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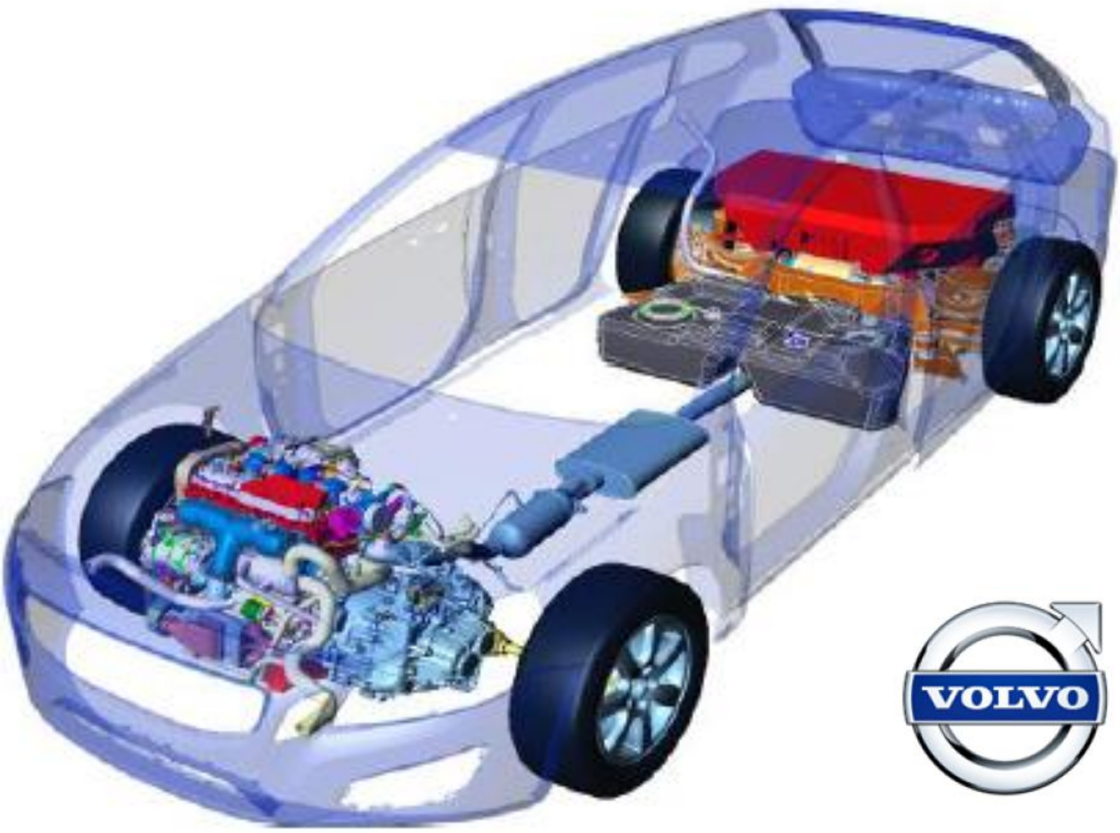

Electrical Insulation in a 400 V Battery Module for Hybrid Vehicles

Master of Science Thesis

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Electrical Insulation in a 400 V Battery Module for Hybrid Vehicles

by

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Cover:
A configuration of the electrical components connected to the high voltage bus in a hybrid vehicle, showing where the traction voltage battery is positioned.
Photo: [Volvo Car Corporation]

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ABSTRACT

The growing interest in the use of electric vehicles worldwide has resulted in awareness of the importance of ensuring the safety of these vehicles for users. The safety of electric vehicles is greatly determined by the state of the insulation between the high voltage system and the ground. In this thesis, the behaviour of the insulation in a high voltage traction battery used in a hybrid vehicle has been studied and evaluated under different operational conditions. The objective of this thesis was to assess how much the insulation resistance of the battery system is affected by the battery geometry and its environment of operation. The international standards applicable to insulation in electric vehicles have been studied to determine the requirements that the battery insulation system must adhere to and to determine which tests are recommended for testing the battery insulation system.

In this work the results from the insulation resistance tests, partial discharge tests and environmental tests performed on a battery system are presented. The results from insulation resistance tests combined with environmental tests under varying temperature and humidity conditions show that the presence of moisture on the insulating surfaces of the battery greatly decreases the insulation resistance of the battery. The partial discharge tests show that grounding of the conducting non-current carrying parts of the battery through a path of low resistance is important to minimize discharges. At operational voltages, the weakest areas of the battery system insulation have been located inside the battery module on the edges of the cells.

Keywords: Battery system, electric vehicle, insulation resistance, high voltage system.

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Mohammad H. Memari
Victoria J. Nakanwagi
Gothenburg, 2014

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List of Abbreviations

AC	Alternate Current
BEV	Battery Electric Vehicle
BMS	Battery Management System
C	Celcius
DC	Direct Current
DUT	Device Under Test
HEV	Hybrid Electric Vehicle
HV	High Voltage
$HVIL$	High Voltage Interlock
$HVMS$	High Voltage Management System
IR	Insulation Resistance
$M\Omega$	Mega Ohm
MSD	Manual Service Disconnect
PD	Partial Discharge
$PHEV$	Plug-in Hybrid Electric Vehicle
V	Voltage

Contents

1

Introduction

About 35 years have passed from the first world climate conference but global warming and Carbon Dioxide (CO_2) emissions is still a problem for the world. The need to reduce the amount of (CO_2) emissions has reached the transportation sector in recent years [1, 2]. According to [3], one of the highest producers of greenhouse gases is the transportation sector which includes public, industrial and private transportation so that even a small percentage of reduction of (CO_2) emissions in this sector will have a large impact on this problem. There are two main ways to perform this reduction, the first one is by changing the fossil fuels in combustion engines with alternatives such as biofuels and the second is electrifying the transportation sector in terms of shifting the conventional vehicles towards electric vehicles [4, 5]. The term electric vehicle covers different types of vehicles that use electrical energy in form of propulsion [6]. These types are battery based electric vehicle (BEV), which operate directly from an onboard battery supply, and plug-in hybrid electric vehicle (PHEV) which has a battery and a combustion engine.

The transition from conventional vehicle to battery based vehicles is bringing new challenges. One of the important challenges is safety of the vehicle in order to protect the passengers and vehicles sensitive component from high voltage system. HEVs are included of many different parts like battery, motor, power electronic etc. As it is introduced in [7, 8], the voltage of power supplies of these kind vehicles may reach more than 400 V up to 600 V and the nominal working current may reach tens to thousands of amperes. These amounts of voltage and current are high enough to make electrical hazard to harm passengers and the vehicle. For this reason research on the electrical insulation of vehicle is very important.

