PWM) waveform is filtered by the inherent inductance in the motor that smoothes the current waveform into the motor. Each time a transistor pair is switched on, current is provided by the filter capacitor and sent into the motor and each time this happens the voltage on the capacitor drops. As a result the inverter also causes an AC ripple on the DC bus voltage across the capacitor. Generating an example simulation that shows the ripple voltage induced by an inverter connected to a permanent magnet synchronous motor or DC brushless motor is beyond the scope of this effort because of the complexity of the flux vector control algorithm that must be employed to make the simulation realistic. The principles introduced in the previous section still apply because a capacitor is repeatedly charged and discharged. The ripple voltage on the capacitor that is induced by the inverter is dependent on the motor current, the switching frequency, duty cycle, and the characteristics of the capacitor. Generally when sizing the capacitor on the input of an inverter the ripple voltage should be 5 percent or less for the worst case load. If we assume a bus voltage of 500V, the result is 25V peak to peak at 5 percent, and the energy of peak to peak voltage is spread across several frequencies that are related to the switching frequency of the inverter.

Regenerative Braking Waveforms

The inverter may also allow energy to be recovered from the motor and sent back into the battery. Regenerative braking slows down the vehicle by using the energy generated by the back electromotor force (emf) of the motor. During regenerative braking the diodes located in the transistors in the inverter conduct in pairs and allow current to flow from the motor to the filter capacitor. The capacitor voltage increases until the DC/DC converter transfers the energy building in the capacitor back to the battery. This concept is shown in Figure D-2. The red arrows indicate the direction of power flow.

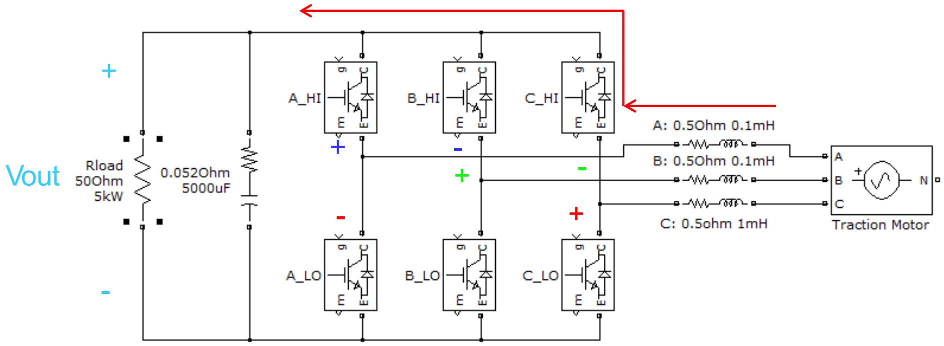


Figure D-2. Schematic showing regenerative braking.

Using the schematic in Figure D-2 and some assumptions about the system, the ripple voltage on the DC bus can be obtained from a simulation. For this simulation the motor is modeled with a 3 phase voltage source with a fixed magnitude and a variable frequency from 0 to 83Hz. The frequency of the voltage is ramped to simulate the variable frequency that would occur while slowing down a vehicle. In the model the frequency ramps up from 0 to 83Hz in one second, but in a vehicle the frequency of the voltage would ramp down with a decrease in the rotational velocity of the motor. In a practical application, the back emf developed by the motor would decrease with motor speed. This decrease in voltage is not modeled in order to keep the model simple. This model serves to illustrate the concept of ripple on the DC bus from regenerative braking. It does not attempt to approximate exact ripple magnitudes. It was assumed that the motor had 4 poles, a max rpm of 2,500, and a nominal back emf of 372Vrms. Based on the assumed number of poles and the maximum rpm, the electrical frequency of the motor is approximately 83Hz at the maximum rpm. If these numbers are inserted into a simulation, results are obtained as shown in Figure D-3. The impact on the ripple voltage is illustrated best in the Zoom 2 plot in Figure D-3. Only the highest frequency section of the plot (75Hz to 83Hz) is highlighted because of the lack of sufficient detail to accurately represent the varying voltage magnitude of the back emf as the motor slows down. The peak to peak ripple voltage over these frequencies is approximately 2.5V that is less than 1 percent of the total bus voltage of approximately 500VDC.

