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Insulation Resistance Measurement in Automotive Environment

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Abstract

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This thesis aims to explore the measurement challenges and identify the primary causes of insulation breakdown in high-voltage EV components, contributing to advancements in EV safety and performance optimisation.

This thesis investigates the factors influencing the insulation resistance of high-voltage components in the electric vehicle (EV) environment, focusing on ensuring system safety and reliability. Conducted as a comprehensive literature review, the study examines the effects of environmental conditions, such as temperature variations, vibrations, and moisture on insulation resistance measurement accuracy.

The research emphasises high-voltage batteries, which are critical to the operation of modern electric and hybrid vehicles. Insulation resistance is vital to effectively separating high-voltage system elements and the vehicle chassis, preventing electrical risks and ensuring operational safety.

Given the increasing adoption of 400–800 V high-voltage systems in electric vehicles (EVs), the study underscores the importance of stringent safety protocols to ensure reliable performance while addressing potential electrical hazards.

The results demonstrate that factors such as temperature fluctuations, vibration, and humidity significantly affect the accuracy and reliability of these measurements. The findings highlight the challenges of ensuring consistent and precise insulation resistance assessments. This thesis contributes to a better understanding of these influencing factors, providing insights that can help improve measurement techniques and enhance the safety and performance of high-voltage automotive systems.

Keywords: insulation resistance, electric vehicles, high-voltage system, battery management system, insulation monitoring

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Tässä opinnäytetyössä tutkittiin korkeajännitekomponenttien eristysvastukseen vaikuttavia tekijöitä sähköajoneuvoissa ja keskitytiin järjestelmän turvallisuuden ja luotettavuuden varmistamiseen.

Työn tavoitteena oli tutkia eristysvastuksen mittaamiseen vaikuttavia tekijöitä ja eristyksen rikkoutumisen syitä sähköajoneuvojen korkeajännitekomponenteissa.

Tässä työssä keskityttiin erityisesti korkeajänniteakkuihin, jotka ovat nykyaikaisten sähkö- ja hybridiajoneuvojen olennaisia osia. Eristysvastuksella on ratkaiseva rooli sähköjärjestelmän korkeajännite-elementtien ja ajoneuvon alustan välisen eristysvastuksen varmistamisessa, mikä suojaa mahdollisilta sähköisiltä riskeiltä. 400–800 V:n korkeajännitejärjestelmät ovat välttämättömiä sähköajoneuvoille ja vaativat turvallisuusprotokollia luotettavan suorituskyvyn varmistamiseksi ja sähköisten riskien vähentämiseksi.

Työssä tutkittujen lähteiden mukaan testejä tehtiin korkeajännitekomponenttien eristysvastuksen mittaamiseksi erilaisissa olosuhteissa. Tulosten mukaan lämpötilan vaihtelut, tärinä ja kosteus voivat vaikuttaa suuresti mittausten tarkkuuteen ja luotettavuuteen.

Avainsanat: eristysvastus, sähköajoneuvot, korkeajännite
Järjestelmä, akun hallintajärjestelmä, eristyksen valvonta

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List of Abbreviations

IRM: Insulation Resistance Measurement

HEV: Hybrid Electric Vehicle

EV: Electric Vehicle

AC: Alternate Current

DC: Direct Current

DUT: Device Under Test

HV: High Voltage

BEV: Battery Electric Vehicle

RESS: Rechargeable Energy Storage System

BMS: Battery Management System

MSD: Manual Service Disconnect

IMD: Insulation Monitoring Device

MIT Megger Insulation Resistance Tester

HVMS High-Voltage Management System

ICEVs Internal Combustion Engine Vehicles

UNECE United Nations Economic Commission for Europe

CAN Controller Area Network

ADC	Analog-to-Digital Converter
ECU	Electronic Control Unit
IGBT	Insulated-Gate Bipolar Transistor
MOSFET	Metal-Oxide-Semiconductor Field-Effect Transistor
SiC	Silicon Carbide
EOS	Electrical Overstress
PMW:	Pulse Width Modulation
HVAC:	Heating, Ventilation, and Air Conditioning
CSI	Current Source Inverter
SEI	Solid Electrolyte Interphase
SOC	State of Charge
MCU	Microcontroller Unit

1 Introduction

The demand for hybrid and electric vehicles (HEVs and EVs) is rising due to environmental concerns and the need to reduce greenhouse gas emissions. These vehicles use high-voltage batteries to store energy and power the wheels, typically at 60 V or higher. The energy is sourced from onboard chargers or external DC converters and used by components such as DC/DC converters and motor control inverters to drive the vehicle and power subsystems such as heating, ventilation, and air conditioning (HVAC), all of which operate on high voltage. [1.]

The high-voltage components in HEV and EV systems are isolated from the vehicle's chassis for functional and occupant safety. The isolation level required depends on the specific application, the location of the subsystem of a vehicle, and the system's peak operating voltage. Typically, HEV and EV systems use three types of isolation: functional, basic, and reinforced. Functional isolation is designed to prevent ground loops and ensure proper operation. Basic isolation provides a single layer of protection against electric shock, while reinforced isolation offers higher safety with two layers of security. [1.]

Insulation is crucial for the safe operation of HEV and EV systems. Various factors, including faulty motor windings, ageing wiring harnesses, and power dissipation, can increase operating temperatures and electrical stress on semiconductors, potentially causing isolation breakdown over time. Although the failure of a single isolation point may not immediately affect system operation, it poses a serious safety risk if a person encounters a high-voltage environment. [1.]

Low insulation resistance in high-voltage components of electric vehicles can cause many problems, such as reduced system performance, safety risks, and energy losses. The operating environment of vehicles (e.g. temperature variations, humidity, and vibration) makes it difficult to measure the insulation resistance. This literature review examines how vehicle insulation resistance can be accurately and reliably measured. [1.]

Measuring insulation resistance and leakage currents helps verify the safety of occupants in HEVs and EVs. According to the UNECE R 100 standard, a minimum insulation resistance of 500 Ω/V must be maintained between the high-voltage systems and the chassis ground, and when the electric vehicle uses AC circuits (AC- Motor) based on the leakage current detected, error-handling functions within the HEV/EV system can be programmed to respond by disconnecting high-voltage relays and discharging the DC-link capacitors as needed. [2.]

Monitoring for leakage or low-resistance paths from high-voltage systems to the low-voltage chassis ground is critical. The required isolation resistance is calculated based on the battery voltage, creating a path to detect insulation failure, with deflections monitored according to the guidance provided in the design documentation. The number of sampling points for measuring isolation leakage may vary depending on the vehicle's architecture. [1.]

This thesis focuses on high-voltage batteries in electric vehicles (EVs) and aims to explore and evaluate current methods for measuring insulation resistance in an automotive environment. The structured literature review was conducted to comprehensively understand this topic, analyzing relevant academic publications, industry reports, and international standards related to insulation resistance measurement. Sources were selected based on their relevance, credibility, and contributions to advancements in this field, with particular emphasis on studies addressing the challenges posed by environmental conditions such as temperature fluctuations, humidity, and vibration.

This thesis presents a study of the basics of insulation resistance, explaining key concepts and the role of insulation in high-voltage automotive applications. Explores various measurement devices used for assessing insulation resistance in the automotive sector, comparing their principles and performance. Focuses on testing methodologies for evaluating the current insulation of battery packs in electric vehicles (EV). Proposes a control strategy for maintaining high-voltage battery insulation, discussing monitoring techniques and safety measures. Examines insulation resistance breakdown mechanisms in different automotive components, highlighting failure modes and contributing factors. Discusses design considerations for electrical insulation in high-voltage EV battery systems, emphasizing best practices for enhancing reliability and safety.

By outlining existing methods and identifying areas for improvement, this thesis aims to contribute to the ongoing development of safer and more reliable insulation resistance measurement techniques in electric vehicles.

2 Insulation resistance basics

Insulation resistance measurement is a method used to evaluate insulators, which typically block the flow of electricity. While conductors allow electricity to flow easily, materials that resist this flow are classified electromagnetically as non-conductors or insulators. Insulators lack free electrons, so their electrons experience only a small change in potential when exposed to high energy levels. Insulators in which the energy state of electrons shifts upon the application of electrical energy (such as voltage) are indicated as dielectrics. [3, p. 5.]

2.1 Insulation resistance (IR)

Insulators are materials that block the flow of electricity. The greater their resistance, the more effectively they block electrical current. Insulation resistance refers to the very high resistance typical of insulating materials. This resistance is generally measured by applying a DC voltage across the insulator and observing the current that passes through it, as depicted in (figure 1). [3, p. 8.]

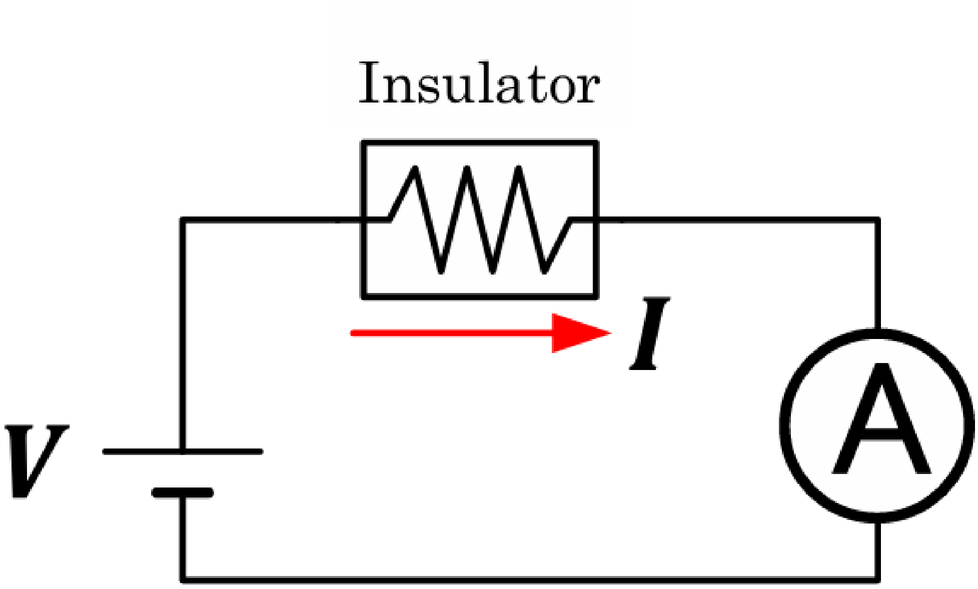


Figure 1. Insulation with applied DC voltage. [3, p. 8.]

In this circuit, the relationship between the DC voltage V and the low current (I) is governed by Ohm's law, similar to what is observed in a typical DC circuit. [3, p. 8].

$$R = \frac{V}{I} \qquad (1)$$

The insulation resistance value is determined using the equation above. In an actual measurement, the applied voltage and the measured current are substituted for V and I, respectively. [3, p. 8].

In this context, resistance specifically means electrical resistance, it is measured in Ohm’s (Ω). When a potential difference V exists across a pair of terminals, charges (electrons or holes) move toward the oppositely charged electrode. Resistance hinders this movement. Based on Ohm's law, the current I can be represented as follows:

$$I = \frac{V}{R} \qquad (2)$$

This law suggests that a greater potential difference V and a lower resistance R will result in a higher current I flow. The resistance value is given by formula (3):

$$R = p\,\frac{l}{s} \qquad (3)$$

$where$:

p indicates resistivity

l is the length of the resistor

s is the cross-sectional area of the resistor.

Resistance rises with the length and narrowness of the conductor. Consequently, the resistance value changes based on physical dimensions, typically falling within the range depicted in (figure 2). [3, p. 6].

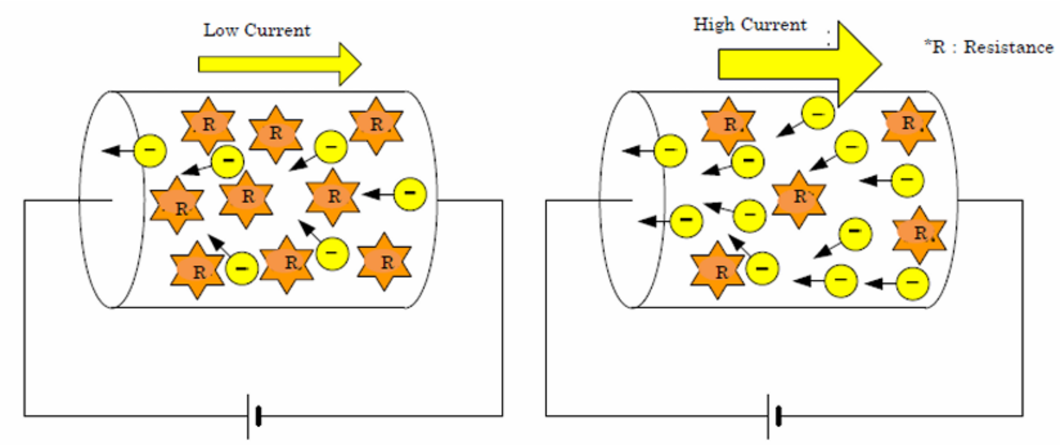


Figure 2. The left picture shows high resistance and the right picture shows low resistance. [3, p. 6.]

2.2 Fundamentals of insulation testing and influencing factors

According to the Chauvin Arnoux Group, Insulation resistance measurement is conducted based on Ohm's law. A DC voltage is applied to a circuit, and the resulting current is measured to calculate resistance. Although insulation resistance is generally very high, it is measurable, and this value reflects the quality of insulation between two conductors. Potential leakage current risks are identified through this test, with resistance values commonly expressed in kilohms (KΩ), megohms (MΩ), gigohms (GΩ), or terohms (TΩ), depending on the measurement device utilized. [4.]

Several factors impact the measurement of insulation resistance, including:

1. Temperature: Insulation resistance varies significantly with temperature. A 10°C rise in temperature can reduce insulation resistance by approximately half, while a 10°C drop can double it. The general guideline highlights the sensitivity of insulation materials to temperature changes. For preventive maintenance, it is important to conduct tests under similar

temperature conditions or corrections to align results with a reference temperature. Insulation resistance should not be measured when the temperature falls below the dew point. Condensation on surfaces can lead to inaccurate results as the moisture interferes with the test. [4.]

2. Humidity: Humidity affects insulation based on the level of contamination on insulating surfaces. High moisture levels create conductive paths, decreasing resistance. [4].

3. Testing Conditions: Variations in test setup or applied voltage can affect results. [4].

2.3 Dielectric measurement and insulation resistance measurement

The dielectric measurement tests the voltage tolerance of the insulation. The main purpose of the measurement is to ensure that insulation distances and leakage current are within acceptable levels. This measurement uses either AC or DC voltage. The measurement requires an instrument suitable for high-voltage measurements. The measurement results in a leakage current value in milliamperes, mA. A dielectric measurement can damage the test object, so this test should only be performed when testing new installations. [4.]

Under normal conditions, the insulation resistance measurement will not damage the being tested. The measurement uses a DC and a lower voltage than a dielectric measurement. The results obtained shall be reported in the form KΩ, MΩ, GΩ, or TΩ. The resistance in question indicates the resistance between two conductors. For example, the test method is suitable for monitoring the ageing of insulation in cables, transformers, capacitors, motors, and generators. The measurement is carried out using an insulation resistance tester. [4.]

2.4 Insulation leakage current theory

According to Texas Instruments, isolation leakage measurements are typically performed within specific subsystems of hybrid or electric vehicles. Predicting the precise location of an isolation failure is challenging and cannot be achieved using isolated measurement methods alone. The most reliable technique to measure leakage current involves deliberately creating a known resistance break in the system's insulation. If no current is detected in the switched circuit, it confirms the absence of a parallel path, indicating the system is free from insulation faults and safe to operate. [1, p. 8.]

For accurate fault analysis, designers must identify the failure type and calculate critical parameters, such as the breakage point (voltage) and resistance, to determine the severity of the fault. Isolation leakage resistance provides valuable insight into potential leakage currents through secondary paths, which could pose electrocution risks to operators or passengers. The isolation should be deliberately broken at two points with predetermined resistance paths for a thorough system diagnosis. [1, p. 8.]

Figure 3 shows an example of isolation breakage measurements using this reference design. S**1** and S**2** are relays that control the switching of the measurement paths. Rps1 and Rps**2** are resistors placed in the high-resistance path on the positive side, while Rns1 and Rns**2** are used on the negative side. Rs1 and Rs2 are series resistors employed for measuring isolation current. An inverting op-amp setup with Vref (bias supply) is used to perform the measurements. [1, p. 8.]

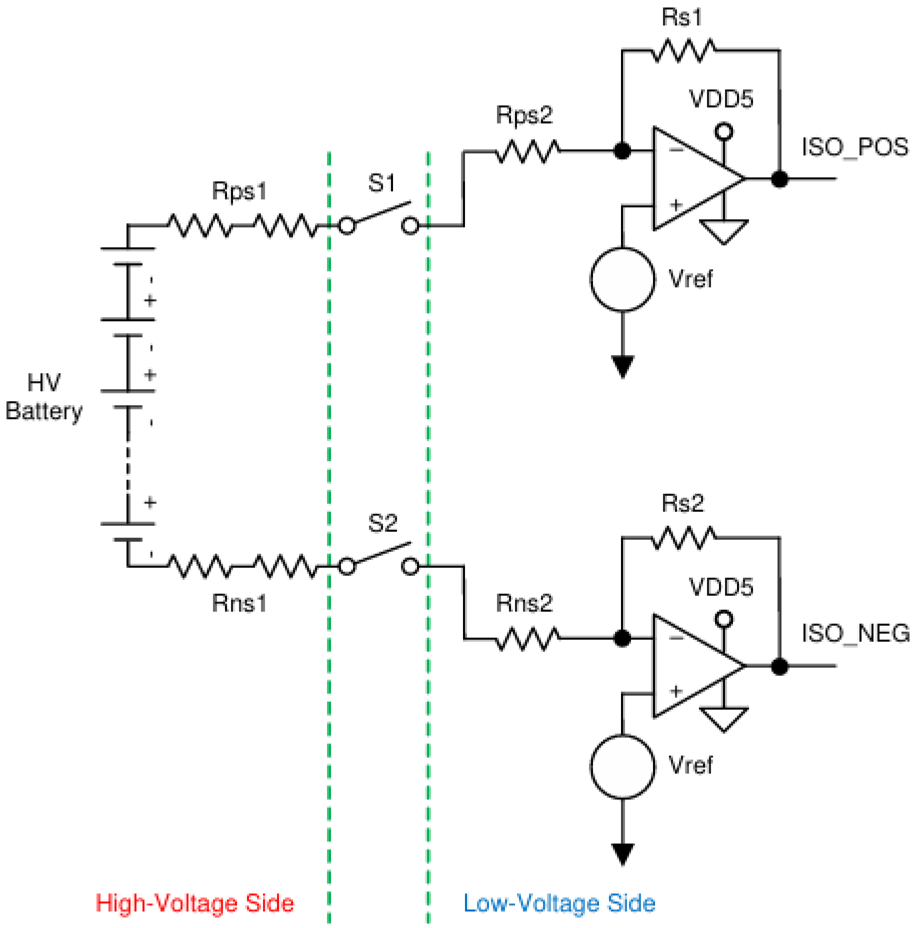


Figure 3. Insulation mechanism in HEV and HV [1, p. 8].