Another aspect in this research is environmental impacts and overvoltages on the insulation. HEVs must work in different conditions like vibrations, temperatures changes, wet and salty conditions. For this reason, car manufacturer shall not consider only the normal operating conditions but also likely foreseeable misuse and external influences such as electrical and mechanical stresses, pollution, moisture, temperature in the system. These conditions may deteriorate insulation over the time and may lead to breakdown of the dielectric materials which can cause damage to the vehicle safety and as a result danger to passengers [9, 10]. In order to ensure the safety of the vehicle in all environmental conditions, it is important to have a broad range of test scenarios to detect any kind of failures and act upon it.

1.1 Problem statement

One of the most important design aspects of all vehicles meant for use on public roads is vehicle safety. It is important that vehicle users and operators are protected from the high voltage components that exist in electric vehicles such as the charger, traction battery, motor, and auxiliary battery charger at all times. The electric insulation between the high voltage system and ground plays a vital role in the safety of electric vehicles. However, exposure to harsh environmental conditions including temperature changes, humidity, vibrations and electrical stress may accelerate insulation aging or breakdown of power cables and other insulating dielectric materials thus endangering passengers' lives [11]. The insulation of motors and cables typically used in electric vehicles has been extensively researched in [12, 13, 14, 15, 16, 17]. However, few studies have been done on the insulation of the traction battery and the number of available publications is small. The battery is a primary component in the operation of hybrid and electric vehicles and there is a need for research into the different stresses affecting the electrical insulation of its high voltage system as to ensure vehicle safety at all times. There is also need for knowledge on how the battery electrical insulation resistance is affected by the stresses it is exposed to through the vehicle's lifetime and to determine the weaknesses in the insulation's geometries used. In addition, there is a need for further research towards determining an insulation resistance value that the battery should have in the beginning of its life such that its insulation resistance remains within the limits required by the standards at the end of life.

This thesis was designed to include a theoretical and experimental study of the electrical insulation of the traction battery used in electric vehicles to meet the need for further research in this area. The theoretical study involved a review of existing publications and standards relevant to the electrical insulation of batteries used in electric propulsion vehicles. Based on the applicable standards, the requirements for the traction battery insulation were identified. In addition, experiments were performed on a known battery to determine the weakest areas on its insulation and how its insulation resistance is affected by temperature and humidity variations. The results from the experiments performed were used to make recommendations on how the battery insulation can be improved.

1.2 Aim

The overall aim of the thesis was to study the insulation of the high voltage battery system used for propulsion in electric and hybrid vehicles. The specific aims of the thesis were:

i. To review existing publications and standards relevant to insulation of batteries used in electric vehicles.

ii. To measure insulation resistance of a known battery system under dry conditions.

iii. To identify the weak points of the battery's insulation using excessive voltages in combination with PD measurements.

iv. To investigate the effects of temperature and humidity variations on the battery system's insulation resistance.

v. To give recommendations on what improvements should be made to the battery system.

1.3 Method

The thesis study was divided into two main parts, the theoretical and the practical/experimental study. The thesis started with a study survey to examine the high voltage electrical insulation of a known hybrid vehicle insulation system. The study survey involved a review of relevant international standards and available research papers on existing vehicle insulation systems to realize the requirements for the insulation of a high voltage traction battery. The battery used as an Electrical Storage System in the vehicle was chosen as an area of interest since not a lot of research has been done on the battery insulation and it plays a major role in the performance of hybrid vehicles. Additionally, a theoretical study on the test plans and applicable international standards in automotive relevant legislation was performed in order to determine the stated requirements for the battery's isolation and the recommended tests for battery isolation.

The tests in the experimental study were performed based on the guidelines recommended by international standards. Insulation resistance tests were performed on a selected battery insulation system in a laboratory setup. The insulation resistance under dry conditions was evaluated using a megger (insulation multimeter) and an electrostatic voltmeter (electrometer). The megger enables insulation measurement of up to 2 $G\Omega$ and the electrostatic voltmeter has a measuring range of up to $10^6\Omega$. The weak points in the insulation and the corresponding critical voltages were investigated using excessive AC voltages in combination with partial discharge measurements. The change in insulation resistance under varying climate conditions (temperature and humidity) was investigated using a climate chamber and the megger. The results from the insulation resistance tests were analyzed to determine which environmental conditions affect the insulation resistance the most. The results from the partial discharge test were used to make recommendations on how the geometries of the insulation can be improved upon.

1.4 Scope and limitations

A theoretical and experimental study was performed on the insulation system in a selected battery used in electric vehicle propulsion. The insulation system of a 400 V traction battery responsible for motion in hybrid and electric vehicles was chosen for the studies. The theoretical study considered the critical factors affecting the insulation of various battery insulation systems. The experimental study involved performing insulation resistance tests, partial discharge tests and environmental tests on a known selected system. Guidelines from relevant standards were followed to formulate the test plans and to determine the failure criteria for all tests. The insulation system was stressed and measurements were done to determine the critical geometries and materials. The effect of pollution on insulation and the phenomenon of insulation ageing have been left out of the scope of this thesis. The tests were performed on a discharged short-circuited battery to reduce the chances of charging up the battery and so the equivalent behaviour of a charged battery has not been considered.

The difference between the AC and DC field distribution on the battery high voltage bus was not put into consideration when analyzing the results from the PD measurements. Additionally, the results obtained from the tests apply to a distorted electric field distribution due the short-circuit connections on the battery. The tests that were performed on a single battery module were considered relatively comparable to those performed on the battery modules in the battery. The results obtained from the tests were used to make recommendations on how the insulation of the battery can be improved based on applicable automotive standards.

1.5 Thesis outline

The thesis is made up of eight chapters. Chapter one gives the introduction to the research undertaken in this thesis. The literature review on the battery and the insulation of the battery is presented in chapters 2 and 3 respectively where the factors affected insulation and cases of insulation failure are given. Chapter 4 gives an overview of the relevant standards that been reviewed in this study.

In chapter 5 the details on performance of partial discharge tests, the measurement procedures and interpretation of the partial discharge results are presented. The details on performance of high voltage withstand test and insulation resistance test (high voltage tests) is given in chapter 6. Chapter 7 focuses on giving the experimental procedures and presenting the results from the partial discharge tests and the insulation resistance tests. And in chapter 8 the results obtained are discussed and the conclusions and recommendations are given in chapter 9.