The ripple on the DC bus generated by regenerative braking is only sustained for short periods of time during the braking process. The magnitude and duration of the energy absorbed during braking is dependent on the vehicle dynamics, the driver, and the battery management system.

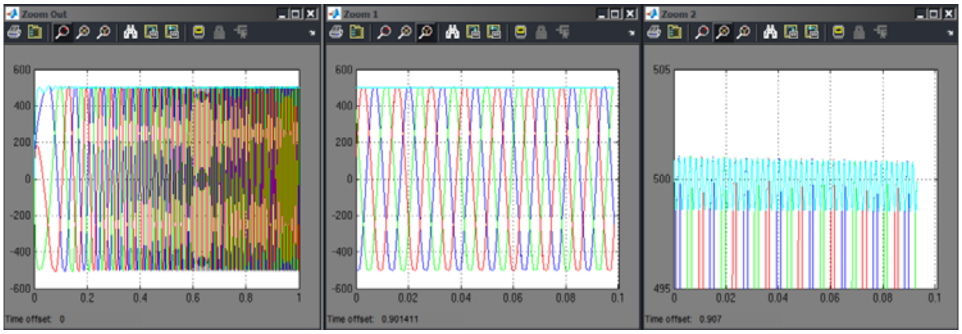


Figure D-3. Waveforms of regenerative braking using assumptions and circuit above.

DC/DC Converter Step Up Waveforms

During normal operation when the battery provides power to the motor, the battery voltage is boosted up via the DC/DC converter. The voltage is boosted by switching the “Boost” transistor at high frequencies. Each time the boost transistor is gated on, energy is stored in the inductor. The stored energy is then released through the diode in the “Buck” transistor into C2 during the off-time of the Boost transistor. C2 acts to filter the ripple that is generated on the voltage from the switching frequency. This ripple is dependent on the switching frequency, duty cycle, the load, the magnitude and type of capacitance used for the C2 filter, and whether the converter is in continuous or discontinuous current mode. This method serves to increase the voltage between C1 and C2 and is a common circuit topology used for this type of conversion. In the text below, the term “boost converter” refers to this type of circuit operation.

As stated previously the ripple voltage observed on the filter capacitor is dependent on several factors. Technically, the voltage across the filter capacitor is a DC voltage; however, the fact that there is some ripple on this voltage means that AC components are present. The extent to which they are present depends on the magnitude and frequency components of the ripple and is generally analyzed using a Fourier analysis. The peak-to-peak ripple voltage on the DC bus can be estimated using documented equations that generally assume ideal conditions (no parasitics, instantaneous switch times, etc.). A simulation using MATLAB Simulink was developed to demonstrate the presence of ripple on the DC bus. For this simulation only the battery and the boost converter are evaluated. The battery is represented in a simplified form with the voltage source and a source resistance. The schematic used in the simulation is shown in Figure D-4. The red arrows show the power flow in the circuit. This circuit topology was provided by OEMs and is assumed to representative of what is actually used in vehicles. It should be noted that several different circuit topologies can be used to boost voltage from one magnitude to another.

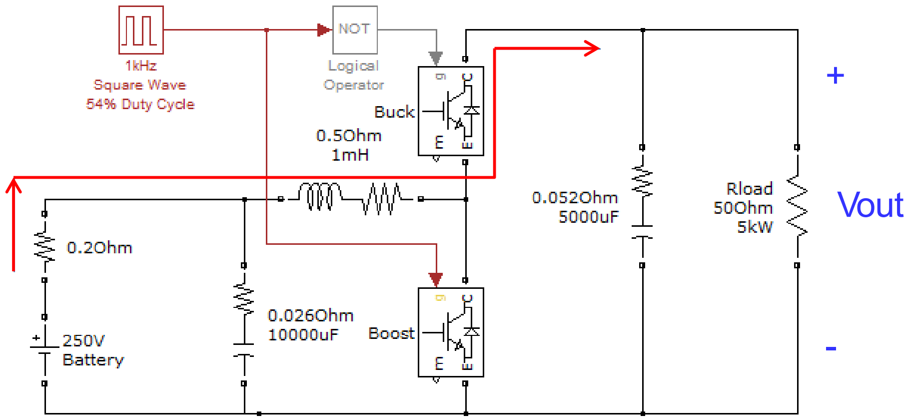


Figure D-4. Battery and boost converter circuit, MATLAB Simulink.