Under normal conditions, when S**1** is closed, no leakage occurs in the circuit because there is no completed path. Ideally, the Vref potential should be set at Rps**1** and Rps**2** for the chassis ground. ISO_POS should remain at the Vref voltage when S**1** is closed. However, depending on the op-amp type, input differential voltage, and bias currents, a real circuit may have some variation in ISO_POS voltage measurements. The circuit behaves similarly when only S**2** is closed, as illustrated in (figure 4). [1, p. 8.]

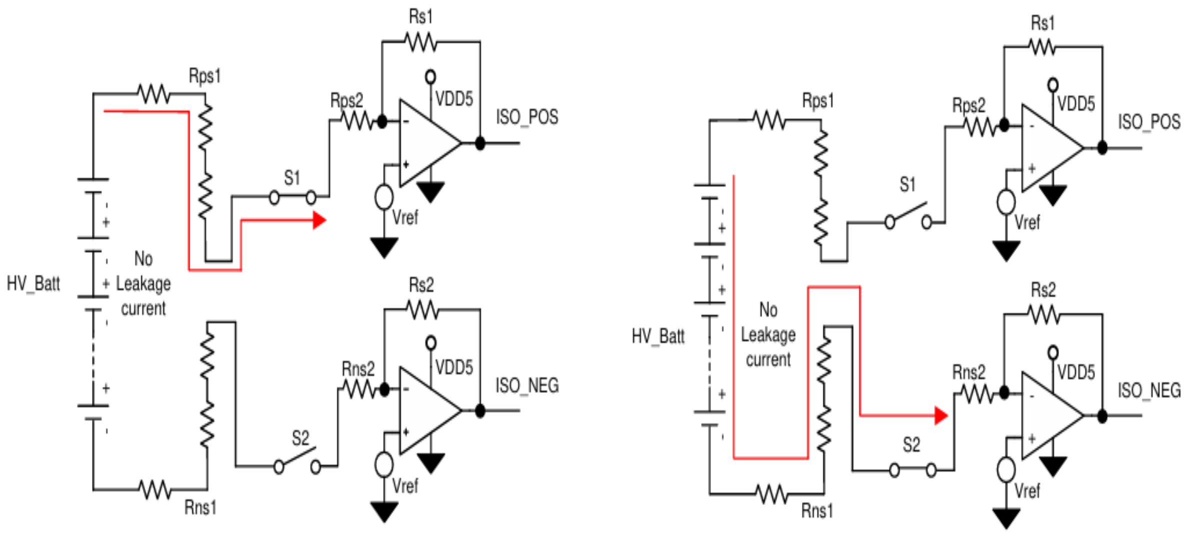


Figure 4. Normal condition: Only one switch is activated [1, p. 8].

Figure 5 demonstrates that when both switches are closed, leakage current from the high-voltage battery flows through the chassis ground of the HEV or EV. The resistors Rps**1**, Rps**2**, Rns**1**, and Rns**2** should be selected to ensure that the leakage current in the chassis ground remains minimal (< 1 mA) even at the maximum battery voltage. [1, p. 9.]

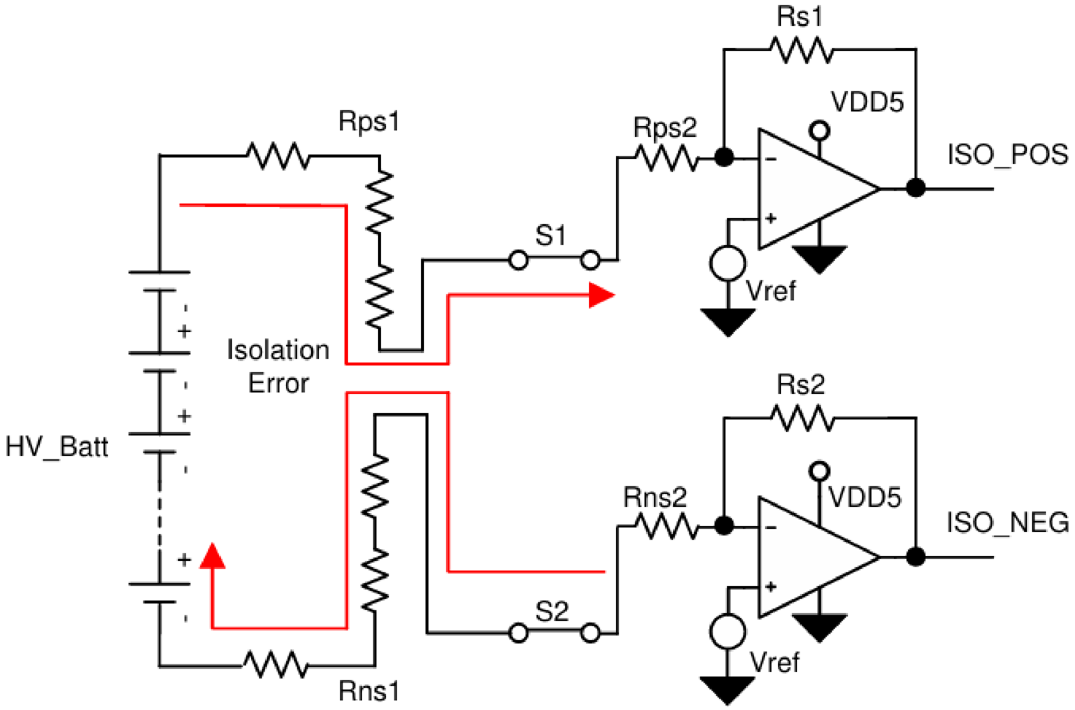


Figure 5. Normal condition: Both switches closed [1, p. 9].

2.5 Insulation monitoring device (IMD)

The insulation resistance in high-voltage ungrounded systems, such as those used in electric vehicles, is monitored using a specialized insulation monitoring device (IMD). According to Bender ISOMETER, this device is designed to operate within a voltage range of DC 0–1000 V, continuously measuring the insulation resistance between the active conductors of the high-voltage (HV) system and the vehicle's chassis ground. The IMD provides early alerts for potential ground faults, ensuring system safety. [5.]

The insulation monitoring device meets the increasing automotive requirements for environmental conditions such as temperature and vibration. The insulation monitoring device connects to the high-voltage potentials, the accumulator ground, and the vehicle's main ground point, as illustrated in (figure 6). [5.]

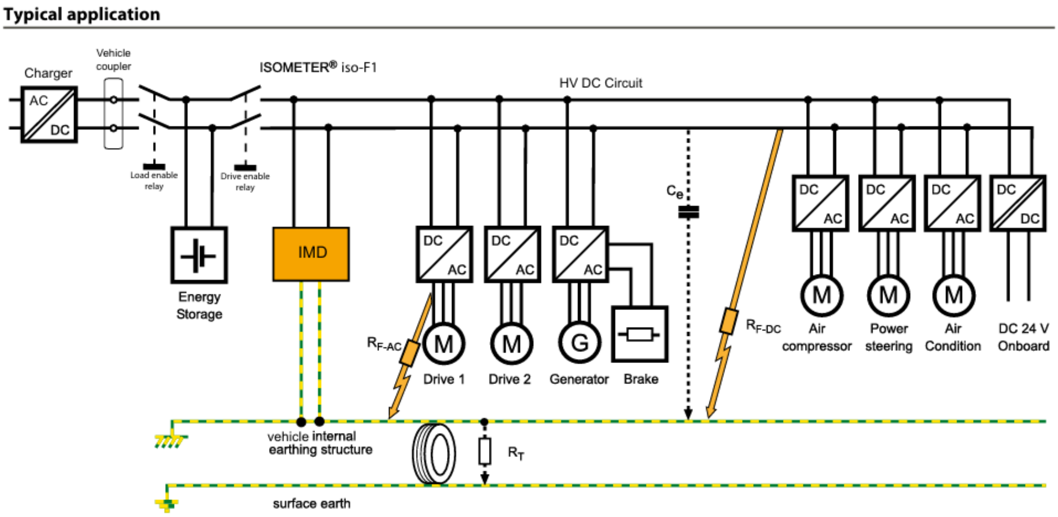


Figure 6. Typical application for IMD [5].

The IR155-3203 and IR155-3204 models are pre-set to monitor resistance in the 0–10 MΩ range, with response thresholds adjustable up to 1 MΩ for customizable fault detection. The minimum permissible resistance between the high-voltage (HV) potential and ground can be determined by multiplying the system's maximum voltage by a set response value, such as 500 Ω/V. [5.]

3 Automotive insulation resistance measurement devices

3.1 Megger insulation resistance tester (MIT 400)

The Megger insulation tester (MIT 400) (figure 7) is a compact, portable device used to measure insulation resistance in units of ohms or megohms. In well-maintained insulation systems, the resistance typically falls within the megohm range. [6].

Figure 7. MEGGER (MIT) 400 SERIES [6].

This tester operates as a high-range ohmmeter with an integrated DC generator. It features specialised construction with current and voltage coils, allowing for accurate resistance measurements regardless of the voltage applied. Importantly, this testing method is non-destructive, meaning it does not harm or degrade the insulation during the process. [6.]

The MIT400 Series provides testing voltages ranging from 10-1000 V and features a customizable low voltage testing mode adjustable in 1 V increments from 10-100 V. It boasts an extensive insulation resistance measurement range from 20-200 GΩ. Additionally, the device allows users to view the test voltage or the leakage current on a secondary display for greater flexibility and precision during testing. [6.]

3.2 High-voltage configuration

In the automotive sector, 60 V and above voltages are categorised as high voltage (HV). Battery packs in electric vehicles are typically designed to meet high voltage safety standards, as specified in relevant international guidelines. A battery pack includes series-connected modules and other high-voltage components, generally enclosed in a secured and insulated box that ensures electrical insulation through physical separation. The overall layout of the high-voltage system in hybrid and electric vehicles incorporates a high-voltage management system (HVMS) installed to prevent accidental contact with high voltages that could result in damage or injury. For safety, the conductive but non-current-carrying parts of the high-voltage system are usually grounded to provide a low-resistance path for high currents if a fault or insulation breakdown occurs between the ground and the high-voltage bus. Figure 8 illustrates the typical configuration of the high-voltage circuit within the HVMS. [7, p. 25.]

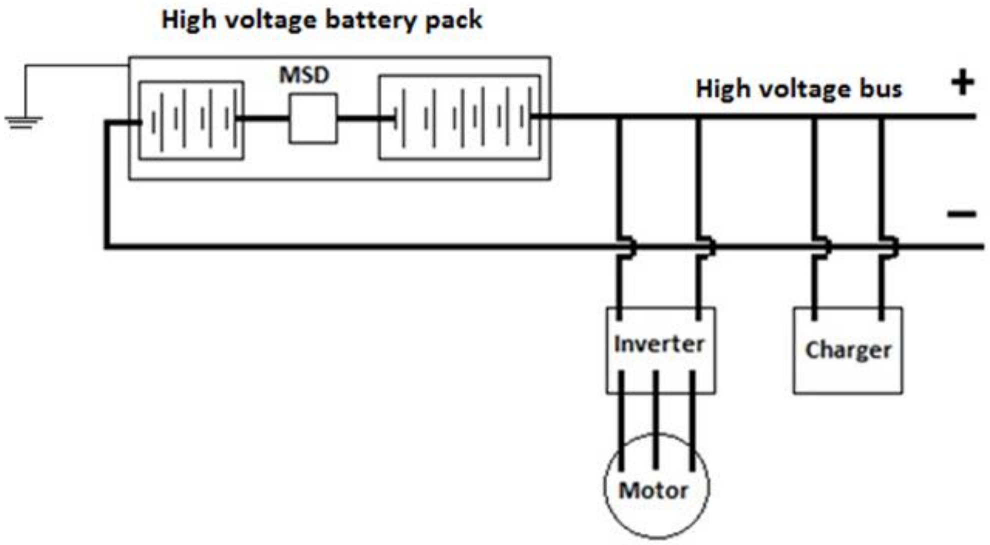


Figure 8. High-voltage circuit configuration. [7, p. 25.]

This thesis focuses specifically on high-voltage batteries. The HVMS performs key functions across the entire high-voltage system:

1. Power control: Manages the high-voltage system's power-up and power-down operations by controlling relays near the battery terminals and disconnecting power in case of a system fault. [7, p. 25].

2. Manual service disconnects (MSD) and high voltage interlock: These features provide a safe environment for battery maintenance and repairs. The interlock circuits indicate the connection status of the high-voltage circuit. If an interlock circuit is broken, the HVMS triggers alarms and disconnects the battery from the high-voltage system. [7, p. 25.]

3. Electric Leakage Protection: The HVMS continuously monitors the insulation of the high-voltage system, cutting power in the event of an electric leakage to protect passengers from potential electric shocks. [7, p. 25].

4. Communication: The communication network facilitates interaction between the battery management system (BMS) and the vehicle ground

(chassis). The battery management system monitors the high-voltage (HV) bus and diagnoses, its status by assessing all high-voltage (HV) components' insulation resistance, leakage currents, relay conditions, and grounding status. [7, p. 25.]

3.3 Hazards of high-voltage systems

In automotive engineering, high voltage refers to electrical voltages ranging from 30-1000 V AC (alternating current) or 60-1500 V DC (direct current). This range is considered high enough to pose significant safety risks, such as electrical shock or arc flash, requiring specialised insulation, handling, and safety measures in vehicles, especially in electric and hybrid designs. [8.]

Electric vehicles (EVs) have durable, long-lasting batteries that enhance their appeal, but high-voltage systems can be hazardous if mishandled. While drivers are as safe in EVs as in conventional cars, technicians and mechanics face higher risks from exposure to high-voltage components, requiring proper training and safety measures. [9.]

3.4 Potential hazards of electric vehicles (EVs)

Electric and hybrid vehicles undergo extensive testing and certification to ensure safety. Batteries are rigorously evaluated under varying conditions, such as overcharging, vibration, extreme temperatures, short circuits, fire, collisions, and water immersion. These measures allow manufacturers to design vehicles that prioritise safety ensuring drivers and passengers only need to focus on routine precautions like wearing seat belts. [9.]

Testing electric vehicle (EV) systems poses risks, particularly for technicians and engineers. Damaged lithium-ion batteries can release toxic chemicals, cause fires, or explode, emphasising the need for stringent safety protocols. High-voltage systems require specialised handling, as they can retain a dangerous charge even when the vehicle is off. Proper training and evaluation are critical, especially for those new to EV technology, to ensure these vehicles' safe manufacture and maintenance. [9.]

3.5 Applying the safety criterion of 500 Ohm’s per volt in the high-voltage system

The standard of 500 Ohm’s per 1 volt for high-voltage systems in vehicles is based on safety principles. It aims to limit the leakage current that could flow between the HV system and the chassis. This standard ensures that, in the event of an insulation failure, the resulting current is low enough to avoid harm to humans. [10.]

In practice, the resistance of the insulation in high-voltage components is often much higher than the minimum requirement, ensuring that the leakage current remains well below levels that could be dangerous. [10].

3.6 Transition to higher DC-link voltage in EVs

Figure 9 highlights the comparison between 400 V and 800 V electric vehicles (EVs), underscoring the inevitability of adopting higher DC-link voltages. The need for fast charging and increased power density primarily drives this shift. Passenger EVs, operating at 800-1000 V voltage levels, are designed to offer charging times comparable to the refuelling time of internal combustion engine vehicles (ICEVs). This makes higher voltage systems a likely standard in future EVs to meet growing customer demands for faster charging solutions. [11, p. 12.]

Higher DC-link voltages can be realized by increasing battery voltage or adjusting the voltage ratio of the boost converter. However, raising the battery voltage adds complexity to the system and necessitates the development of more efficient balancing circuits. As a result, advancements in battery management system (BMS) technologies are expected to play a crucial role in addressing these challenges and enabling the adoption of higher-voltage electric vehicle (EV) architectures. [11, p. 12.]

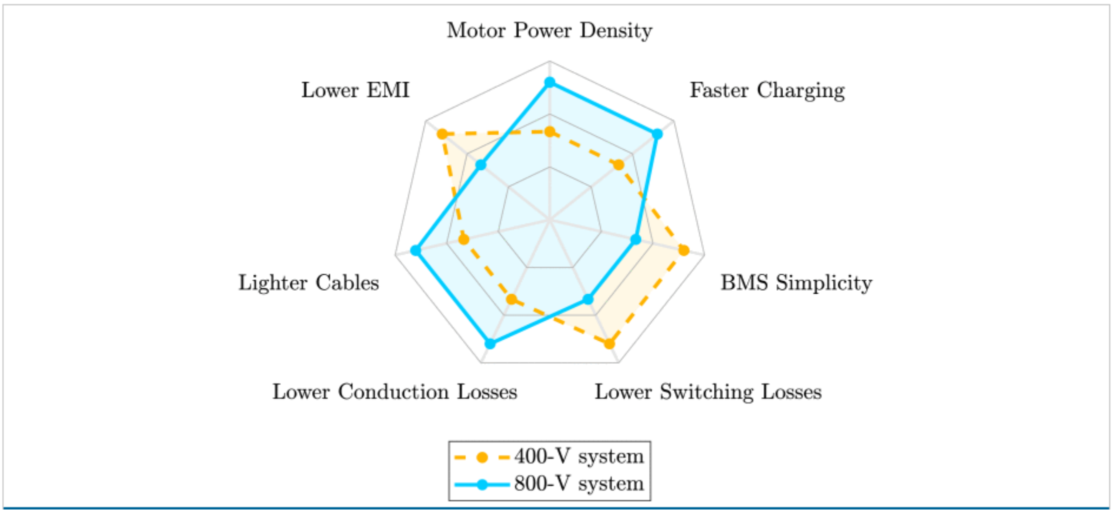


Figure 9. Benefits and limitations of increasing the DC bus voltage in electric vehicle systems. [11, p. 5.]