2

Battery system

The key areas of the high voltage system in electric and hybrid vehicles system are the drive battery and drive motor [18]. In hybrid and electric vehicles the battery functions as a rechargeable electrical storage system (RESS). A RESS is defined as a rechargeable energy storage system that provides electric energy for electric propulsion and could be batteries in [19]. Batteries used for propulsion in electric vehicles (also referred to as traction batteries) are normally connected in series to provide high voltages up to 600 V in order to improve drivability and energy efficiency. Today, electrochemical battery systems with lithium-ion cells are widely used to power electric and hybrid vehicles and have been accepted as state of the art in regard to energy and performance [20]. Standard UL2580 defines a battery pack as batteries that are ready for use in an electric powered vehicle contained in a protective enclosure, with protective devices, a battery management system and monitoring circuitry, with or without cooling systems [21].

This section describes the different parts of a battery system including the battery's general high voltage configuration. It details the structure and arrangement of the modules used in a battery pack. It also details the specifications under which the battery pack under study has been designed to operate.

2.1 High voltage configuration

In the automotive industry voltage magnitudes of 60 V and above are classified as High Voltage (HV). Typically, the battery pack is designed to ensure high voltage safety in electric vehicles as depicted in relevant international standards [22]. A battery pack consists of series connected modules and other high voltage components that are usually enclosed in a locked and insulated box to provide electrical insulation in the form of physical separation. The general topology of the high voltage configuration in hybrid and electric vehicles comprises a High Voltage Management

System (HVMS) which is installed to ensure the safety of electric vehicles by avoiding the inadvertent contact with high voltages that may cause damage or injury. The conducting non-current carrying parts of the high voltage system are usually grounded to provide a path of low resistance for high currents in case of faults or insulation failure between ground and the high voltage bus. Figure 2.1 shows the typical configuration of the high voltage circuit in the HVMS described in [23], and this study directs its focus on the high voltage battery. The general functions of the HVMS apply to the entire high voltage system and are outlined in [23] as:

a. Power-up and power-down control of the high voltage system. This involves control of relays that are mounted close to the battery terminals to cut off power output in the event of a fault on the HV system.

b. The Manual Service Disconnect (MSD) and High Voltage Interlock provide a safe environment for battery repairs during maintenance [24]. The interlock circuits symbolize connection status of the high voltage circuit and when the circuits' interlock breaks, the HVMS sends alarm signals to disconnect the battery from the high voltage system.

c. Electric leakage protection of the HV system. The HVMS continuously monitors the insulation of HV system is and when an electric leakage takes place the system cuts of power to protect passengers from electric shock.

d. Communication. The communication system enables interaction between the Battery Management System (BMS) and Vehicle Management System . BMS is responsible for monitoring the HV bus and provides diagnosis for the status of the HV bus. The BMS monitors the insulation resistance, leakage currents, relay state and the ground state of all HV components.

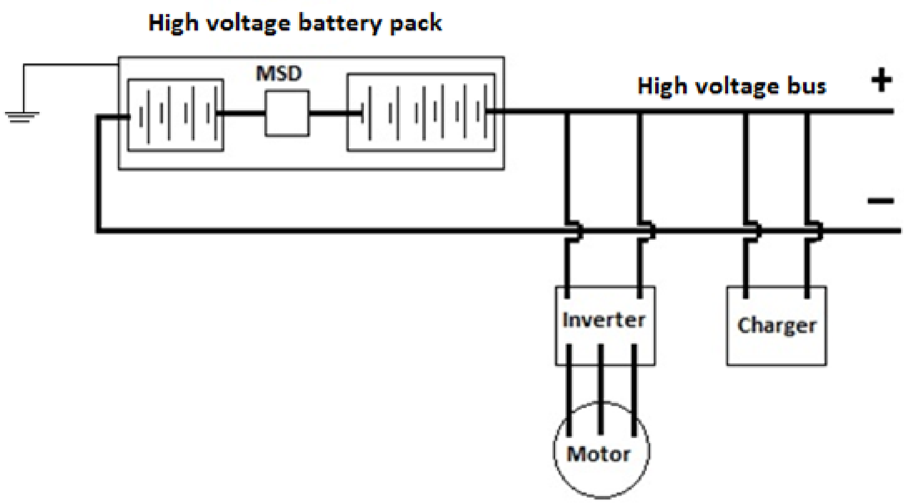


Figure 2.1: High voltage circuit configuration

2.2 Battery pack configuration

In this study, a battery pack has been defined as batteries that are ready for use in an electric powered vehicle contained in a protective enclosure, with protective devices, a battery management system and monitoring circuitry, with or without cooling systems [21]. The battery pack under study is made up of battery modules, power cables, power electronics circuits and contactors all placed in a single containment. The single containment is employed to limit the ingress of environmental factors like moisture, dust, and humidity from the outside into the battery pack. When designing the battery pack, thermal considerations have also been taken into account. A liquid cooling method is used to keep the batteries at a stable temperature.

The whole battery pack consists of 200 capacity Lithium-ion cells packaged in battery modules. The battery pack under study is made up of 10 battery modules with 20 lithium-ion cells per module. According to [21], a cell is defined as a basic functional electrochemical unit containing an electrode assembly, electrolyte, separators, container, and terminals. It is a source of electrical energy by direct conversion of chemical energy. A single cell can also be defined as a complete battery consisting of two current leads and separator compartment holding electrodes, separator and electrolyte [25].

Within a single battery module, every two lithium-ion cells are welded together to form parallel connected paired cells so each module is made up of 10 paired cells. The paired cells are connected in series giving 10 series connected cell pairs per module and a module voltage capacity of 40 V.