The transistors in this example are ideal, the capacitor attributes were selected based on Nichicon capacitor part number, LNC2V103MSEH, the inductor attributes were assumed, and the load resistance was arbitrarily selected to be a constant 50Ω in order to produce approximately 5kW at the output. This simulation was constructed such that the boost circuit doubles the input voltage at the output yielding approximately 500VDC. The voltage waveform at the output of the circuit is shown in Figure D-5.

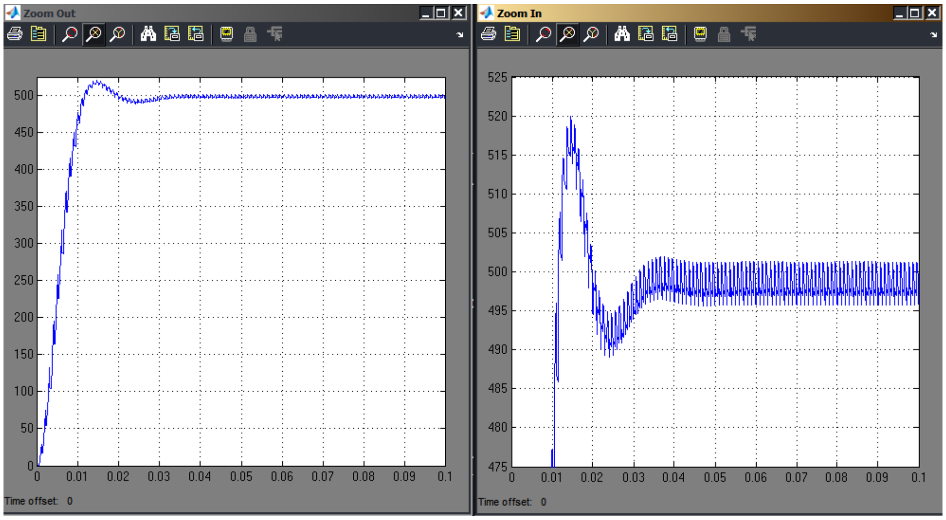


Figure D-5. Ripple voltage on the DC bus due to switching characteristics of a Boost Converter.

The peak-to-peak ripple is approximately 5V or one percent of the total DC voltage. A ripple on the DC bus of one to two percent is generally good design practice but higher ripple voltages are acceptable depending on the application. In this example, the boost converter was the only section of the circuit in Figure D-4 that was evaluated; however, it is important to note that it is not the only section of the circuit that affects the ripple voltage seen across the filter capacitor between the DC/DC converter and the inverter. The inverter also induces a ripple voltage onto the DC bus as the transistors that control current into the motor are turned on and off.

DC/DC Converter Step-Down Waveforms

In a regenerative braking scenario, the DC/DC converter acts as a buck converter to step the voltage down to a level that is suitable to charge the battery. During this step-down process, the "buck" transistor switches at a high frequency. If the buck transistor is on, current flows into the inductor. Once the buck transistor turns off, the stored energy in the inductor is released and current is provided to the capacitor and battery. The diode in the boost transistor conducts to complete the circuit and the boost transistor may even be turned on to increase efficiency. In the text below, the term "buck converter" refers to this type of circuit operation. A schematic of this topology is shown in Figure D-6. The red arrow indicates the direction of power flow. This circuit is active during regenerative braking. The 500V source and source impedance on the right side of the circuit are a simplified representation of the inverter and motor from the regenerative braking section. The battery has an assumed nominal voltage and series resistance and the transistors are ideal.