4 Testing the current insulation of the battery packs in automotive

This chapter reports on a study by Memari and Nakanwagi, where an insulation resistance test was performed on the positive and negative battery terminals, including the cables and batteries, to evaluate the insulation condition of the battery pack. The measurements were conducted from the ground (chassis) to identify potential insulation weaknesses. Additionally, the individual components of the battery pack were tested, with particular attention given to the high-voltage cables on both the positive and negative sides, as well as the series-connected battery modules within the battery pack. [7, p. 66.]

4.1 Measuring insulation resistance on the positive terminal of the battery pack

The insulation resistance of the positive terminal of the battery was evaluated concerning ground (chassis) using a megger and an electrometer in the study by Memari and Nakanwagi. During the megger testing, the bleeder resistors remained connected, reflecting their influence on the measurement results. For the measurements, the device was connected between the positive current-carrying cable and the chassis, as depicted in (figure 10). The setup for the megger was the same as that used for the electrometer. [7, p. 66.]

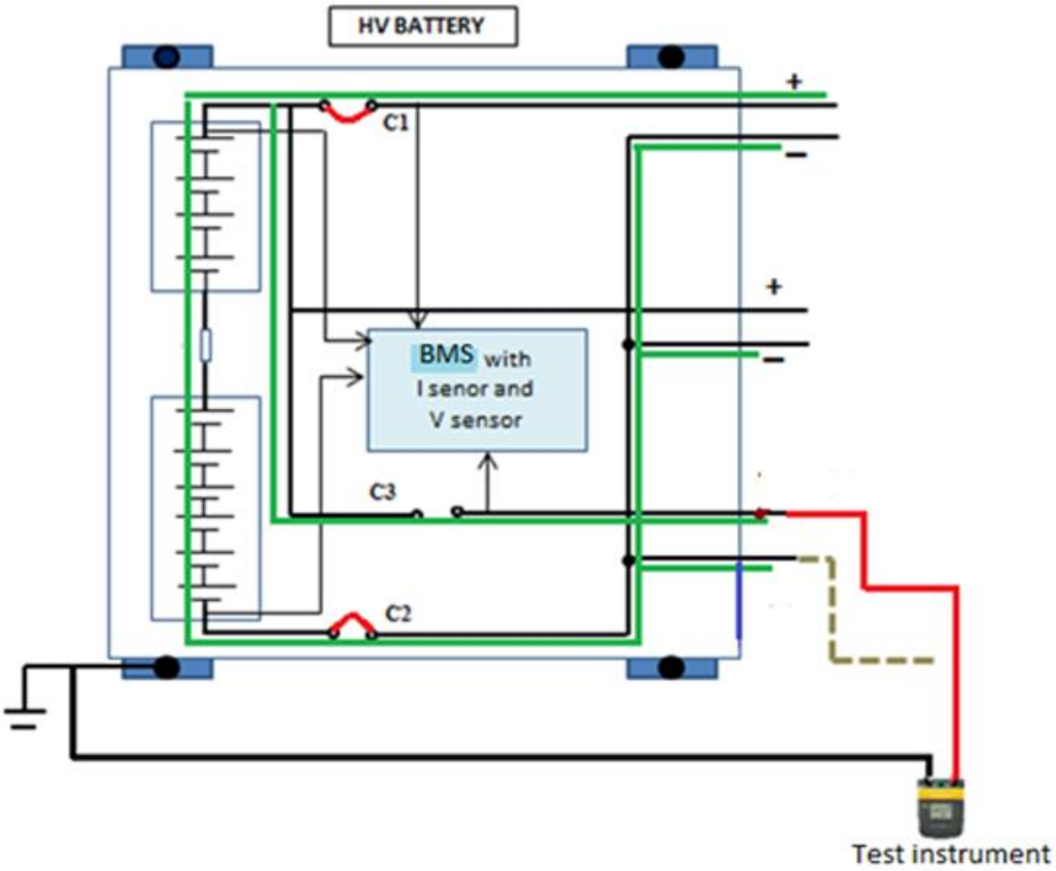
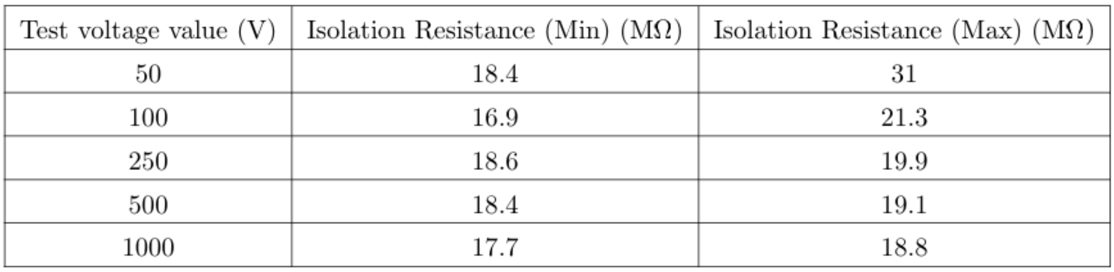


Figure 10. Setup for measuring the insulation resistance of the entire battery pack. [7, p. 66.]

The insulation resistance test was conducted by Memari and Nakanwagi using the megger at test voltages of 50, 100, 250, 500, and 1000 V, with each voltage applied for 60 seconds. After each application, the minimum and maximum values were recorded. The results are presented in (table 1). When the test voltage reached 1000 V, sparking was audible during both the application and disconnection of the DC voltage. [7, p. 66.]

Table 1. Results of the insulation resistance test on the positive side of the battery pack using a Megger. [7, p. 48.]

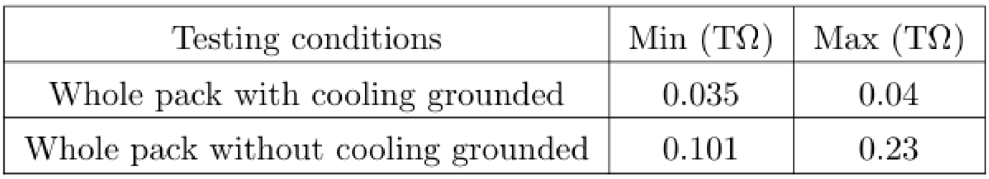


Test voltage value (V)	Isolation Resistance (Min) (MΩ)	Isolation Resistance (Max) (MΩ)
50	18.4	31
100	16.9	21.3
250	18.6	19.9
500	18.4	19.1
1000	17.7	18.8

This test was conducted by Memari and Nakanwagi to evaluate the insulation resistance of the entire battery pack using the electrometer at an applied voltage of 500 V. The bleeder resistors were excluded from assessing the insulation condition without their influence. Two configurations were tested: one with the cooling system grounded and the other with the cooling system ungrounded. The test was carried out for approximately 5 hours until a stable result was achieved. [7, p. 66.]

The results in (table 2) indicate that the measured insulation resistance value is higher when the cooling system is grounded than when it is not. The notable difference in results when using the electrometer can be attributed to the electrical properties of the coolant that connects the battery pack to the ground. [7, p. 48.]

Table 2. Insulation resistance testing of the battery pack using an electrometer. [7, p. 48.]



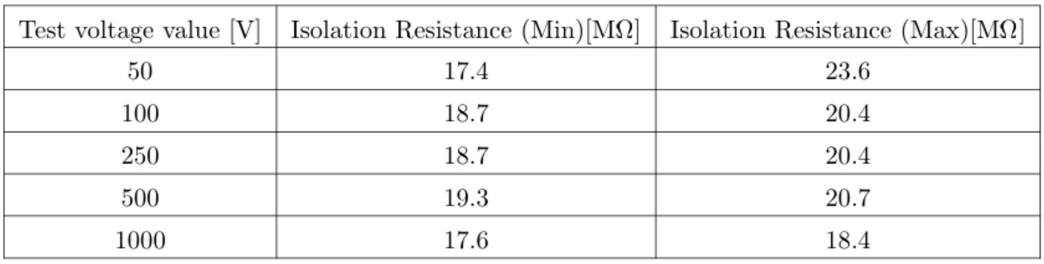
Testing conditions	Min (TΩ)	Max (TΩ)
Whole pack with cooling grounded	0.035	0.04
Whole pack without cooling grounded	0.101	0.23

4.2 Measuring insulation resistance of the negative terminal

The insulation resistance of the negative side of the battery pack to the ground (chassis) was evaluated using a megger. This test was conducted by Memari and Nakanwagi. The bleeder resistors remained connected during the test, ensuring that their influence was reflected in the results. The test device was connected between the negative current-carrying cable and the chassis, as shown in (figure 10), with the instrument attached to the MAIN (-). [7, p. 68.]

Insulation resistance tests were performed at applied voltages of 50, 100, 250, 500, and 1000 V, with maximum and minimum values recorded every 60 seconds, as presented in (table 3). At a test voltage of 1000 V, sparking was audible during both the application and disconnection of the DC voltage. [7, p. 68.]

Table 3. Insulation resistance test results for the negative terminal of the battery pack using the megger. [7, p. 68.]



Test voltage value [V]	Isolation Resistance (Min)[MΩ]	Isolation Resistance (Max)[MΩ]
50	17.4	23.6
100	18.7	20.4
250	18.7	20.4
500	19.3	20.7
1000	17.6	18.4

4.3 Measuring insulation resistance of the HV bus bar (cable)

The importance of separately evaluating the high-voltage bus bar (cable) insulation condition relative to the ground has been emphasized by Memari and Nakanwagi, as it carries the entire voltage output from the battery. To perform insulation resistance tests, all conductors connected to the battery modules were disconnected, and separate tests were conducted on the positive and negative cables. [7, p. 68.]

The testing setup involved connecting the measuring device between the current-carrying parts of the cable and the chassis, as illustrated in (figure 11). In this setup, the solid line represents the positive cable, while the dotted line represents the negative cable. They employed both a megger and an electrometer for the tests. For the Megger test, measurements were taken over 60 seconds at selected voltages of 50, 100, 250, 500, and 1000 V. Notably, the tests on the positive side were conducted without connecting the bleeder resistors at the contactor, while the negative side tests included the bleeder resistors. [7, p. 68.]

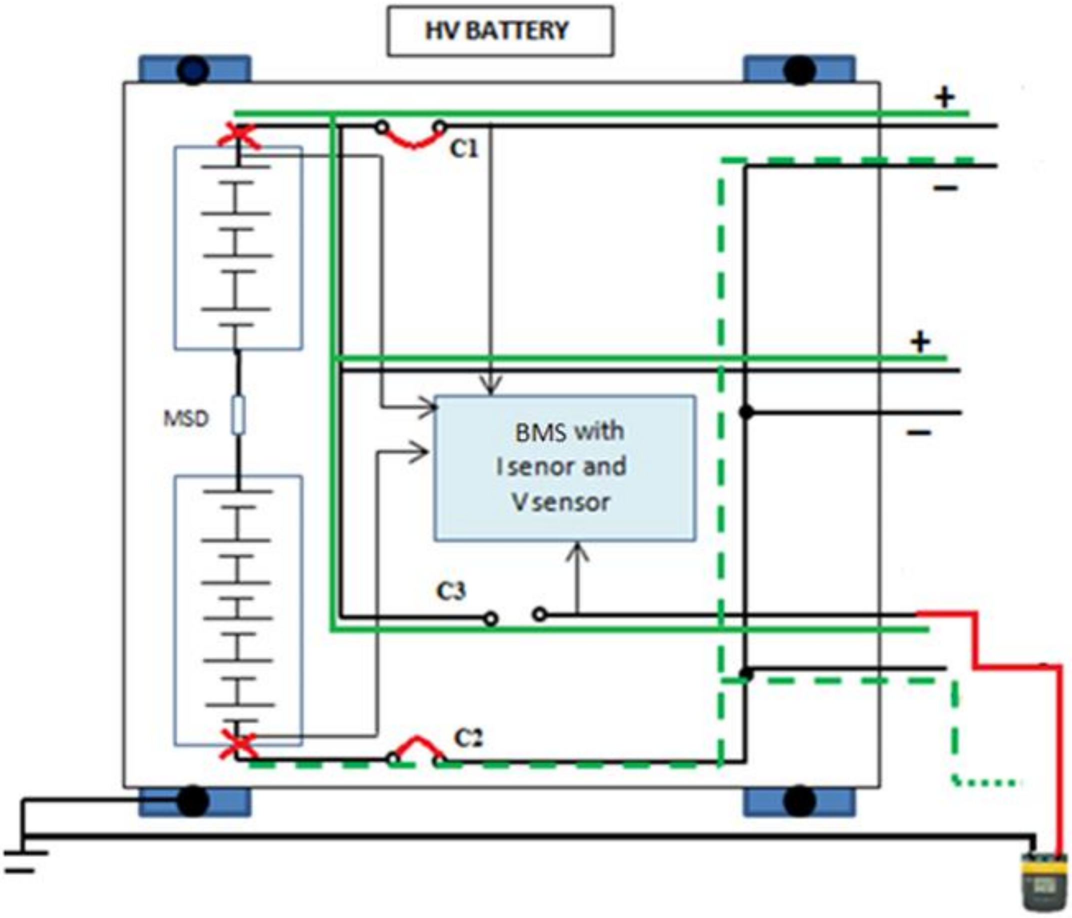
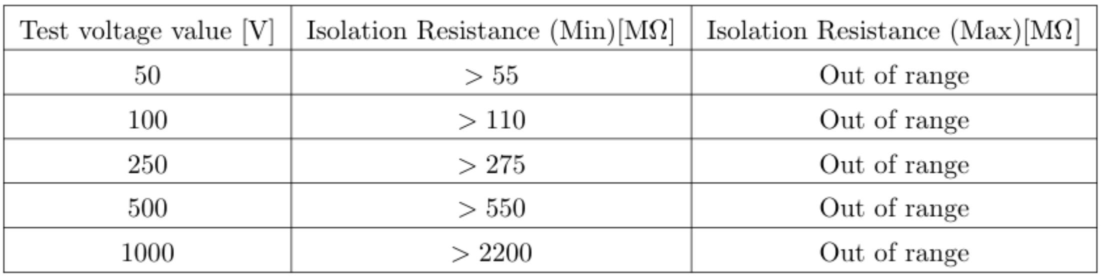


Figure 11. Setup for measuring the insulation resistance of cables exclusively. [7, p. 66.]

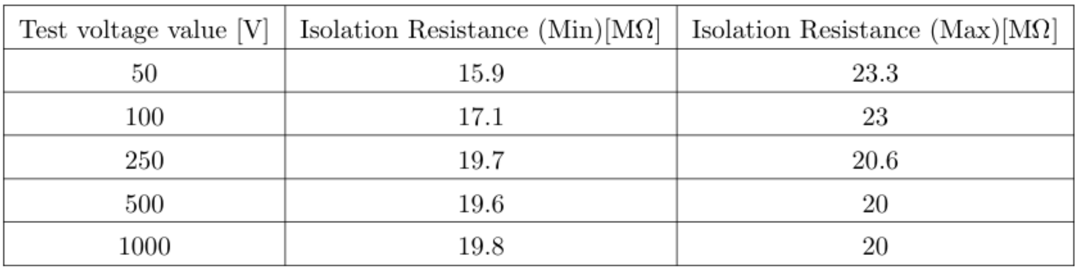
The results of the insulation resistance tests for the positive and negative cables are presented in (tables 4 and 5) respectively. The data in (table 5) highlights the impact of the bleeder resistors on the negative cable during testing. In contrast, the values in (table 4), for the positive cable exceeded the Megger's measurement range. The discrepancy between the results can be attributed to the influence of the bleeder resistors connected to the negative cable during the insulation resistance tests. [7, p. 68.]

Table 4. Insulation resistance test results for the positive HV cable excluding bleeder resistor using the Megger. [7, p. 68.]



Test voltage value [V]	Isolation Resistance (Min)[MΩ]	Isolation Resistance (Max)[MΩ]
50	> 55	Out of range
100	> 110	Out of range
250	> 275	Out of range
500	> 550	Out of range
1000	> 2200	Out of range

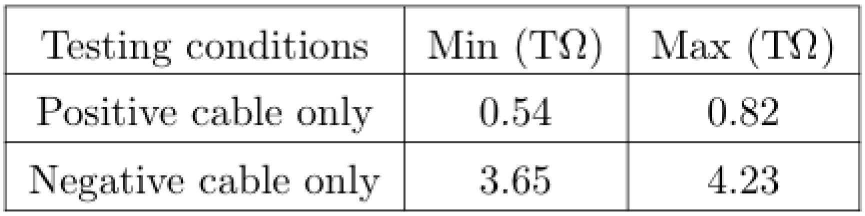
Table 5. Insulation resistance test results for the negative HV cable, including the bleeder resistor, measured with a Megger. [7, p. 68.]



Test voltage value [V]	Isolation Resistance (Min)[MΩ]	Isolation Resistance (Max)[MΩ]
50	15.9	23.3
100	17.1	23
250	19.7	20.6
500	19.6	20
1000	19.8	20

A new test was conducted by Memari and Nakanwagi using an electrometer to obtain accurate measurements of the insulation resistance of the high-voltage cables without the influence of the bleeder resistors. The test was performed on negative and positive cables, with all bleeder resistors disconnected. A voltage of 500 V was applied over four hours to achieve stable readings. The results, presented in (table 6) indicate that the insulation resistance of the negative cable was slightly higher than that of the positive cable. [7, p. 70.]