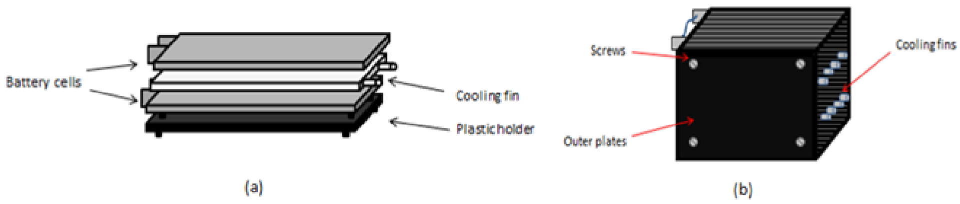


Figure 2.2: Configuration of battery module a) sub stack of the battery module b) showing the grounding points

Figure 2.2-a shows the sub stacking of the different parts inside the battery module. The mid-plates (plastic holder) are placed after every cell pair to provide structure to the module and support the weight of the battery cells and the cooling fins. Figure 2.2-b shows the complete structure of the battery module and the points through which the module is grounded which include the screws, cooling fins and outer plates. The two end plates (outer metallic plates) sit along either ends of the terminal cells to protect the cells from mechanical damage. Four metallic screws passed though the four corners of the end plates and then through the mid-plates along the length of the cells. The screws secured and aligned the end plates and mid-plates and take on the weight on both plates. The screws are also used to fasten the end plates in place together with the mid-plates and maintain the structure of the module. The cooling fins are placed between every cell pair and have a coolant liquid made of 51% glycol and 49% water flowing at a rate of 7l/min through them. The purpose of the coolant is to maintain the cell

temperature within the operational ranges specified in table 2.1. The cooling fins are connected to ground through the coolant. The battery pack is divided into two sections; one section

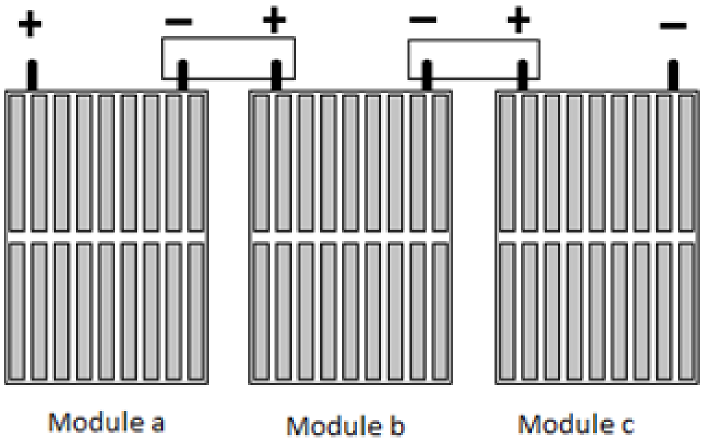


Figure 2.3: Series connection of battery modules.

consists of 4 battery modules connected in series with an operating voltage range from 168 V to 126 V. The other section consists of 6 battery modules also connected in series with an operating voltage range from 252 V to 189 V. The series connection between the battery modules is as shown in figure 2.3. The two sections are connected in series using the MSD (Manual Service Disconnect) giving a series connection of all the 10 modules. The maximum operating voltage of the battery pack when all modules are connected in series is 420 V. Each module containing 10 series connected cell pairs has an operating voltage range from 31.5 V to 42 V. At the start of the battery life, the battery insulation resistance with reference to the insulation between the ground and high voltage bus was specified to be greater than 10 $M\Omega$ in accordance with ISO 16750-2 [25]. Insulation resistance is defined as the electrical resistance between two conductors (ground point and high voltage point) separated by an insulating material. More detailed specifications of the battery are given in table 2.1.

Table 2.1: Specifications of the battery

Parameter	**Specification**
Nominal operating voltage	375 V
Maximum operating voltage	420 V
Minimum operating voltage	315 V
Maximum operating temperature	50°C
Minimum operating temperature	-30°C
Cell operating temperature range	10 – 35°C
Maximum coolant temperature	5 – 29°C
State of charge range	20 – 90%
Peak discharge current	257 A
Total pack energy	10.7 kWh
Usable pack energy	7.5 kWh
Weight	150 kg

3

Battery pack insulation

Insulation resistance gives an indication of the leakage current flowing through a circuit. In an electric vehicle, the insulation resistance of the high voltage bus with respect to ground depicts the safety state of the HV bus and is an indicator of the electric vehicle's safety performance [24]. The insulation resistance between the HV circuit and the chassis varies with applied voltage, temperature and level of moisture. A low insulation resistance level may result in exposing passengers to dangerous voltage levels [18]. The insulation resistance must always remain within the limits specified by international standards. According to ISO 6469-1:2009 [22], the insulation resistance divided by its maximum working voltage should be maintained at least greater than 100 Ω/V for DC circuits and 500 Ω/V for combined AC and DC circuits but having a value greater than 500 Ω/V is preferred to ensure safety of vehicle users. This requirement is for the entire circuit including all components; therefore each component is required to have a higher insulation resistance [5].

The insulation resistance value of the battery with respect to ground is expected to remain within the safety requirements throughout the vehicles' life, approximately 10 years; therefore the monitoring of the insulation resistance is necessary. A decrease in insulation resistance at any point in the battery will significantly affect the monitored value and may be detected as an insulation failure by the High Voltage Management System.

This section describes the different causes of insulation failure in electrical equipment and specifies which of these are most likely to contribute to insulation failure in a battery pack. It further presents some examples of insulation failure that may originate from within the battery pack.

3.1 Insulation degradation

Typically, the insulation of electrical equipment is made up of different components carefully chosen to withstand stresses such as electrical, thermal, mechanical and environmental to which it is subjected. Insulation material in electrical equipment degrades over time due to one or multi stresses affecting the equipment. This degradation often referred to as aging of the electrical insulation is a process that causes irreversible changes in the properties of the insulation due to interaction of one or more factors of influence (stresses) [27]. As a result of significant degradation, the electrical resistivity of the insulating material reduces due to developed cracks, moisture and foreign matter that penetrate the insulation surface [28]. Consequently, the leakage currents are provided with a low resistance path to flow and these currents may lead to incidents that could cause damage to lives and equipment [29].

The ability of the insulation to withstand the stresses will depend on the severity of the stresses that it faces, the material of the insulation and the environment within which it operates. This will therefore determine the length of useful time of the insulation. In addition, since the degradation process is usually a gradual one, the insulation resistance can be checked periodically to avoid complete failure. Electric vehicles operate in different conditions such as vibration, temperature changes combined with humidity and salt which may cause aging of the HV power cables and other dielectric materials [30]. Long term exposure to these stresses could lead to lower values of the insulation resistance and consequently endanger passengers' lives. However, ISO 16750:2003 [25] requires that the battery's insulation resistance fulfills the requirements stated in [22] when operating in different the environmental conditions within which the battery operates. It is therefore important to monitor the insulation resistance and to study the factors that may lead to degradation of insulation materials and eventually failure in the battery pack.