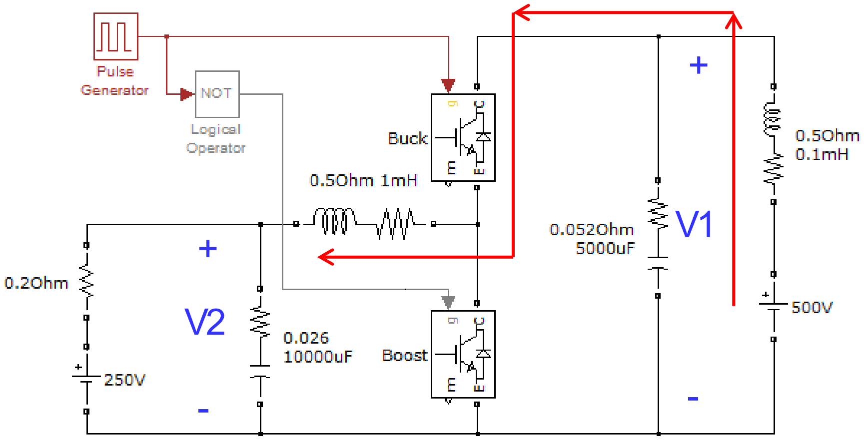


Figure D-6. Schematic of a buck converter topology.

The switching waveforms for this circuit are similar to others in this section. The voltages on both the input and output of the converter have a ripple component. This is shown in Figure D-7. The ripple on the 500V side of the converter is approximately 7 volts peak to peak and the ripple on the 250V side of the converter is approximately 3.5 volts peak to peak. The percent ripple for each side is between 1 and 2 percent in this example. As stated in the regenerative braking section, the buck converter only operates for short intervals when energy is moved back into the battery.

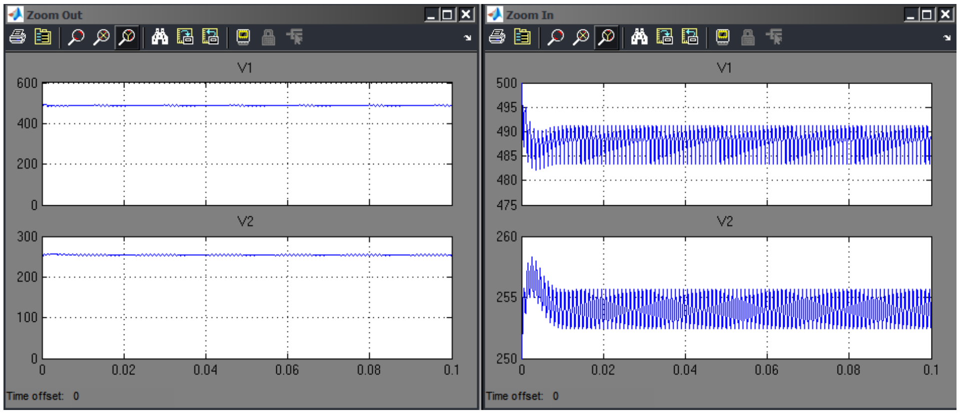


Figure D-7. Buck converter simulation ripple voltages.

Ripple Voltages with Respect to Isolation Voltage

The intention of this section was to develop models and simulations that demonstrate the existence of AC voltages on the DC bus. The actual magnitude of these voltages is dependent on the design of each vehicle.

The voltages selected for these simulation, 250VDC and 500VDC, both are within the lower portion of the range for a high-voltage DC bus defined in the ELSA 2010 Draft document. If a similar analysis was applied to a DC bus voltage closer to 1,500V the acceptable ripple voltage magnitude would be proportionally higher. For example, if the DC Bus was 1,500VDC with a 5 percent ripple, the peak to peak voltage would be 75V. At 2 percent it would be 30V. Once again the energy of the ripple voltage is not concentrated at a single frequency but over many frequencies that are related to switching frequency.

The DC bus isolation resistance measurement is obtained using a meter that is meant to measure resistance or a resistor insertion method that measures the isolation resistance at an unspecified vehicle state (is the inverter operating, the DC/DC converter, etc.). The AC components on the DC bus may have a different leakage path to the chassis that could affect the overall isolation impedance measurement. In addition, the human body responds differently to AC than to DC signals and the resistance of the body varies with the frequency of the AC signal. The Y capacitors and stray capacitance throughout the vehicle cabling and equipment could provide alternate paths for these high frequency AC components that are generated by the switching power electronics in the vehicle.

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