Table 6. Insulation resistance test results for cables measured with an electrometer. [7, p. 70.]



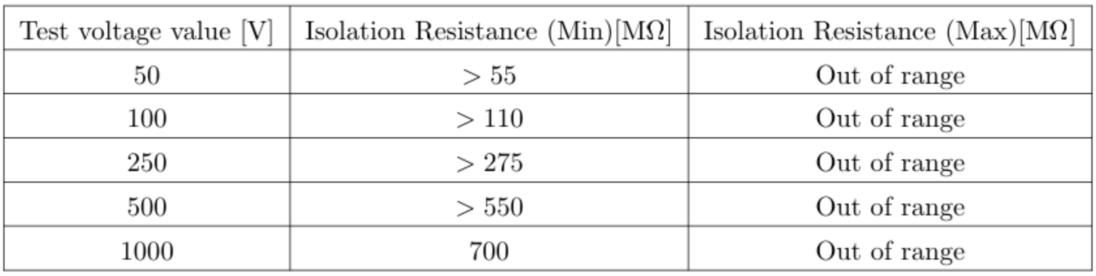
Testing conditions	Min (TΩ)	Max (TΩ)
Positive cable only	0.54	0.82
Negative cable only	3.65	4.23

4.4 Measuring insulation resistance of the battery modules

Battery modules, as the primary source of stored energy for propulsion, require careful assessment of their insulation resistance relative to the ground. Memari and Nakanwagi highlighted this necessity and conducted tests to evaluate the insulation condition. To ensure accurate measurements, all cables connecting the battery modules to other systems were disconnected, isolating the series-connected modules within the battery pack. During the test, the positive and negative terminals of the battery modules were short-circuited to facilitate insulation resistance measurement. [7, p. 70.]

Insulation resistance measurements were performed by Memari and Nakanwagi using a Megger, which was connected between the short-circuited terminals of the battery modules and the ground (chassis). The tests were conducted at various voltages, including 50 V, 100 V, 250 V, 500 V, and 1000 V. As reported in table 7, the insulation resistance values exceeded the Megger’s measurement range. To achieve more precise results, an electrometer was utilised to measure the insulation resistance of an individual battery module. [7, p. 70.]

Table 7. Insulation resistance test results for 10 battery modules were conducted using a Megger. [7, p. 70.]



Test voltage value [V]	Isolation Resistance (Min)[MΩ]	Isolation Resistance (Max)[MΩ]
50	> 55	Out of range
100	> 110	Out of range
250	> 275	Out of range
500	> 550	Out of range
1000	700	Out of range

4.5 UNECE R100 (5.1.3.1)

An electric powertrain with separate DC or AC high-voltage buses, where the AC and DC buses are electrically isolated from each other, must adhere to specific isolation resistance requirements. For DC high-voltage buses, the isolation resistance between the high-voltage bus and the electrical chassis should be at least 100 Ω / V of the operating voltage. For AC high-voltage buses, the required isolation resistance should be at least 500 Ω/ V of the operating voltage. [8, p. 13.]

4.6 Determining insulation resistance of single battery module

An insulation resistance test on a standalone battery module was conducted by Memari and Nakanwagi using a Megger. The results were found to be consistent with those reported in (table 7), for the series-connected battery modules. To achieve more precision measurements, an electrometer was utilised to assess the insulation condition of the individual battery module. [7, p. 71.]

The test setup, illustrated in (figure 12) involved connecting the electrometer between the module’s short-circuited terminals and its cooling fins. The tests were carried out at voltage levels of 400 V and 1000 V, producing high insulation resistance values, as shown in (table 8). [7, p. 71].

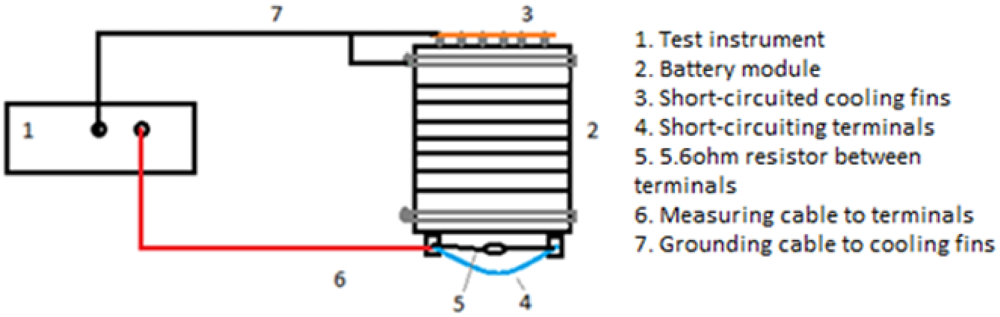
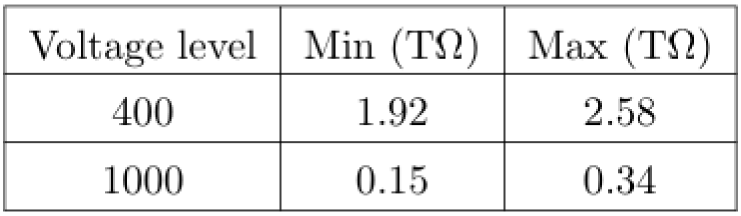


Figure 12. Setup for measuring the insulation resistance of a battery module. [7, p. 71.]

Table 8. Performing an insulation resistance test on a single battery module with an electrometer. [7, p. 71.]



Voltage level	Min (TΩ)	Max (TΩ)
400	1.92	2.58
1000	0.15	0.34

The significant decrease in insulation resistance observed when increasing the test voltage from 400-1000 V may indicate insulation issues stemming from imperfections or cracks in the insulation, exacerbated by moisture or dirt. [7, p. 71].

4.7 Environmental testing

Tests were conducted to simulate the environmental conditions experienced by the battery pack and to evaluate its ground insulation resistance by Memari and Nakanwagi. These tests were performed under controlled temperature and humidity conditions in a climate chamber, with ionized water used to replicate real-world environmental factors. These tests mainly focus on the amount of condensation accumulating on the battery modules due to changes in temperature and humidity. [7, p. 72.]

A standalone, discharged battery module with short-circuited positive and negative terminals was tested. The module was placed in the climate chamber, where temperature and humidity were cycled according to a predefined profile. Throughout the testing period, the climate chamber conditions were closely monitored. Insulation resistance relative to ground was measured at five-minute intervals using a Megger, which was connected to the short-circuited battery module terminals and the cooling fins at ground potential. The test setup is shown in (figure 13). [7, p. 72.]

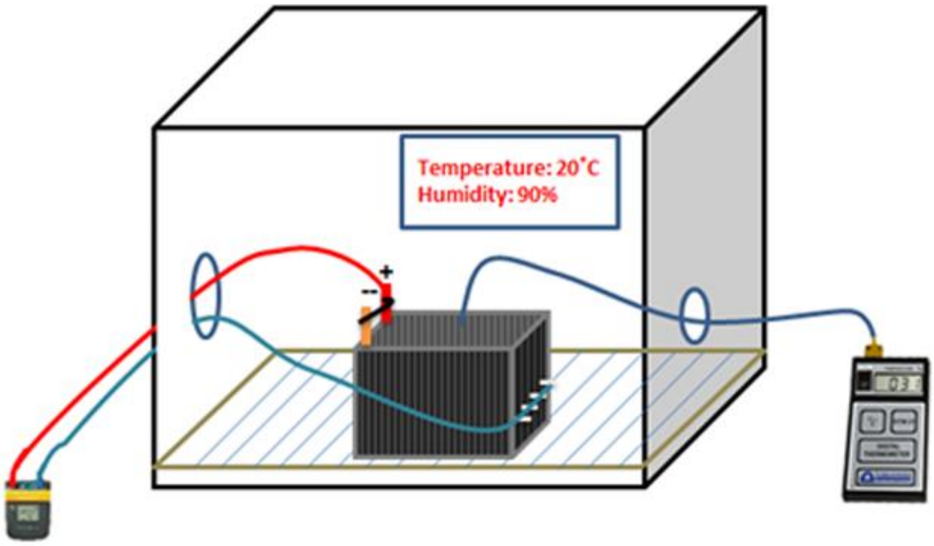


Figure 13. Test setup for environmental test. [7, p. 72.]

5 Developing a control strategy for high-voltage battery insulation in electric vehicles

Growing energy demands and concerns over environmental pollution drive the increasing popularity of electric vehicles (EVs) over conventional vehicles. Electric vehicles are viewed as the future of the automotive industry due to their low emissions, fuel efficiency, and environmentally friendly nature. High-voltage batteries, essential for electric vehicle operation, require proper management through battery management systems (BMS). These batteries must be compact, lightweight, cost-effective, and well-insulated. Effective monitoring systems are necessary to track battery health, charge status, and insulation integrity, including detecting potential leakage. Given the high-voltage systems in EVs, proper isolation of battery terminals is crucial to prevent safety risks and short internal circuits and ensure passenger protection. [12.]

To address this issue, a control system is proposed by Deshmukh, Balaji, Sahasrabudhe, Khubalkar, and Parameswaran to measure and monitor the insulation of the battery terminals before vehicle startup and during continuous operation. This strategy was designed to ensure stability and decoupling, preventing disturbances from affecting battery terminal isolation and on-board charger operation, thereby mitigating system disturbances. [12.]

5.1 Suggested system

A robust system for controlling high-voltage battery isolation and insulation was proposed by Deshmukh, Balaji, Sahasrabudhe, Khubalkar, and Parameswaran. It continuously monitors battery isolation in both electric vehicles and charging stations. The system is based entirely on an isolation circuit, ensuring proper functionality regardless of whether the battery is active or inactive and under significant voltage fluctuations. [12.]

The resistance between the vehicle's power system or battery and the ground (chassis) is checked for signs of insulation degradation or dangerous leakage current levels. Additionally, it can detect all sources of leakage and any resistive paths between the battery terminals and the chassis that share the same potential. Communication is managed via an isolated CAN bus interface. The system's layout is depicted in the block diagram (figure 14) showing the proposed system. [12.]

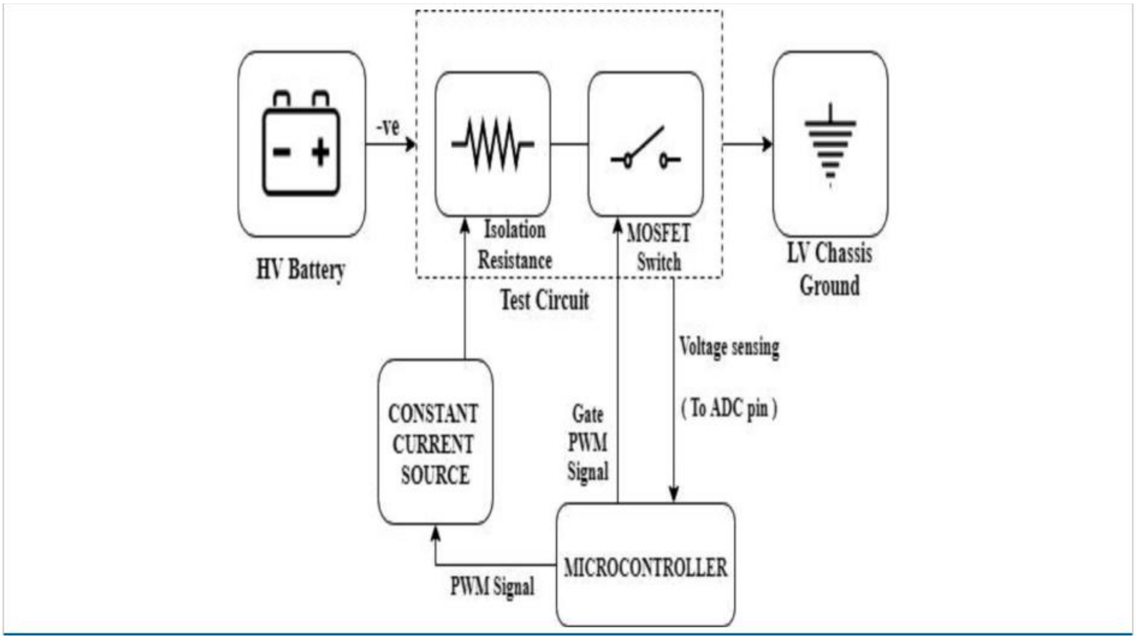


Figure 14. Suggested system block diagram [12].

5.2 Working and Control Strategy

In electric vehicles, two batteries are typically used: a high-voltage battery for motor operation and a low-voltage battery for auxiliary functions. Since the high-voltage battery is not directly grounded to the vehicle chassis, proper isolation of the battery pack is crucial. To ensure this, the system proposed by Deshmukh, Balaji, Sahasrabudhe, Khubalkar, and Parameswaran continuously monitors the isolation between the battery pack and the vehicle chassis by measuring the resistance between these points. Ideally, this resistance should maintain a typical value of approximately 5 MΩ/V. [12.]

To measure the resistance, a constant current is applied across the ideal resistance. This current is generated using a small hardware setup controlled by a microcontroller. For testing purposes, a separate test circuit was developed, incorporating an ideal resistance and a variable resistance connected in parallel and grounded to the chassis through a MOSFET switch, as shown in (figure 15). [12.]

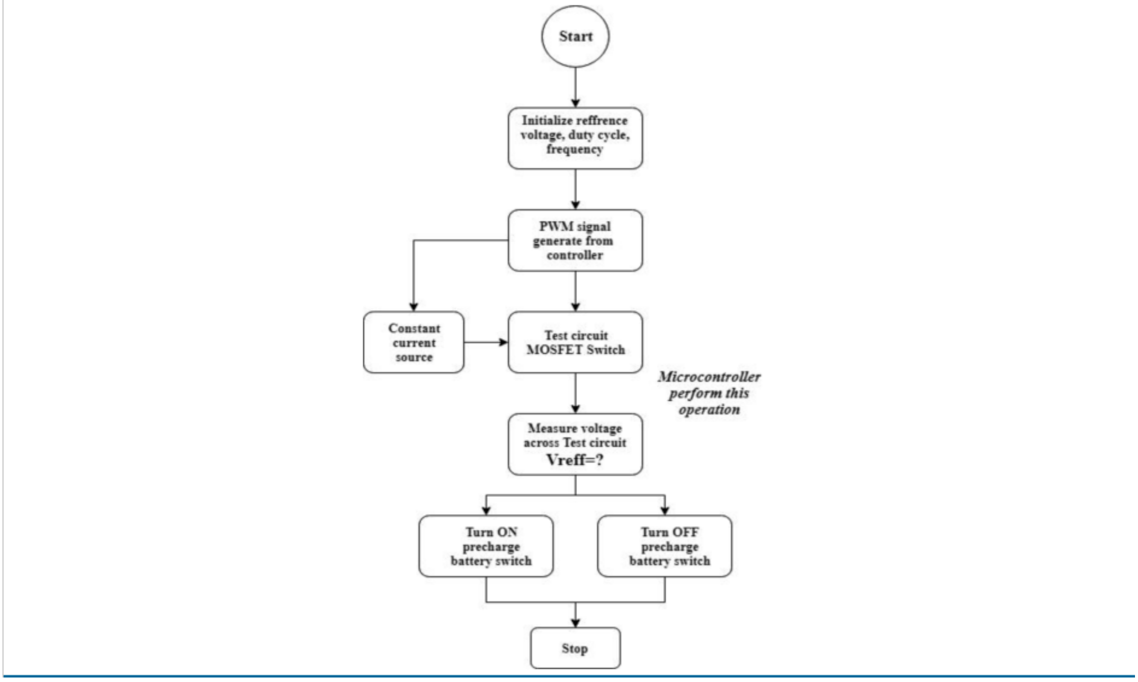


Figure 15. Flowchart of the control strategy [12].

When the constant current is applied to the test circuit, the voltage across the resistance is measured. This voltage is detected and sent to the microcontroller's ADC module, where it is analysed to assess the isolation condition. Based on the results, the microcontroller outputs a signal to the pre-charge switch, the main switch that activates the high-voltage battery for motor operation. Additionally, the output signal is transmitted to the ECU, enabling communication with the battery management system (BMS). [12.]

Figures 14 and 15 illustrate the proposed system's operation and the flowchart detailing the control strategy for insulation resistance measurement.

5.3 Empirical result

A constant current source circuit was designed using TINA-TI simulation software as part of the proposed system for measuring battery isolation by Deshmukh, Balaji, Sahasrabudhe, Khubalkar, and Parameswaran. The circuit diagram is presented in (figure 16). An ideal reference resistance of 25 KΩ/V was assumed for the experimental setup between the battery and the chassis ground, with the constant current source set at 50μA. As the isolated resistance varies, the corresponding voltage changes proportionally. This voltage is detected and sent to the controller's built-in ADC for processing. [12.]

The measurement process was performed regularly to monitor the isolation between the battery terminals and the vehicle chassis, ensuring safety and functionality in electric vehicles. The simulated circuit diagram, including the ideal resistance of 25 KΩ, is illustrated in (figure 16). [12].