3.1.1 Causes of insulation failure

The major causes of insulation degrading of insulation materials can be classified into groups as listed below. Since the battery is contained in an enclosure during operation, the level of stress on its insulation caused by each of these factors will vary.

3.1.2 Mechanical stresses

Mechanical stresses resulting from shock or vibration during operation could cause cracking, breaking-up or delaminating of insulation materials. Mechanical shock could lead to insulation failure particularly when the impact strength of the insulation material has been reduced. The factors responsible for reducing impact strength of insulation as stated in IEC 60664 [31] include;

- When the material becomes brittle as a result of the temperature falling below its glass transition temperature.

– When the insulation is subjected to prolonged exposure to high temperatures that leads to degradation of the base polymer.

Mechanical stresses in the battery pack occur usually in the form of vibrations when the vehicle is in motion. The effect of vibrations is the loosening of fasteners which results in misalignment of different parts which may result in accelerated wear of moving parts [27]. Consequently, high voltage points may get in contact with the ground causing high currents to flow to ground thus endangering the lives of passengers and operators.

3.1.3 Electrical stresses

Increased electrical stresses occur in the form of overvoltages, or as an effect of partial discharges in the insulating material. The role played by overvoltages is considered significant if they occur frequently during operation. The frequency of the voltages to which an insulation material is subjected greatly influences its electric strength. The probability of thermal instability and dielectric heating increases proportionally to the voltage frequency and so an increase in frequency reduces the electric strength of insulating materials [31].

Corona is a form of electrical discharge that happens when the corona inception voltage is reached resulting in a breakdown in air. Corona is harmful to insulating materials, its byproducts such as nitrogen formed from the ionization of air forms acids which when combined with moisture cause insulation degradation. Furthermore, it produces ozone which speeds-up oxidation of organic materials in insulation.

As is stated in the standard IEC 60664 [31], it is possible for partial discharges to occur at peak voltage above 300 V but have a lower probability of occurrence below peak voltage of 500 V. Furthermore, the failure in insulation due to partial discharges is manifested by gradual erosion or treeing resulting in punctures or surface flashover [31]. The frequency of the applied voltage also influences the partial discharge behaviour. For the generation of partial discharges to be taken into consideration, they should be expected to happen at the operating voltage.

During battery operation, overvoltages do not occur frequently since the rated battery voltage range is between 420- 375V DC, this assumption however does not apply for any external voltages that the battery may be subjected to. Furthermore, within this voltage range there is a probability that partial discharges will occur within air gaps or deformations of the insulation materials used in the battery pack.

3.1.4 Thermal stress

Temperature is an important factor that greatly contributes to insulation aging (degradation). Since the temperature coefficient of resistance in an insulation material is a negative fairly large value, a small increment in temperature will result a large decrement in the insulation resistance [32]. Organic insulating materials will become brittle when operating in high temperature environments due to loss of plasticiser. High temperatures also cause expansion of tightly bonded materials which leads to mechanical stress and increased dielectric losses leading to thermal instability and failure. The range of temperature expected within the battery pack on the battery modules/ cells during operation lies between $20 - 32\,^{\circ}$C. When parked this temperature could be higher due to ambient and sun. But when cooling is activated the cooling parts (cooling fins) will have a temperature of $15\,^{\circ}$C. Within the high temperature ranges, temperature stress is expected to play a major role in the degradation of the insulation materials within the battery pack. The area considered to be prone to thermal stress is the battery modules since they heat up often and they are closely packed such that the heat they generate is not quickly dissipated by the cooling fins.

3.1.5 Environmental stress

Environmental stresses are continuously found in the immediate surroundings of equipment when it operates or when it is shut down [27]. These stresses could be in the form of moisture, humidity, radiation, chemicals, dirt and oils. According to UL840 [**?**], the addition of contaminants, solids, liquids or gases and moisture that may produce a reduction of dielectric strength or surface resistivity are referred to as pollution. The environmental conditions that immediately surround the creepage distance of the insulation material determine the effect of pollution on it. The degree of pollution for the battery under study has been classified as pollution degree 3 (the pollution degree to which the battery is expected to be subjected). International standard ISEN60664 states that pollution degree 3 refers to conductive pollution or dry non-conductive pollution that becomes conductive due to condensation. This pollution degree level is achieved through the use of an enclosure to exclude or reduce environmental influences like moisture in the form of water droplets.

When an insulation material is covered in or absorbs moisture its insulation resistance will decrease since the moisture is conductive [32]. In case the insulation has developed cracks and pores the moisture will penetrate them and thus provide a low resistance path for leakage currents. Furthermore, a combination of dirt, dust and moisture becomes conductive enabling the flow of leakage currents and inhibiting dissipation of heat from the insulator leading to insulation degradation [32]. Also, insulation resistance is permanently lowered by chemical fumes like acids and alkaline [18].

Some of these contaminants are not of concern for the battery under study since it exists in a single containment within the vehicle keeping out several environmental factors. The factors considered to play a major role in insulation degradation included existing pollution like dust particles during manufacture which become conductive in the presence of humidity, moisture in the form of water droplets (condensation) and salt. Vehicle operation in salty environment and areas of high humidity leads to corrosion of metal parts. The effect of exposure of insulation materials to moisture is loss of dielectric integrity leading to reduced insulation resistance.

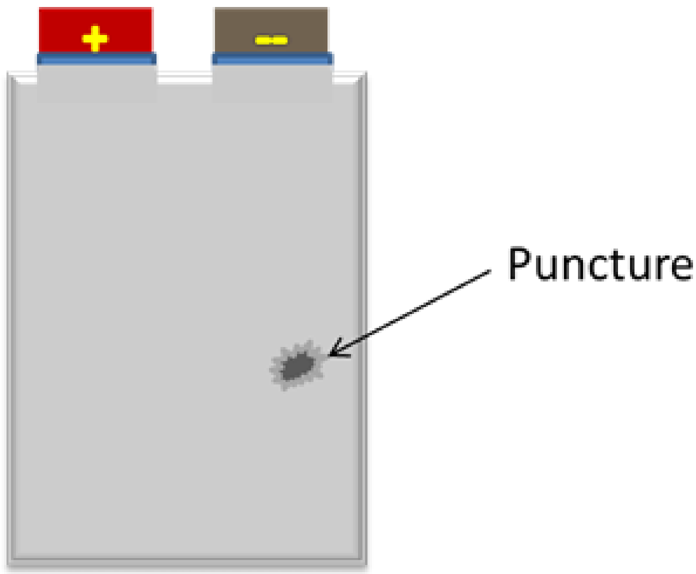


Figure 3.1: Punctured cell pouch.