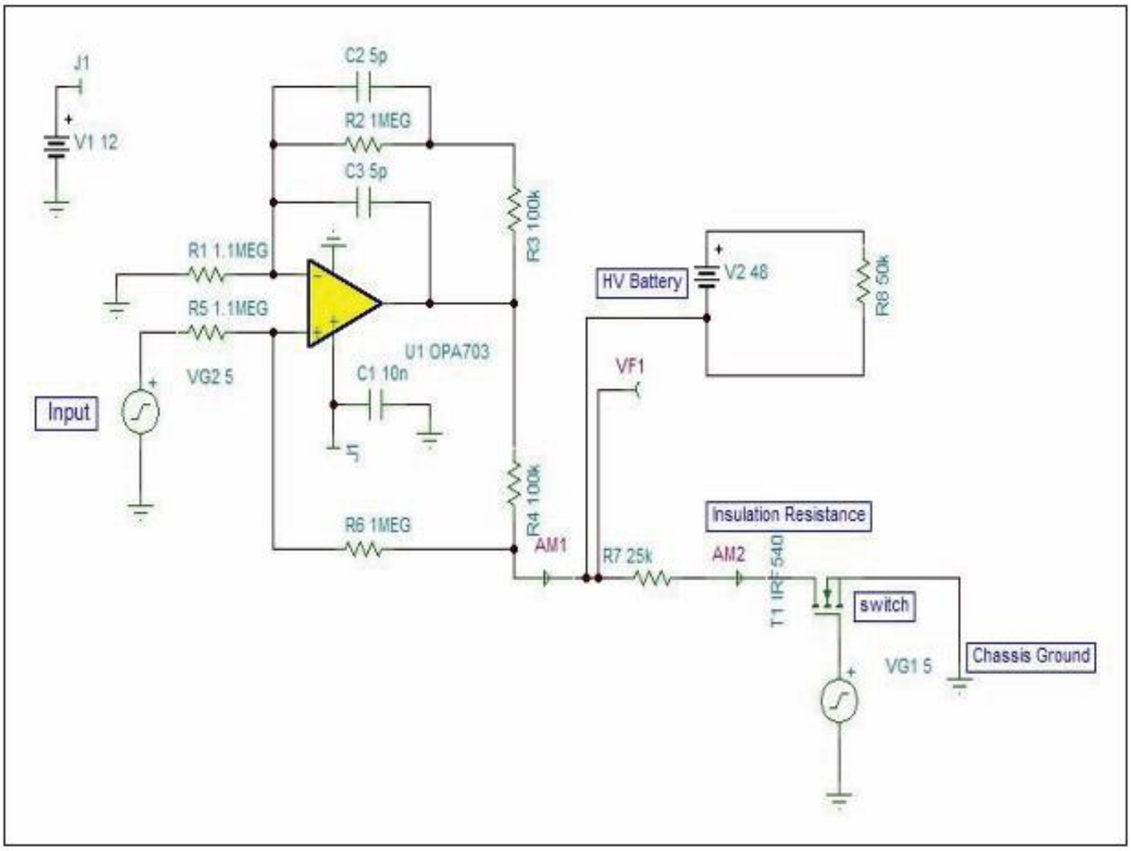


Figure 16. Circuit simulation diagram of the proposed system [12].

Figure 17 presents the output waveform under ideal conditions, showing an output voltage of 1.25 V across the resistance. This voltage was detected by the ADC module, and the digital count was calibrated using 5 V as the input while maintaining a 12-bit resolution. Calibration was conducted through developed code interfacing with the controller. The proposed algorithm for ADC calibration considered the number of bits, resolution, input voltage, and reference voltage. The calibration formula used for the ADC is outlined below. [12.]

ADC Calibration (Count) = [Output analog*ADC resolution] /Input voltage

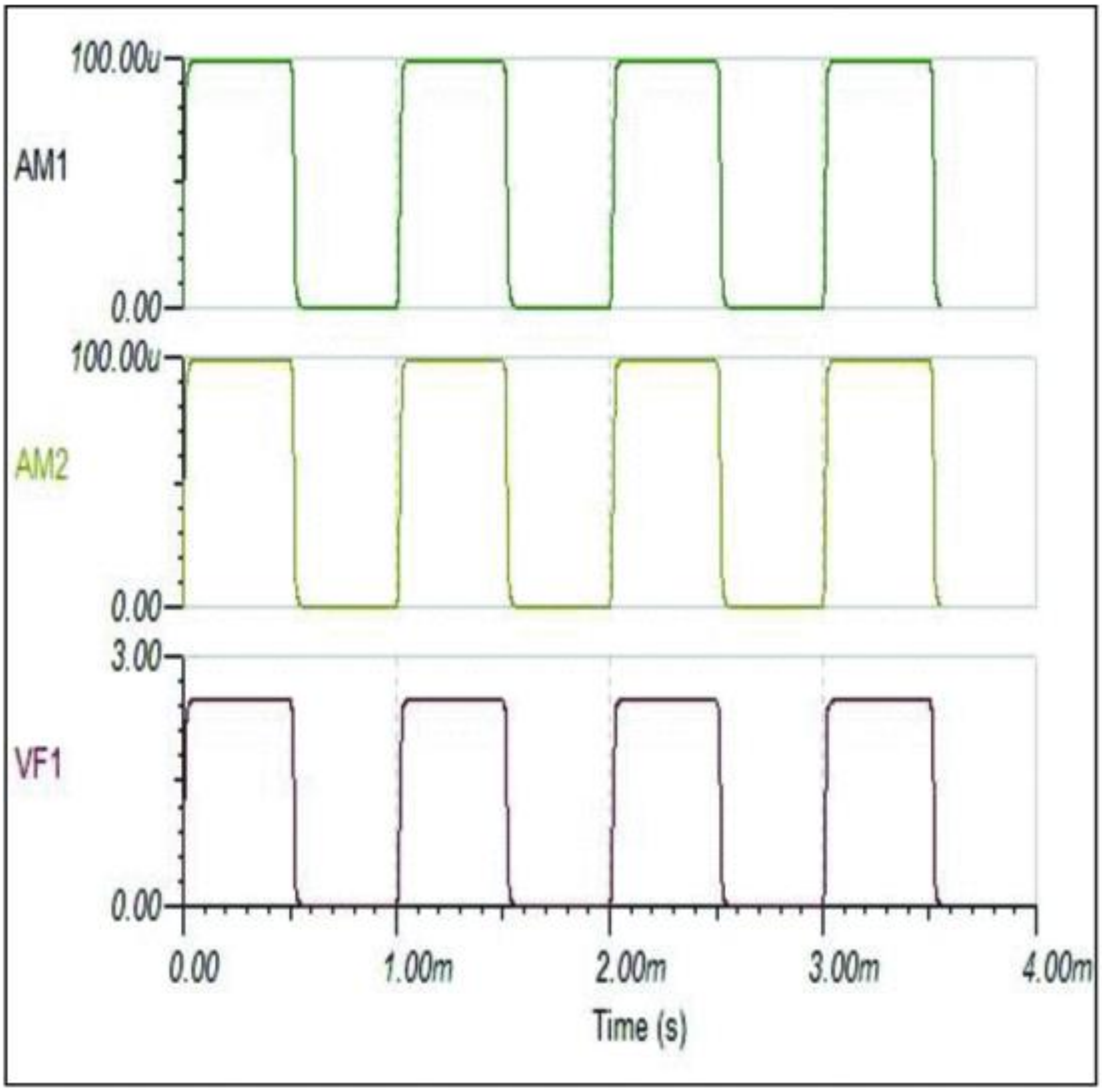
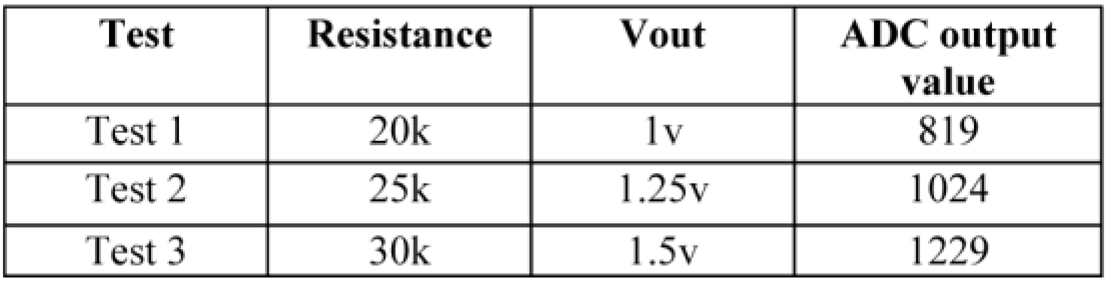


Figure 17. Output signals from the empirical circuit [12].

5.4 Analysis of experimental results

For resistance values of 20 KΩ, 25 KΩ, and 30 KΩ, the output voltages measured are 1 V, 1.25 V, and 1.5 V, respectively, as shown in (table 9). The ideal resistance and corresponding voltage are 25 KΩ and 1.25 V, with the ADC calibrated to 1024 bits. The controller detects this voltage and compares it to the reference voltage. Based on this comparison, the controller sends a signal to the battery pre-charge switch to either turn the switch on or off. This system can also be useful for checking insulation in bidirectional DC-DC converters and Charger circuits. In the future, this circuit will integrate with the BMS system. [12.]

Table 9. Empirical test [12].



Test	Resistance	Vout	ADC output value
Test 1	20k	1v	819
Test 2	25k	1.25v	1024
Test 3	30k	1.5v	1229

5.5 Pre-charge circuit

The high-voltage system in electric vehicles (EVs) requires per-charged circuits to limit the current flowing when the contactors are closed. By managing in-rush current, these circuits safeguard system components, enhance durability, and improve overall reliability. Pre-charge circuits are crucial in electric vehicles, battery management systems, onboard chargers, and industrial applications like power supplies and distribution units. Welding can occur within the contactor without a pre-charge circuit, leading to a brief arc and pitting. A pre-charge circuit can prevent stress and damage to the electric system by implementing a resistor and a switch to limit in-rush current. [13.]

In a high-voltage system, a standard configuration includes two high-current contactors and a dedicated pre-charge contactor, alongside a DC-link capacitor connected parallel with the load, such as a traction inverter. Figures (18-20) outline the pre-charging process for a DC-link capacitor. [13].

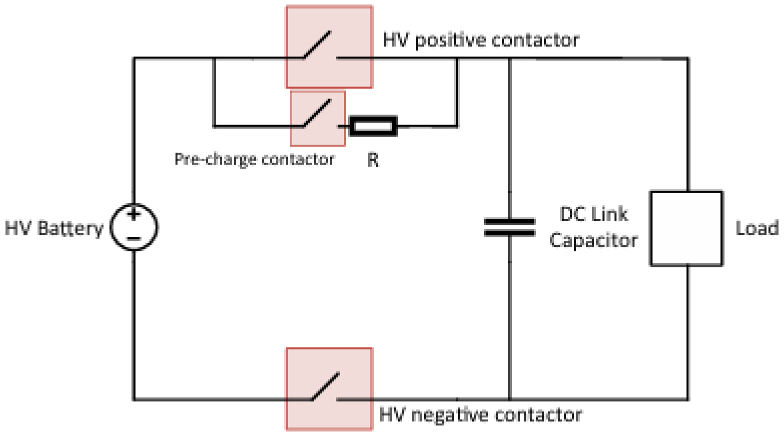


Figure 18. Pre-charge Initial state

Figure 18, both high-current contactors, HV positive and negative, are open, isolating the HV battery from the load.

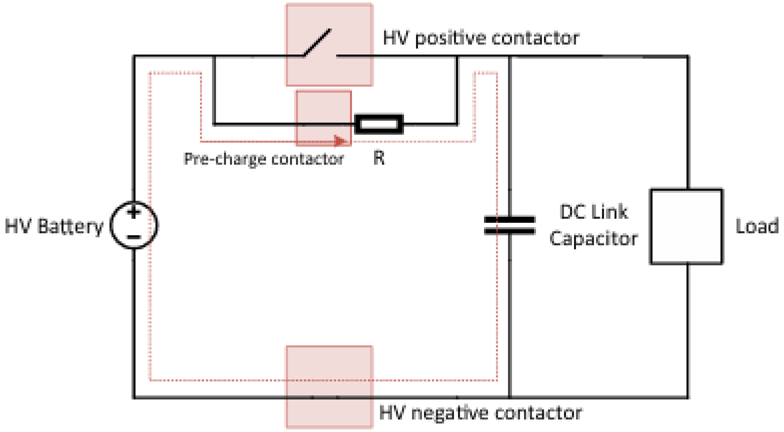


Figure 19. Pre-charge state

At this point, the DC-link capacitor is uncharged. The system then enters a pre-charge state, where the pre-charge contactor and the high-voltage (HV) negative contactor are closed (figure 19). This allows the capacitor to charge up to nearly the same voltage as the source. [13].

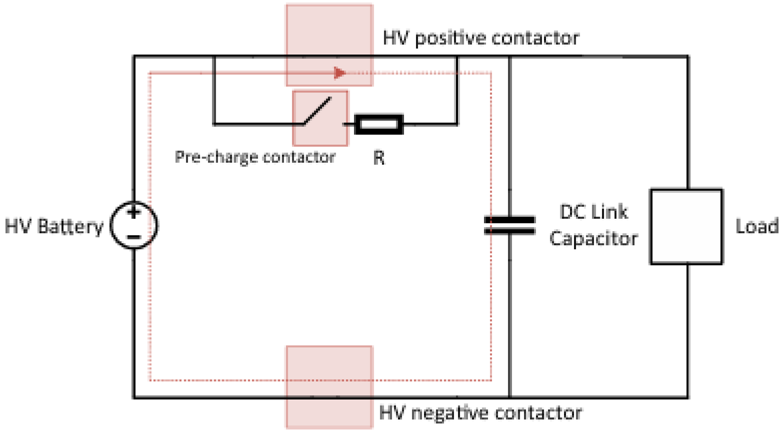


Figure 20. Pre-charge steady state

Figure 20 shows that once pre-charging is complete, the pre-charge contactor opens, and the high-voltage (HV) positive contactor closes to connect the system or enable battery charging. Because the capacitor has already been charged during the pre-charge phase, there is no sudden surge of inrush current when the main contactors close, ensuring smooth operation. [13.]

6 Automotive components and their insulation resistance breakdown methods

6.1 The concept of dielectric breakdown

Dielectric breakdown occurs when a strong electric field is applied to an insulating material, causing a rapid loss of its insulating properties. Different materials require varying intensities of electric fields to reach this point. Unlike conductors such as copper wire, where free electrons are readily available, Insulators such as rubber or plastic coatings need an intense electric field to provide sufficient energy to their electrons. Once energized, these electrons can jump across the material's bandgap into the conduction band, significantly increasing its conductivity. This process is known as dielectric breakdown, and the minimum electric field needed to initiate it is termed the material's dielectric strength or breakdown strength. [14.]

6.2 Inverter

Insulation resistance (IR) is crucial in automotive inverters for the safety and reliability of high-voltage components. Breakdown can cause faults, overheating, or system failure, posing risks in electric vehicle powertrains. Essential components, including power semiconductors (IGBTs and MOSFETs), busbars, DC-link capacitors, cooling system components, and PCBs/connectors, need reliable insulation, as illustrated in (figure 21). [15.]

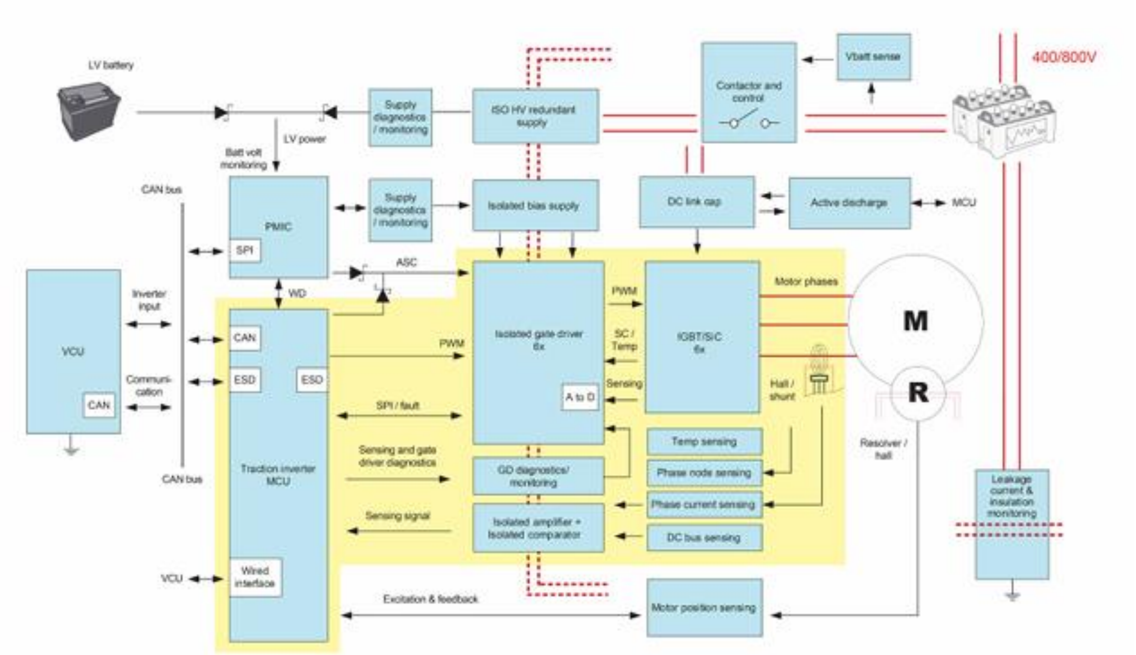


Figure 21. Block diagram of the traction inverter system [16].

Essential components of an inverter:

1. Power semiconductors: Such as Insulated Gate Bipolar Transistors (IGBTs) and Silicon Carbide (SiC) MOSFETs, are crucial components that manage the switching and regulation of power within the inverter system. [15].
2. Gate drivers: These are responsible for managing the operation of power semiconductors and ensuring precise switching between them on and off states. Isolated gate drivers are commonly employed to separate high-voltage and low-voltage circuits properly. [15].
3. Capacitors: Play a key role in energy storage and filtering, helping to stabilize power delivery by reducing voltage fluctuations within the inverter. [16].
4. Inductors and transformers: Serve distinct purposes, with inductors used for energy storage and transformers employed for converting voltage levels. [16].
5. Cooling systems: Are essential for efficient thermal management, ensuring that power semiconductors and other components do not overheat. [17].

Insulation Resistance Breakdown Methods:

1. Insulation resistance testing: Involves applying high voltage to inverter components and measuring their resistance. A high resistance value signifies strong insulation, whereas a low value may indicate areas prone to breakdown points. [15].

2. Partial Discharge Testing: This method detects small electrical discharges within insulation material, indicating potential breakdowns due to high voltage. [16].

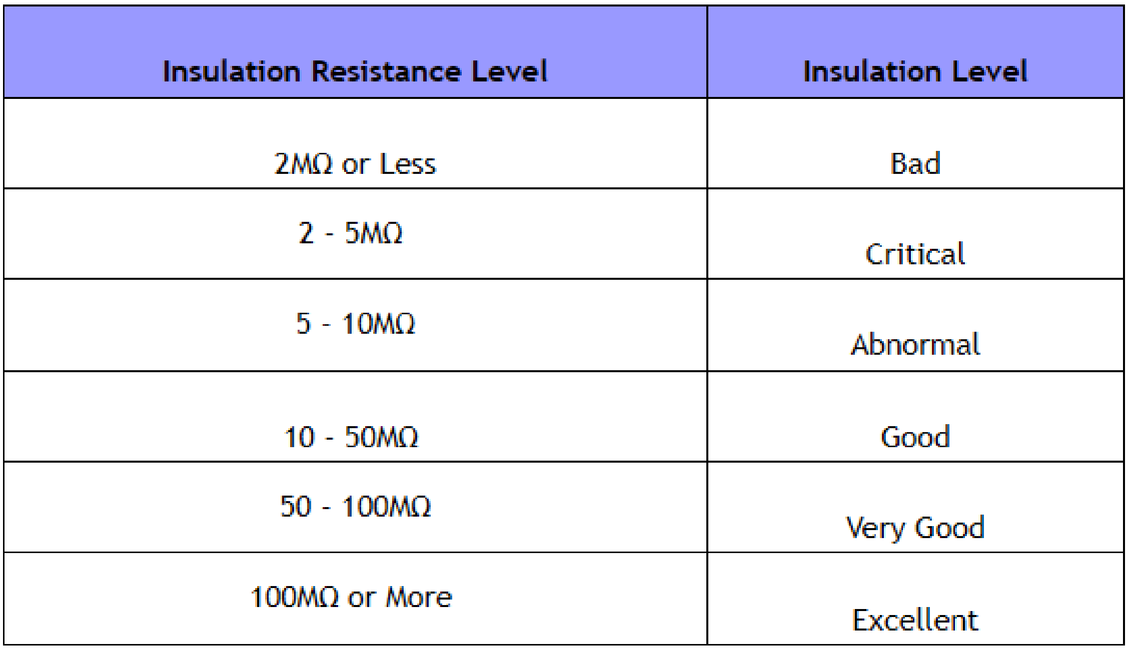
3. Thermal imaging: This can be utilized to identify areas of insulation failure due to excessive heat in an inverter. [17].

4. Dielectric Withstand Testing: Involves high voltage to an inverter for a specific period to ensure insulation can withstand operating conditions without breaking down. [16].

6.3 Electric motor

Insulation resistance breakdown in automotive electric motors can occur due to heat, contamination, mechanical stress, or ageing. Regular testing with a megohmmeter is crucial for motor health monitoring. Insulation resistance values below 10 MΩ are critical and may require immediate maintenance. Thermal ageing often causes cracks or failures in winding insulation, potentially leading to electrical faults or fires. Preventive measures include periodic maintenance, drying windings, and adhering to insulation resistance thresholds. [18.]

Table 10. Typical insulation resistance level for electric motors [18].



Insulation Resistance Level	Insulation Level
2MΩ or Less	Bad
2 - 5MΩ	Critical
5 - 10MΩ	Abnormal
10 - 50MΩ	Good
50 - 100MΩ	Very Good
100MΩ or More	Excellent

Measure the insulation resistance of a motor

According to Learning Electrical Engineering, insulation resistance measurements are performed using a mega ohmmeter, a device designed to measure high resistance values. The measurement involves applying a DC voltage of 500 V or 1000 V between the motor windings and the ground, as depicted in (figure 22). [18.]

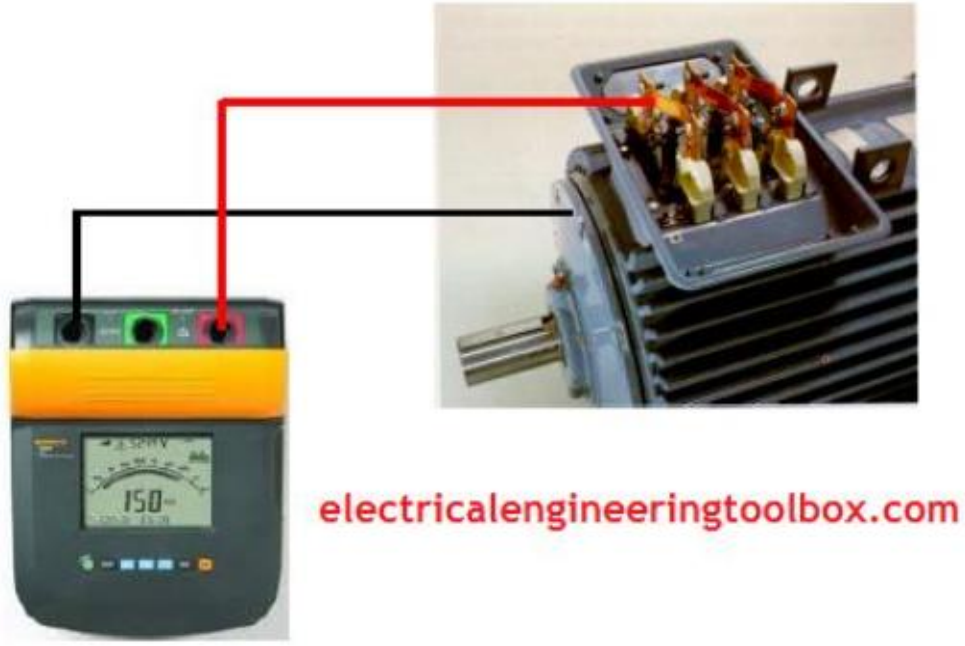


Figure 22. Measure insulation resistance [18].

The insulation resistance of a motor can be measured at 500 V under various winding temperature conditions, ranging from -15°C to 20°C and 80°C to 120°C, depending on the motor type and efficiency. It is essential to avoid touching motor terminals during measurement, as they carry potentially hazardous voltages. [18]

The minimum insulation resistance of a motor, Rmin, can be determined by multiplying the rated voltage, VR, with a constant factor of 0.5 MΩ /kV. [18].

6.4 Battery

Insulation resistance in electric vehicle (EV) batteries is crucial for safety, reliability, and performance. Breakdowns can cause hazards like electric shocks, thermal runaway, or fire. Understanding breakdown methods and detecting failures can effectively mitigate risks. [19].

The key methods of insulation resistance breakdown include:

1. Electrical Overstress (EOS):
   This happens when the voltage applied to the battery insulation surpasses its designed dielectric capacity. This can result in a localized dielectric breakdown, causing current leakage and ultimately failure to system malfunction. [19].

2. Contamination-Induced Breakdown:
   Dust, moisture, or chemical pollutants can compromise insulation integrity by forming conductive pathways that enable current leakage. Exposure to such environmental factors during manufacturing or operation significantly raises the risk of this type of failure. [19].

3. Thermal Stress:
   High temperatures can degrade insulation materials, leading to a gradual decline in their resistance. Repeated temperature fluctuations (thermal cycling) can create micro-cracks in the insulation, further speeding up its deterioration. [19].

4. Mechanical Stress:
   Vibrations, shocks, or mishandling during manufacturing or use can physically compromise insulation, creating localized weak spots that increase the likelihood of insulation breakdown. [19].

5. Aging and Material Degradation:
   Extended use and environmental exposure contribute to the deterioration of insulation materials over time, diminishing their performance. Processes like oxidation or hydrolysis of the insulation material accelerate this degradation. [19].

6. Electrochemical Factors:
   Leakage of electrolytes inside battery packs can erode insulation layers, forming conductive paths. Over time, interactions among materials within the battery's internal structure can weaken the insulation, resulting in potential failures. [19].

Higher energy density requires powerful high-voltage batteries that operate up to 900 volts. Higher voltages necessitate greater precautions to prevent arcing between electrical components. Thus, increased energy density creates a need for increased battery safety. [19].

One major focus area is improving the electrical isolation performance of dielectric materials, their adhesion to battery/pack components and thermal interface materials and ensuring their application process is efficient and straightforward. [19].

Dielectric protection plays a vital role in the construction of high-voltage battery packs. Polymeric dielectric materials are commonly used and must possess the following performance characteristics:

1. Exceptional dielectric strength
2. Strong adhesion to various substrates
3. Resistance to chemical, thermal, and mechanical stress over time
4. Capability to be applied as thin films (50-250 microns)
5. Compatibility with high-speed manufacturing processes.

Electrical insulation for EV components is essential at the cell, module, and pack levels. This includes battery cells, side plates, cooling plates, enclosure walls, and bus bars, as shown in (figure 23). [19].

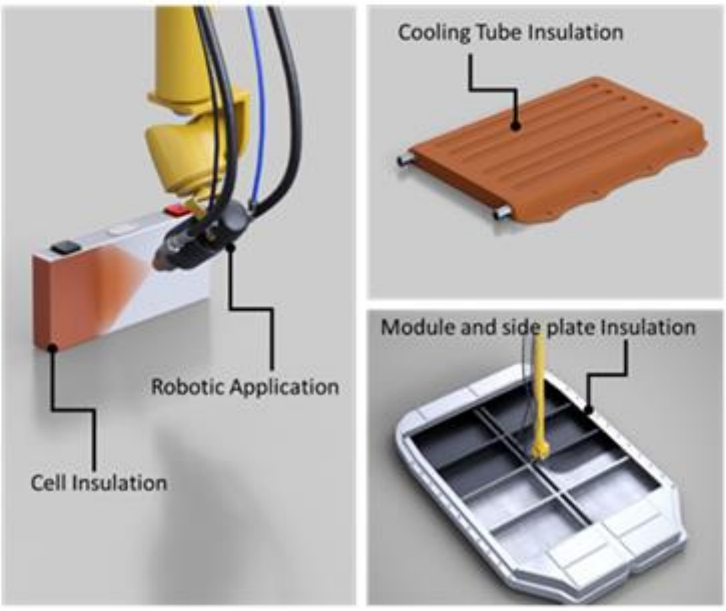


Figure 23. EV components requiring electrical insulation include battery cells, cooling plates, and module enclosures. [19].

According to Eric Dean, Manager of Global Business Development at Parker Lord, a company specializing in advanced materials and adhesives, adhesion is a critical factor when evaluating dielectric materials. It ensures that the material remains on the component surface for product protection and effective heat transfer. His expertise in dielectric protection technologies for battery system components in high-voltage EV applications underscores the importance of proper adhesion in enhancing battery safety, performance, and manufacturability.

The required adhesion strength varies depending on the application, particularly in electric vehicle (EV) battery components such as side plates and battery lids. Higher adhesion strength is crucial for EV manufacturers transitioning from 'cell-to-module' to 'cell-to-pack' designs, which require structurally bonded components to withstand vibration, impact, and environmental factors. Among the tested materials, Sipiol UV, powder coating, and LORD JMC exhibit the highest adhesion strength, while PET film has the lowest. However, plasma treatment could improve PET film’s performance. Environmental testing, including thermal shock cycling and exposure to 85°C / 85% RH conditions, has shown minimal negative effects on adhesion. Additionally, all tested materials demonstrate excellent crosshatch adhesion to aluminium before and after environmental exposure, as shown in (figure 24). [19.]

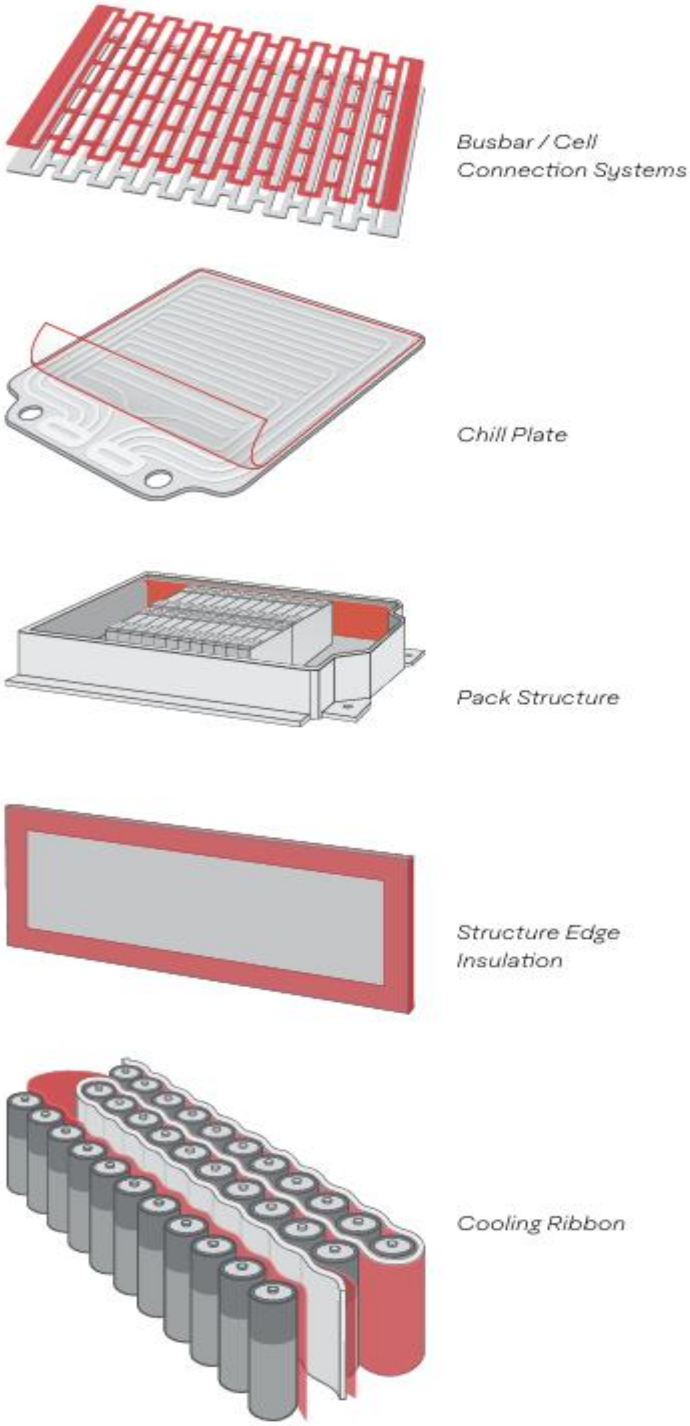


Figure 24. Dielectric tapes [20].

7 Design considerations for electrical insulation in high-voltage electric vehicle battery systems

Designing electric vehicle batteries prioritises boosting power output and capacity while minimising charging time and overall weight. Although 350V batteries remain prevalent and 450V capacitors are widely available, automakers are pushing boundaries by developing batteries capable of operating at as high as 800V voltages. [21.]

7.1 Advantages and disadvantages of high-voltage batteries

High-voltage batteries offer several key advantages, primarily through reducing the required copper for power transmission. Increasing the voltage instead of the current can deliver the same power with a smaller conductor cross-section, leading to lighter and more compact designs. This copper reduction decreases weight and minimises heat generation, enhancing battery efficiency. [21.]

Additionally, higher voltage systems enable faster charging speeds, especially with DC fast chargers. As the demand for fast charging has become a standard in the electric vehicle market, batteries operating at 800V significantly enhance this capability, making it possible to fully charge a battery in under 30 minutes. This represents a major charging technology step, in improving electric vehicle (EV) users' convenience. Raising the voltage level also contributes to increasing the motor's power. [21.]

However, higher voltage battery systems in electric vehicles raise safety concerns. One of the most critical hazards associated with electric vehicle (EV) batteries is thermal runaway or, a process where an exothermic reaction triggers additional reactions, leading to an uncontrollable rise in temperature. If unchecked, thermal runaway can result in fire or even explosions, making its prevention a key priority in EV battery design. [21.]

Thermal runaway may be exacerbated in high-voltage batteries due to the increased likelihood of electrical arcing, where current leaps through the air between two conductive points. This phenomenon generates extreme heat and energy. Such conditions can act as a catalyst for thermal runaway, posing significant safety risks in passenger vehicles. [21.]

High-voltage systems are more prone to arcing because the increased voltage enables current to traverse larger air gaps, reducing the insulating effectiveness of air. To mitigate these risks, robust electrical insulation systems must be implemented to prevent arcing and ensure the safe operation of high-voltage batteries in electric vehicles. [21.]

7.2 Thermal runaway

Thermal runaway in lithium-ion batteries progresses through distinct stages, each contributing to cell failure and potential hazards. The stages are described in more detail below.

1. Breakdown of the solid electrolyte interphase (SEI)
   The SEI layer on the anode can degrade due to overheating or mechanical damage. Overheating may arise from excessive current, high ambient temperatures, or overcharging. At approximately 75°C, this breakdown accelerates an uncontrolled reaction between the electrolyte and anode, generating significant heat. [19.]

2. Decomposition of the organic solvent
   As the temperature rises to about 110°C, the anode's reaction intensifies, breaking down the organic solvent in the electrolyte. This decomposition releases flammable hydrocarbon gases. Though these gases are not immediately combustible due to a lack of oxygen, they increase internal pressure. Most batteries have vent holes to release these gases and prevent cell rupture safely. [19.]

3. Melting of the polymer separator
   At around 135°C, the polymer separator melts, which isolates the battery’s electrodes. This melting creates a direct short circuit between the anode and cathode, further accelerating the heating process. [19].

4. Cathode breakdown and Oxygen release
   When the temperature reaches approximately 200°C (depending on the cathode material, such as lithium cobalt oxide), the cathode material breaks down, releasing oxygen. This oxygen reacts with the electrolyte and flammable gases, igniting them and generating substantial heat and pressure. This stage often results in fire or explosion, marking the critical failure of the cell. [19.]

   Each stage of thermal runaway highlights the importance of robust thermal management and battery design to mitigate risks. [19].

7.3 Battery insulation measurement in battery management system

The insulation monitoring or detection feature in a battery management system (BMS) ensures that the battery's insulation remains intact, preventing leakage currents. This system operates by detecting ground faults. If insulation deteriorates in any battery cell, a ground-fault current flows through a relay, triggering an alarm signal. These relays must handle voltages higher than the nominal voltage of the battery pack, often with a safety margin. For instance, an 800V battery pack typically requires a relay rated for over 1600V to ensure safe operation. [22.]