3.2 Cases of insulation failure

The occurrence of an insulation failure means that the electrical resistivity of insulating materials has reduced to allow a leakage current to flow. An insulation resistance value lower than 10 MΩ for the battery is not acceptable according to ISO 16750-2 and therefore the insulation resistance should be greater than this at the time of manufacture in order to maintain the insulation resistance value above the required value throughout the life of the vehicle. Below are examples of some incidents that could result in insulation resistance reducing below the recommended values and may be classified as insulation failure in the battery pack.

3.2.1 Punctured cell pouch

A new battery pack containing a punctured cell pouch in one of the modules when subjected to 500 V DC high potential voltage test may reveal a low resistance value between the high voltage terminal to chassis. A resistance value on either the negative or positive side lower than the required 10 MΩ would be classified as an insulation failure. The puncture on the cell pouch may have resulted from mechanical stress and vibrations causing sharp edges on the end plate to cut into the cell pouch. An example of a punctured cell pouch is shown in figure 3.1.

3.2.2 Abrasion on pouches after vibration test

Subjecting a battery pack to a lifetime vibration test could result in abrasions along the terraces of cell pouches which are in contact with the grounded cooling fins. This would be classified as a mechanical stress on the insulation between the high voltage sources on the cell and the ground. Carrying out a high potential test on this battery pack to determine the status of the insulation resistance would show that the battery pack insulation has deteriorated. This is considered an insulation failure and is possibly a common incident since the vehicle is subjected to greater vibrations throughout its lifetime.

3.2.3 Bus bar misalignment after vibration test

If the vibration test is conducted on a battery pack and during the test the high voltage bus bar comes in contact with one of the structural brackets on the lower tray at ground potential, insulation failure may be detected. This would be as a result of misalignment of the bus bar too far to the left in the battery pack allowing it to rub on the foam pad support bracket of one of the modules. However, once proper clearance is provided between the two components to correct the misalignment the physical insulation is restored to its original condition.

4

Overview of standards

The growing interest in the use of electric vehicles for transportation has led to the emergence of several international standards written to standardize different aspects of electric vehicles to ensure the safety of the vehicle users. As part of the theoretical study in this thesis, some of the standards relevant to the insulation in electric vehicles have been reviewed to identify the requirements a traction battery is expected to meet. This chapter gives a summarized overview of the applicable requirements from the different standards that have been reviewed. The overview presents the requirements and the tests recommended to verify the state of insulation resistance of a traction battery.

- **ISO 6469-1:2009** Electrically propelled road vehicles-Safety specifications-Part 1: On-board rechargeable energy storage system [22].

  This standard gives requirements for the on-board rechargeable energy storage systems (RESS) used in electrically propelled vehicles for the protection of the people inside and outside the vehicle and its environment. These vehicles include battery-electric vehicles, fuel-cell vehicles and hybrid electric vehicles.

  In this standard, the insulation resistance test is a recommended test to determine the battery insulation resistance. It is required that the measurement of the battery's insulation resistance include auxiliary components in the housing like temperature conditioning devices and liquids. Before any testing is done, the negative and positive terminals of the battery should be disconnected from the electric propulsion circuit and any other external circuit. It is required that any internal auxiliary systems powered by external sources should be disconnected from the sources and connected to the vehicle's electric chassis [22].

  Before measurement is done, the RESS should be subjected to at least 8 hours at (52) deg and there after a conditioning period of 8 hours at 235 deg, humidity of 90 % and atmospheric pressure between 86 kPa and 106 kPa to reach the dew point. During insulation resistance measurement the vehicle chassis is considered as an electric conductor which will give the resistance between the battery and the vehicle chassis.

According to section 6.1.4 of this standard, the minimum isolation resistance should be at least 100 Ω/V for DC circuits and 500 Ω/V for AC circuits with the maximum working voltage as reference. This requirement is for the entire circuit including all components; therefore each component is required to have a higher isolation resistance.

– **ISO 16750:2003** Vehicles - Environmental Conditions and Testing for Electrical and Electronic equipment – Part 1: General [34].

  This standard gives the definitions and general specifications for potential environmental stresses, the corresponding tests and requirements for the electric systems and components mounted on or in road vehicles. This standard specifies that the battery system minimum insulation resistance shall be greater than 10 Ω/V and should remain compliant in different environmental exposures in order to maintain the safety of the users. This requirement has been used as reference when making conclusions on the environmental tests results in the experimental study.

– **ISO 16750-2 2003** Road vehicles – Environmental conditions and testing for electrical and electronic equipment – Part 2: Electrical loads [26].

  This standard is applicable to the electrical loads that affect electric systems and components with respect to their mounting location on or in road vehicles. In section 4.10.3 of ISO 16750-2, it is specified that the insulation resistance of a battery during insulation resistance test should be a minimum of 10 Ω/V. This requirement has been used as reference when drawing conclusions on the insulation resistance test results.

– **ISO 60664-1-2007** Insulation coordination for equipment within low-voltage system-Part 1 [31].

  This standard deals with insulation coordination for equipment with low-voltage systems and is applicable to equipment for use up to 2000 m above sea level with a rated voltage up to AC 1000 V at 30 kHz or a rated voltage up to DC 1500 V. It provides methods for electric testing with respect to insulation coordination. The testing methods described in this standard have been used to verify clearances inside the battery pack in this thesis and to determine the state of the battery's insulation.

  Partial discharge test

  In this standard, the purpose of this test is to verify that no partial discharge are maintained in the solid insulation and no surface discharges occur in the surfaces at the highest of the following values: recurring peak voltage, peak value of the steady state voltage, peak value of the long term temporary overvoltage. It is also used for localization of partial discharges when they occur.

  An AC test voltage with less than 3 % distortion at power frequency is used. The test is performed under conditions of room temperature and average humidity (23 °C, 50 % relative humidity IEC 60068-1). The test voltage should be uniformly raised from 0 V until a partial discharge occurs. If no partial discharge occurs at a voltage of 1.5 times the highest voltages of the following rated voltages; recurring peak voltage, peak value of the steady state voltage, peak value of the long term temporary overvoltage the test voltage should be reduced back to zero. The failure criterion is that no partial discharges should occur during the test.