One of the significant challenges with electric vehicle batteries is insulation failure, which can lead to ground faults and compromise safety. Ground-fault detection is a well-established solution for managing this issue, identifying faults early, and mitigating risks. As battery systems evolve towards higher voltages, selecting the appropriate components- such as MOSFETs capable of handling these increased voltages- becomes crucial for reliable insulation monitoring and overall system safety, as shown in (figure 25). [22.]

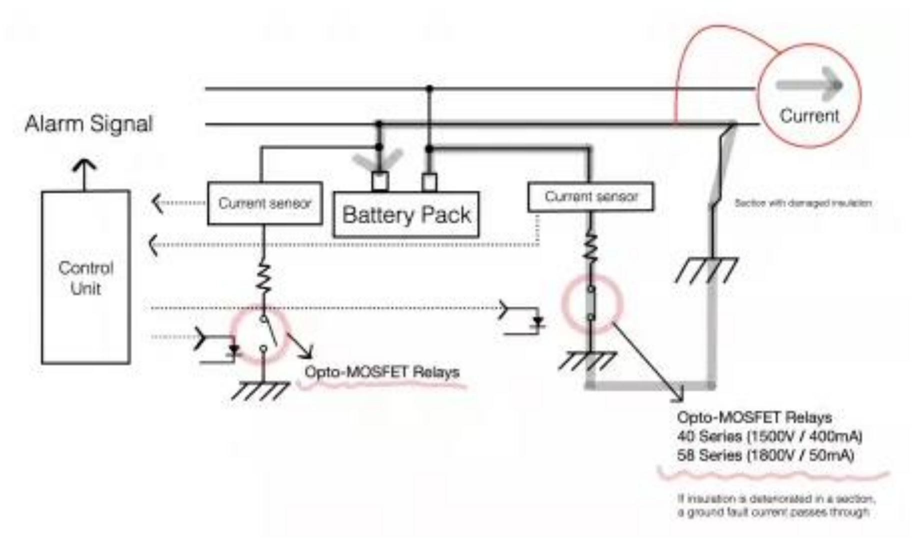


Figure 25. Insulation Detection Circuit in a Battery Management System (BMS) [22].

7.4 Cases of Insulation Failure

Insulation failure occurs when the electrical resistivity of insulating materials reduces, allowing leakage current to flow. ISO 16750-2 requires an insulation resistance value above 10 MΩ for batteries, which should be higher at manufacture to maintain the value necessary throughout the vehicle's life. Examples of insulation failure in battery packs include reduced resistance due to incidents below recommended values. [7, p. 34.]

7.4.1 Punctured cell pouch

A 500 V DC high-potential voltage test was conducted by Memari and Nakanwagi on a battery pack containing a punctured cell pouch. Through this test, a low resistance value was revealed between the high-voltage terminal and the chassis, indicating insulation failure. Specifically, a resistance value below 10 MΩ was observed, serving as clear evidence of compromised insulation, as shown in (figure 26). [7, p. 34.]

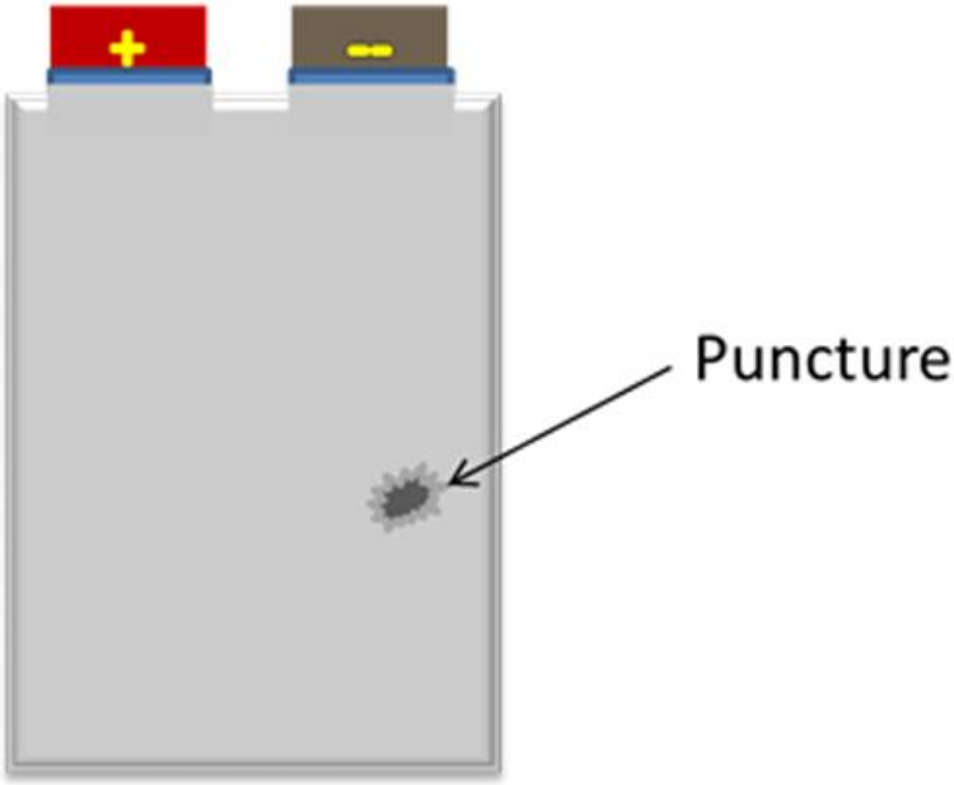


Figure 26. Punctured cell pouch. [7, p. 34.]

The puncture in the cell pouch was likely caused by mechanical stress and vibrations, which resulted in the sharp edges of the end plate cutting into the pouch. This scenario highlights the importance of addressing mechanical design factors to prevent such failures. [7, p. 34].

7.4.2 Cell Expansion

When a cell is charged, it expands, whereas when discharged, it contracts. Over time, as the cell undergoes repeated use, it experiences a gradual and permanent increase in thickness in the darker graphite anode. This overall expansion can be categorized into reversible expansion, which occurs during normal charging and discharging cycles, and irreversible expansion, which accumulates as the cell ages, as shown in (figure 27). [23.]

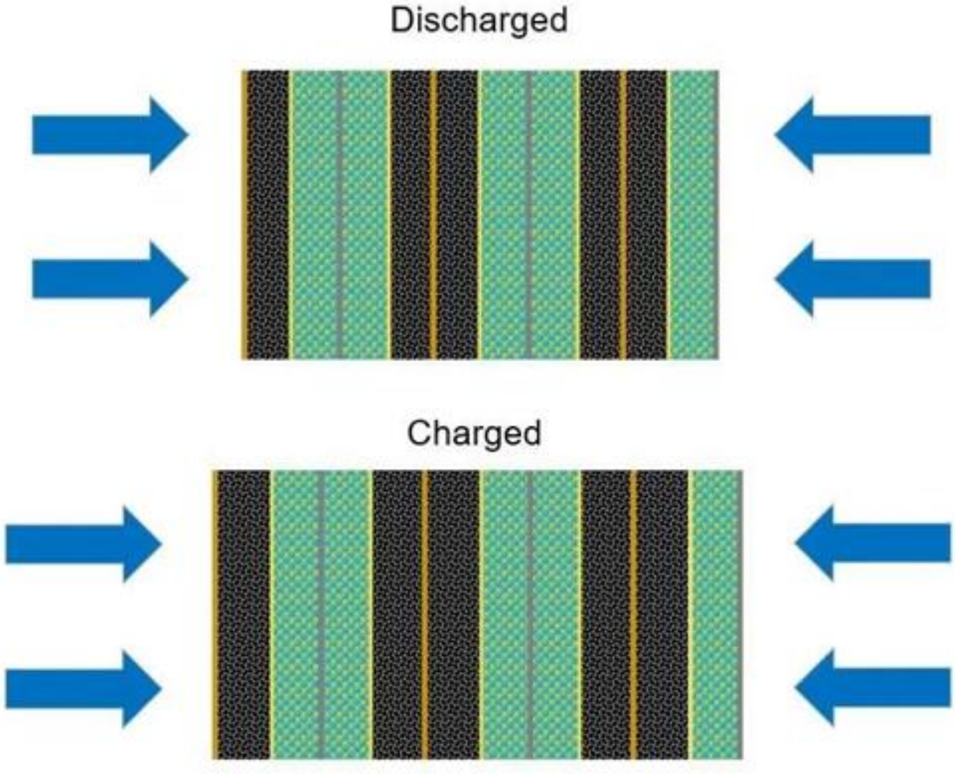


Figure 27. Cell expansion [23].

Li-ion pouch cells require external pressure (preload) to minimise the formation of the solid electrolyte interphase (SEI) on the graphite layers, which helps prevent early capacity loss. Applying preload also improves cell performance by ensuring proper compression and contact between the internal layers, thereby reducing resistance. [23.]

7.4.3 Reversible expansion

Reversible cell expansion occurs due to changes in the spacing between graphite layers caused by the formation of various graphite-lithium intercalation compounds. These changes lead to the graphite electrodes expanding and contracting at a macroscopic level during galvanostatic cycling. Lithium ions interact with the graphite anode when the cell charges, causing it to swell. [23.]

7.4.4 Irreversible expansion

A lithium-ion battery transports lithium ions through a separator during charging and discharging, with the electrolyte acting as a medium. Swelling occurs due to gas generation within the battery due to electrochemical and chemical reactions. [24].

Lithium-ion batteries typically experience swelling towards the end of their life, which should be taken into consideration in system design for safe device operations. However, flawed manufacturing processes, such as improper formation steps, can cause gas generation and swelling during usage. Unsafe conditions such as elevated temperature, overcharge, and over-discharge can also cause rapid gas generation. The battery management system aims to protect against these issues. Figure 28 shows a diagram of all probable causes of gas generation. [24.]

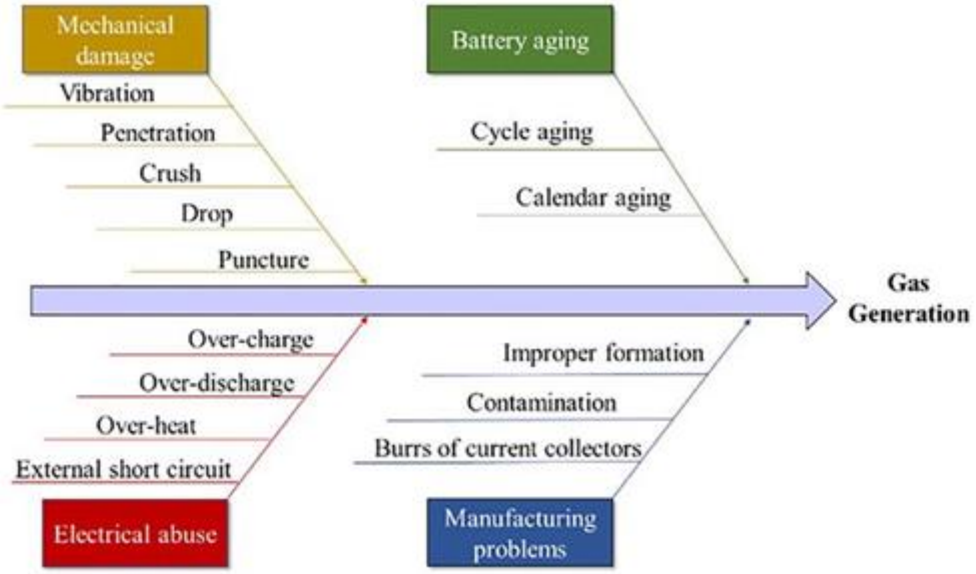


Figure 28. Gas generation [24].

A chemical reaction known as solid electrolyte interphase (SEI) creates a solid layer on the surfaces of the graphite anode, reducing the cell's capacity. If the solid electrolyte interphase (SEI) is allowed to expand freely, without sufficient pressure holding the cell layers together, it can lead to significant premature and irreversible swelling. [24.]

Figure 29 shows a new cell initially measured 4mm in thickness, and as shown in the graph, the irreversible expansion at the lowest pressure of 6.9 kPa (1 psi) was 400 µm (0.4mm), representing a 10% permanent expansion over the cell's lifetime. [23].

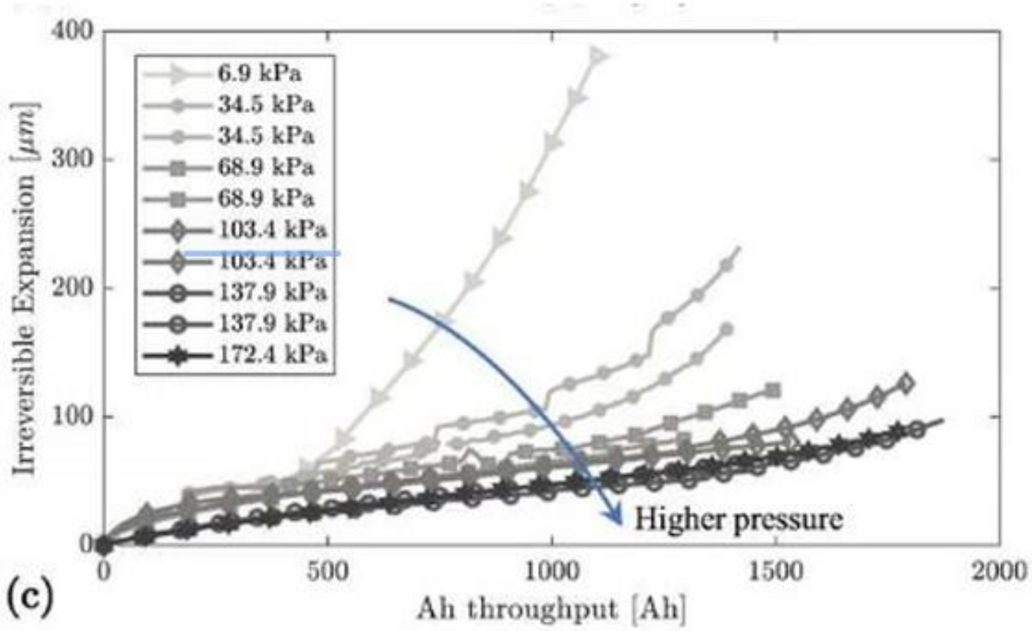


Figure 29. Premature irreversible expansion of an NMC111-Gr pouch cell during 2C cycling at a constant temperature of 45°C [23].

Figure 30, in turn, outlines a process of irreversible solid electrolyte interphase (SEI) expansion. Initially, lithium ions interact with graphite particles, causing them to expand. This expansion creates larger gaps between the graphite layers, which SEI fills. With each charge cycle, additional solid electrolyte interphase (SEI) forms on the graphite and after each discharge cycle, the electrode's ion-receiving capacity slightly decreases while the layers become progressively thicker compared to the previous cycle. [23.]

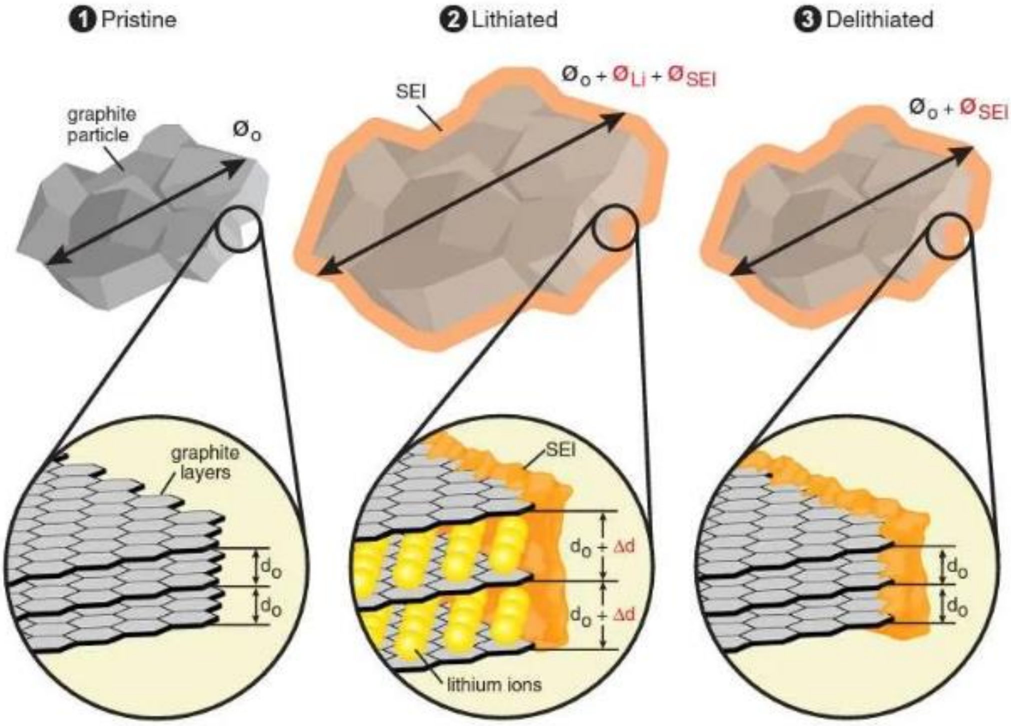


Figure 30. SEI development during a lithiation cycle [23].

The SEI layer can potentially trigger thermal runaway if it punctures the separator and causes a short circuit between the cell electrodes. The effects of irreversible swelling in pouch cells can be mitigated by ensuring the cell operates within its electrical and thermal limits and by designing a controlled expansion space to accommodate the unavoidable dimensional changes. [23.]

7.5 ISO 16750-2

This standard applies to electrical loads that impact electric systems and components based on their installation location in or on-road vehicles. According to ISO 16750-2, the insulation resistance of a battery, during an insulation resistance test, should be at least 10 MΩ. This requirement has been used as a reference for interpreting the results of insulation resistance tests. [25.]

7.6 Preventing Insulation Failure

According to Hsu and Toward, the most widely used method to prevent insulation failure involves monitoring dielectric resistance by detecting ground-fault currents.