The impulse voltage withstand test

The purpose of this test is verification of clearances; this test is used to assess the stresses caused by transient overvoltages for clearances and solid insulation. This test was not performed because it could lead to break down of the battery insulation. It is required that the test is carried under normal lab conditions; temperature $15 - 35\,°C$, air pressure 86-106 kPa at sea level, relative humidity 25-75 %. For a DC voltage source of 400 V such as the battery the test impulse voltage recommended for this test was 2500 V with a 1.2/50 us waveform. It is specified in this requirement that the device under test should be subjected to dry heat (IEC 60068-2-2) and damp heat (IEC 60068-2-78) conditioning prior to performing the test. The test is carried out for a minimum of 3 impulses of each polarity and an interval of at least 1s between impulses. The failure criterion in this test is the existence of flash overs during testing.

In section 4.6.2, the pollution degrees are defined and classified into four categories. The pollution degree for the battery under test has been selected as pollution degree 3 and is defined as follows by the standard: Pollution degree 3 refers to conductive pollution that occurs or dry non-conductive pollution occurs which becomes conductive due to condensation which is to be expected. This pollution degree level is achieved through the use of enclosures to exclude or reduce environmental influences like moisture in the form of water droplets. The pollution in the battery pack includes humidity, condensation and salt.

- **UL 840** Insulation coordination including clearances and creepage distances for electrical equipment [33].

  This standard gives requirements to specify through air and over surface spacing for electrical equipment through the use of insulation coordination principles. It is applicable because it considers the role played by the environment in which electrical equipment operates when performing insulation coordination. The impulse voltage test was given as a test to verify clearances and creepage distances and the details of this are as mentioned in ISO 60664-1-2007 above.

- **UL 2580** Batteries for use in electric vehicles [21].

  This standard covers the requirements for electrical energy storage assemblies such as battery packs and their subassembly modules for use in electric-powered vehicles. It gives methods for evaluating the electrical energy storage assembly's ability to safely withstand simulated abuse conditions without being hazardous to those testing. The tests recommended on the insulation of a battery used in electric vehicles in this standard are the dielectric voltage withstand test and the insulation resistance test.

The insulation resistance test

This standard specifies that the insulation resistance test on a battery used in an electric vehicle should be performed after conditioning the battery in accordance with the Standard for Environmental Testing – Part 2-30: Tests – Test Db: Damp Heat, Cyclic ($12h + 12h$ Cycle), IEC 60068-2-30 using the following parameters: a) Variant 1; b) At maximum temperature of 552 °C (1313 °F); and c) 6 cycles. It is also specifies that the measuring instrument used for insulation resistance test should have an internal resistance above 10 $M\Omega$.

Dielectric voltage withstand test

The purpose of this test as stated in this standard is to evaluate the electrical spacing and insulation at hazardous voltage circuits of the electric energy storage assembly (batteries).The device under test is to subjected to preconditioning at constant temperature of 302 °C for 24 hour duration followed by conditioning at temperature of 232 °C for 48 hours, humidity 93 %5 and atmospheric pressure 86 kPa to 106 kPa.

It is required that the test is performed under room temperature and average relative humidity. During testing a DC test voltage of 1.414 times twice rated voltage is applied between hazardous voltage circuit of the DUT (including the charging circuits) and non-current carrying conductive parts that may be accessible or connected to accessible parts of the vehicle. All live parts of the device under test must be connected together. The test voltage is applied for at least 1 min between positive or negative and accessible non-current carrying part in turn to avoid short circuit between positive and negative. The failure criterion is that arcing or dielectric breakdown should not be evidenced during testing.

5

Partial discharge and measurements

At Volvo Cars Corporation, it is required that insulation of high voltage system like other parts of the vehicle have a high degree of reliability, safety and convenience and all activity that can lead to instability and degradation of vehicle's life needs to be addressed and studied carefully. Insulation of the high voltage system, especially battery system, is one of the important parts to ensure the safety of the system.

Electrical discharges in the non-uniform field in form of corona at the surface or internally in the inhomogeneous material have an important role in the breakdown and ageing of the insulation systems. Presence of these discharges can be seen as an indicator for showing the insulation failure mechanism and ageing processes. These discharges release amount of energy at the point of discharge due to high energy electrons or accelerated ions which causes weakening of the material and causes chemical transformation within insulation system [35]. Thus, these discharges are counted as serious stresses which can lead to degradation of insulation and possibly failure of insulation system. For this reason, detection, measurement and location of these discharges are of too much interest in high voltage engineering and can help the manufacturer to improve their products.

The purpose to perform the partial discharge test is to verify that no partial discharges are maintained in the solid insulation and to identify weak points of the insulation. Also, it is used for localization of partial discharges when they occur. This test is a good method for detection of a range of insulation problem that can be addressed to the manufacturer to prevent happening of failure and controlled outage of equipment [35].

Discharge mechanism is introduced in the beginning of this chapter to give an understanding about what discharge is and how it leads to the breakdown. In the following section a definition of partial discharge is presented and sources where the partial discharges can occurs are specified. In the end of the chapter, a measurement method is introduced to detect and localize the partial discharges.

5.1 Discharges and breakdown

Charged particles are needed to pass the electrical current. In the metals and solid conductors, these particles are electrons. In the liquids, these particles are in the first step ions and in the nest step electrons. Ions are atoms or molecules that have lost one or several of their electrons. In the gases, there are free ions and electrons because of external factors like radiation. In presence of a high voltage electrical field between two electrodes, the charged particles can get sufficient energy to collide neutral molecules and ionize them [36]. As a result of ionization, a significant current is flowing inside the material which causes electric "discharges". By increasing the voltage across the electrodes, the higher electric field causes more and more ionization which leads to a state of significant ionization and consequent conductivity in the end. In this stage, the discharges are self-sustaining that can continue ionization without further external source of ionizations. The transition from non-self-sustained discharges to self-sustained discharges is called "breakdown" [37].

Partial discharges (PD) is localized dielectric breakdown and may or may not lead to total breakdown of the insulation. According to the IEC 60270 [38], "PD is a localized electrical discharge that only partially bridges the insulation between conductors and which may or may not occur adjacent to a conductor."

As it is clear from the definition, the PD is an ionized path within a small part of an insulation which partially bridging the electrodes and can only release very limited energy in comparison with the full breakdown. Partial discharges give lots of information about state of insulation and are a sign for indicating the state and quality of the insulation.