When insulation in a battery cell fails, an energised conductor may contact unintended metal surfaces, typically connected to the equipment-grounding conductor. This contact creates a low-resistance path for electrical currents, resulting in a ground fault. Such faults can trigger an alarm using a MOSFET relay between the current sensors and the ground. [26.]

This insulation monitoring and detection capability in the Battery Management System (BMS) ensures that the insulation remains intact and prevents leakage. Its primary objective is to detect and isolate faults to maintain battery safety, prolong battery lifespan, and avoid premature failures. [26].

In ground-fault detection, high-voltage from the BMS is switched through a MOSFET, utilising a non-contact relay and a network of series/parallel resistors. The microcontroller unit (MCU) then measures the voltage drop across the circuit to compute the insulation resistance. To meet safety standards, the insulation resistance must adhere to specified thresholds, such as AC 500 Ω/V and DC 100 Ω/V. An alarm is triggered if the resistance falls below these levels, providing immediate protection against potential hazards, as shown in (figure 31). [26.]

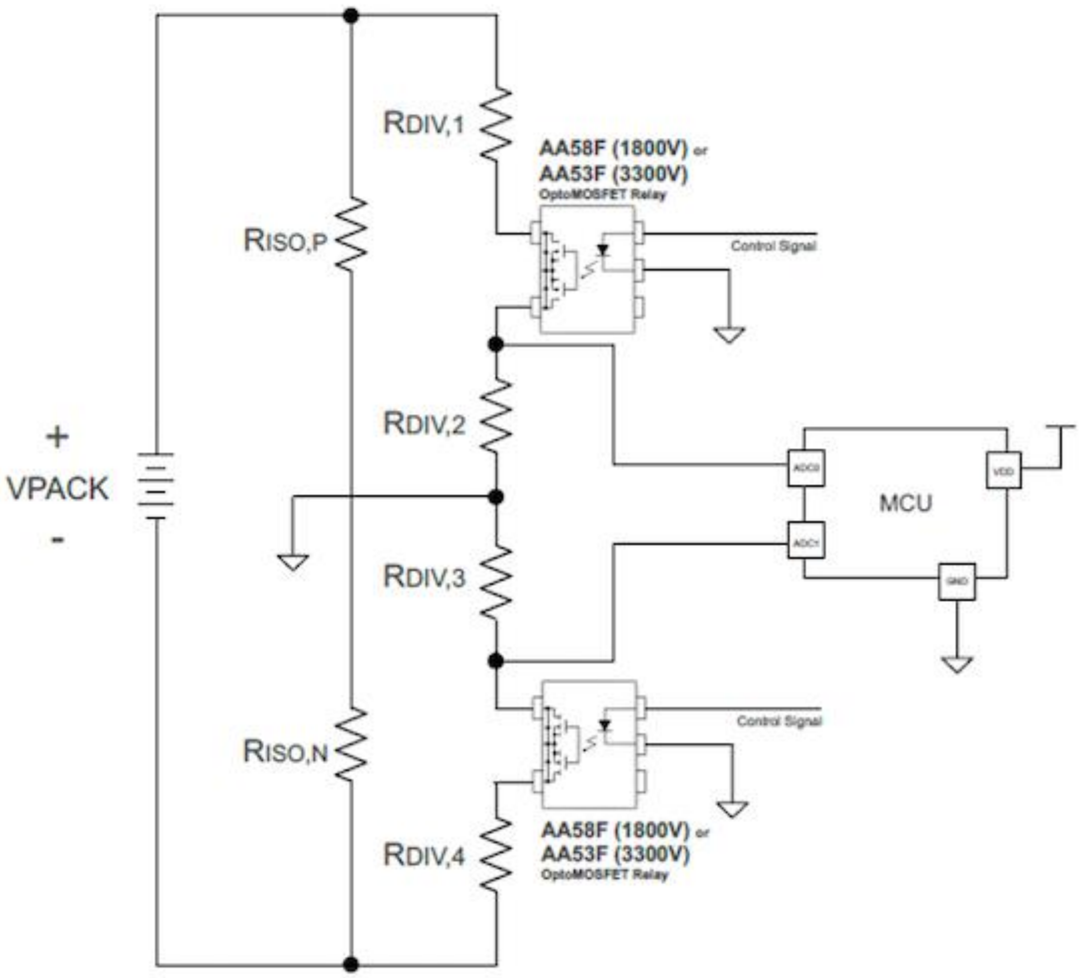


Figure 31. A typical circuit for ground fault detection [26].

7.7 Analysing failures in lithium-ion batteries

7.7.1 Voltage effects

Lithium-ion batteries are susceptible to issues caused by overvoltage and under-voltage conditions. As illustrated in (figure 32), the battery’s operational voltage and temperature must remain within the safe range indicated by the green box. Deviation from this range can result in significant damage to the cells, compromising the battery's performance and lifespan. [27.]

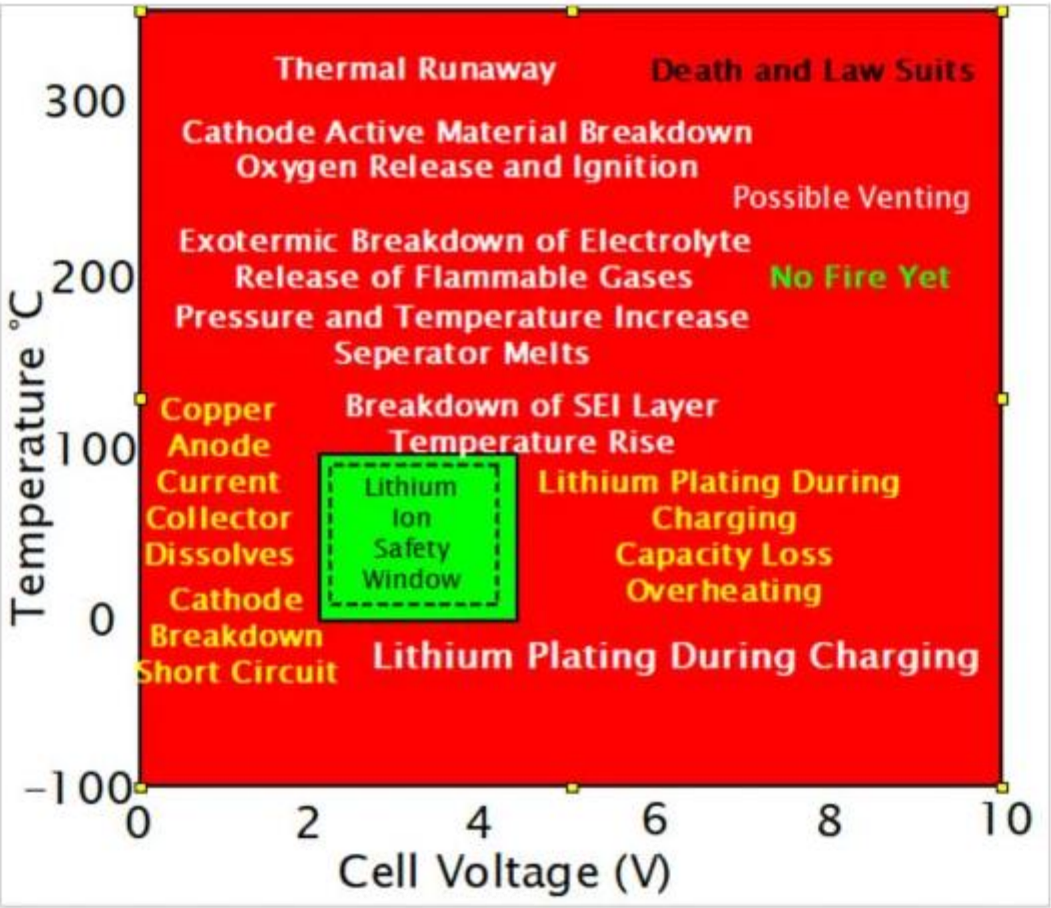


Figure 32. Safe operating range of a lithium-ion cell [27].

Overvoltage

Overvoltage occurs when the charging voltage of a lithium-ion cell exceeds its designed upper limit, typically set around 4.2 V. This excessive voltage increases current flow into the cell, leading to overheating and lithium plating, ultimately causing battery degradation or failure. [27].

When too much current flows, the resulting heat generated through resistive losses raises the cell temperature significantly. This overheating further exacerbates the risk of damage by increasing internal stress within the cell. [27].

The excess current also disrupts the proper insertion (intercalation) of lithium ions into the anode’s carbon layers. Instead of being stored effectively, lithium ions accumulate on the surface of the anode and form deposits of metallic lithium. This process reduces the available lithium ions, leading to diminished cell capacity, and increases the risk of internal short circuits, which can escalate to serious failures. [27.]

Low temperatures can also trigger lithium plating due to uneven charge distribution within the cell, often stemming from manufacturing defects or improper use of the battery. These non-uniformities worsen the cell's performance and lifespan. [27].

Over-discharge and Undervoltage

Over-discharge occurs when a battery cell’s voltage drops below the critical threshold of 2 volts during use. At the same time, undervoltage arises from prolonged storage without recharging, causing the cell voltage to fall below this level. Both conditions severely impact the battery's integrity, damaging its anode and cathode materials. [27.]

In over-discharge scenarios, the anode's current collector begins to dissolve into the electrolyte, which increases the rate of self-discharge as the battery struggles to regain voltage levels above two volts. The dissolved copper ions from the anode can lead to internal short circuits, posing significant safety risks. [27.]

Prolonged undervoltage can result in cathode degradation. For instance, lithium manganese oxide and lithium cobalt oxide cathodes undergo chemical reactions that generate oxygen, leading to corrosion over time. This process permanently reduces the battery's capacity and efficiency, rendering it unsuitable for continued use. [27.]

Both conditions highlight the importance of effective battery management systems (BMS) to prevent voltage levels from dropping too low and ensure safe and reliable battery operation. [27].

Charge state

Lithium-ion battery cells should operate within a specific range known as the state of charge (SOC) to address issues like overcharging, undercharging, and over-discharging. Maintaining the SOC within these recommended parameters ensures optimal battery health and performance, as demonstrated in (figure 33). [27.]

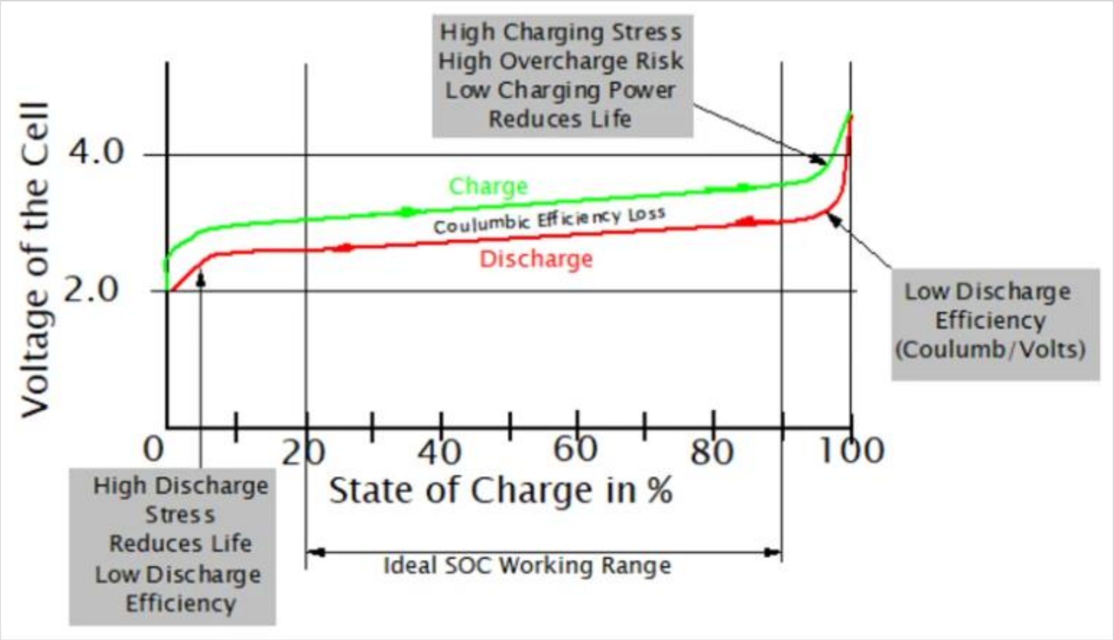


Figure 33. State of charge of the battery [27].

Operating the battery outside these prescribed SOC conditions can lead to diminished cell longevity, reduced capacity, and potential safety risks. Proper SOC management is critical for extending the life cycle and ensuring the reliability of lithium-ion batteries. [27].

7.7.2 Temperature effects

Temperature significantly impacts the performance and lifespan of lithium-ion batteries. Excessive heat or temperatures below the recommended range can degrade battery health, accelerate chemical degradation, and reduce efficiency.

Precise temperature management systems must be implemented to maintain cells within their optimal operating range for battery longevity. [27.]

Low-temperature Operation

Lower temperatures cause a decrease in the chemical reactions of a lithium-ion battery, affecting its ability to handle charge and discharge currents and power output. Additionally, the slower insertion of lithium ions into the anode can lead to irreversible capacity loss over time, as the formation of lithium plating reduces the overall power capacity of the cell. [27.]

High-temperature operation

High-temperature operation poses unique challenges for batteries, including increased energy consumption, power drain due to the Arrhenius effect, and excessive heat generation. This combined with higher currents, can exacerbate thermal dissipation, stressing the battery and potentially accelerating wear and degradation. Effective thermal management prevents these extremes from compromising battery performance and longevity. [27.]

The life of an aluminium electrolytic capacitor is significantly influenced by operating conditions, with ambient temperature having the largest impact. Arrhenius's law of chemical activity states that the capacitor's life doubles with a 10 °C temperature decrease. [27].

8 Conclusion

The thesis examines the essential role of insulation resistance in maintaining the safety and dependability of electric vehicles, with a particular emphasis on high-voltage batteries. By conducting an in-depth literary analysis, the study identifies the challenges associated with insulation deterioration, including potential safety hazards, reduced performance, and the adverse effects of environmental factors such as temperature variations, moisture, and mechanical stress.

The study highlights the importance of implementing precise and reliable measurement methods to effectively assess the insulation condition, ensuring compliance with industry norms and best practices. By delving into the intricacies of insulation resistance in high-voltage battery systems, this thesis offers valuable insights into the factors contributing to insulation breakdown. It further emphasizes the need for advanced diagnostic tools and proactive maintenance strategies to improve the safety and dependability of electric vehicles.

This study lays the groundwork for future research and practical innovations, promoting the development of novel measurement techniques, improved materials, and optimised designs to address insulation challenges. It supports the ongoing advancement of electric vehicle technology by encouraging solutions that enhance safety and reliability in this rapidly evolving industry.

An important focus of the thesis is the role of battery management systems (BMS) in maintaining the insulation integrity of battery components. Battery management systems play a critical role in identifying insulation resistance issues in (real-time), facilitating early detection, and preventing major failures. By continuously tracking key parameters such as voltage discrepancies, leakage currents, and temperature fluctuations, the system helps ensure the durability and reliability of high-voltage batteries, all while meeting stringent automotive safety requirements.

The thesis also highlights the broader importance of insulation resistance across high-voltage systems such as inverters, electric motors, and converters, which are essential to the functionality of electric vehicles. It stresses the critical need for advanced measurement methods and strict compliance with safety regulations to effectively manage and reduce the risks associated with insulation failures in these components.

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Temperature changes drastically impact the insulation resistance values.

	Baseline*	20 MΩ	40 MΩ	60 MΩ	80 MΩ	100 MΩ	250 MΩ	500 MΩ	750 MΩ	1 GΩ	1.5 GΩ	2 GΩ	
Difference from Baseline*	10 %	18 MΩ	36 MΩ	54 MΩ	72 MΩ	90 MΩ	225 MΩ	450 MΩ	675 MΩ	900 MΩ	1.35 GΩ	1.8 GΩ	With less than 25 % difference, the equipment is probably still operating acceptably.
	20 %	16 MΩ	32 MΩ	48 MΩ	64 MΩ	80 MΩ	200 MΩ	400 MΩ	600 MΩ	800 MΩ	1.2 GΩ	1.6 GΩ	
	30 %	14 MΩ	28 MΩ	42 MΩ	56 MΩ	70 MΩ	175 MΩ	350 MΩ	525 MΩ	700 MΩ	1.05 GΩ	1.4 GΩ	If there is a 25 % to 50 % difference, most professionals will recommend additional testing** and inspection to verify proper operation. (Check for potential environmental contamination.)
	40 %	12 MΩ	24 MΩ	36 MΩ	48 MΩ	60 MΩ	150 MΩ	300 MΩ	450 MΩ	600 MΩ	900 MΩ	1.2 GΩ	
	50 %	10 MΩ	20 MΩ	30 MΩ	40 MΩ	50 MΩ	125 MΩ	250 MΩ	375 MΩ	500 MΩ	750 MΩ	1.0 GΩ	
	60 %	8 MΩ	16 MΩ	24 MΩ	32 MΩ	40 MΩ	100 MΩ	200 MΩ	300 MΩ	400 MΩ	600 MΩ	800 MΩ	While equipment may operate at this level for extended periods of time, most professionals would view a change of more than 50 % in insulation resistance as indicative of potential problems somewhere in the system. Additional testing** and diagnostics are highly recommended to ensure continued, uninterrupted operation.
	70 %	6 MΩ	12 MΩ	18 MΩ	24 MΩ	30 MΩ	75 MΩ	150 MΩ	225 MΩ	300 MΩ	450 MΩ	600 MΩ	
	80 %	4 MΩ	8 MΩ	12 MΩ	16 MΩ	20 MΩ	50 MΩ	100 MΩ	150 MΩ	200 MΩ	300 MΩ	400 MΩ	
	90 %	2 MΩ	4 MΩ	6 MΩ	8 MΩ	10 MΩ	25 MΩ	50 MΩ	75 MΩ	100 MΩ	150 MΩ	200 MΩ	
	100 %	0 MΩ	0 MΩ	0 MΩ	0 MΩ	0 MΩ	0 MΩ	0 MΩ	0 MΩ	0 MΩ	0 MΩ	0 MΩ	

Appendix 2