5.2 Classification of Partial Discharge

Partial discharges can be caused due to non-uniform field like surface and corona discharges or due to inhomogeneous material like discharges in cavities or treeing. These classic forms of PD source are shown in the figure 5.1. The main sources of PD are corona, surface, internal and barrier discharges [36].

As it is shown in figure 5.1, the internal discharges are normally due to cavities inside the dielectric. These cavities inside the insulation exist mainly because of bad manufacturing or they are created later due to ageing of insulation material. Voids, delamination and crack shown in the figure above are the typical forms of cavities inside the insulation. By applying voltage on the terminal of the insulation, the electric field will be created. This electric field inside the cavities depends on the geometry of the cavity and it is equal or greater than the field in the surrounding insulation. Cavities have lower electric breakdown strength than the surrounding

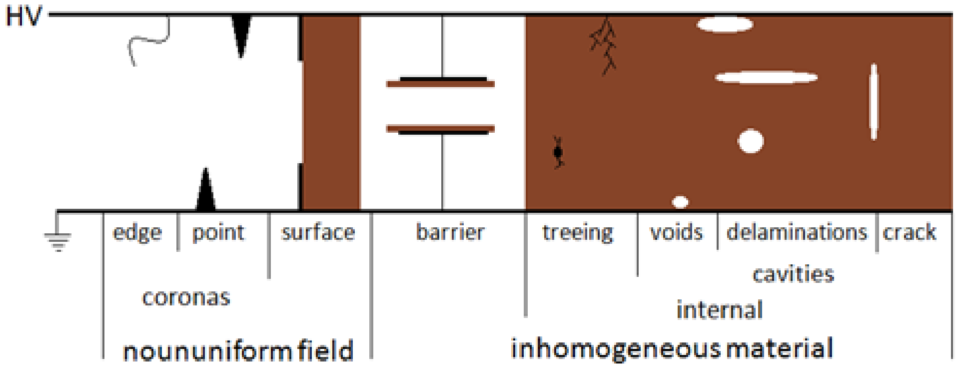


Figure 5.1: Sources of partial discharges [36].

insulation, for this reason partial discharges are initiated in the cavities as soon as the voltage across the cavity reaches the breakdown voltage [39].

Another common type of discharges is corona discharge that occurs around the sharp points at high voltage. The main reason for occurring these kinds of discharges is non-uniform field and higher field strength close to the points and the edges. Corona discharges may be steady state or transient and the number of spots are related to the current in the system so that the number of spots is increased by increasing current [37].

Corona discharges can occur in gases or in liquid. These discharges are behaving different when the applied voltage is negative or positive but based on stroboscopic studies, corona discharges has the same appearance when the applied voltage is AC or DC. Usually these discharges appear as sparks with special audible noises and white luminous which make it possible to detect them easier than other kind of discharges [39].

Surface discharges are another type of partial discharges that occurs in contact with gas or liquid insulation along the surface of the solid insulation. These discharges are happening when there is significant difference in the dielectric strength on the interface of two dielectric insulations [39].

5.3 Partial discharge measurement

Partial discharge measurement categorized as non-destructive insulation test, because the hypothesis is based on that partial discharge is not occurring during the measurement. However, partial discharges in the insulation are categorized as long term stresses that during long time degrade insulation and can lead to breakdown [37].

PD measurement can be based on different phenomena which are based on the exchange of energy at the point of discharge. These phenomena can be listed as: electrical pulse current, dielectric losses, radiation, sound, increased gas pressure and chemical reactions. The oldest and early attempt to recognize discharges in solid insulation was aural methods by listening to the acoustics noises from the discharges which calls "hissing test". In this technique an ultrasonic transducers is utilized to localize discharges. However sensitivity of the device and difficulties to localize the exact position of discharges are drawback of this technique and make it hardly possible to localize the source of the discharges. Another simple technique is visual method in form of sparks that because of short time of appearing can be difficult to record and hardly possible when PDs occurring in the voids. In the other hand, it can be a good method to find corona discharges on the surface of the insulation [36]. To detect the corona discharges, the easiest way is to turn off all light sources and look for the sparks in the darkness.

The most frequent method for detection of charge displacement is based on electrical methods. These methods are based on the appearance of PD voltage or current pulse at the test object terminals. PD voltages and current pulses are caused by rapid movement of charges which leads to a charge distribution on the electrodes [36, 40]. These charges can later be detected by a PD detector in form of apparent charge. The electrical method will be discussed in details in the next section.

5.3.1 PD test circuit

Let us consider the case when the PD event is happening in a gas-filled cavity inside the insulation. Insulation of this case like any other cases can be modeled as simple capacitor arrangement as figure 5.2. As it can be seen from the figure 5.2-a, the electric fields between the electrodes are represented by C_a. The electric field inside the cavity is represented by Cc and field between electrodes terminals are represented as $C_b^{'}$ and $C_b^{''}$. Figure 5.2-b shows the equivalent circuit of the insulation between terminals A and B. In this figure, switch S depends on the voltage V_c which is across cavity capacitance C_c [37].

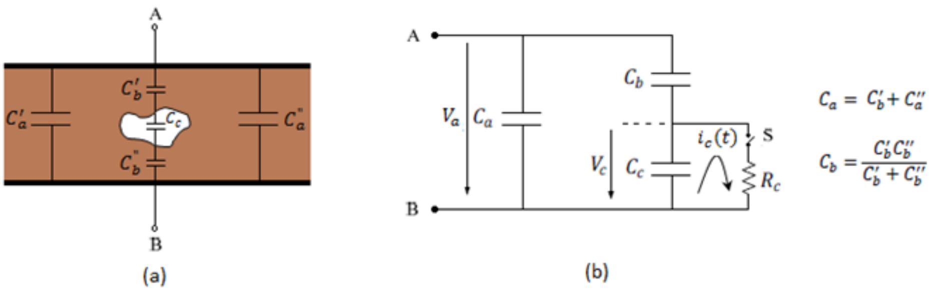


Figure 5.2: a) Insulation system capacitance model. b) Equivalent circuit for PD [37].

When the voltage V_c is significantly increased the discharges starts to occur. Discharges in the cavity are of type of gas discharges and leads to creating positive and negative ions and also electrons. During discharge, the created ions are moving to the surface of the void and forming dipoles inside the insulation. Changes in the charges of the dipole moment cause currents in the circuit. These current are not possible to be measured and are in range of nanoseconds. In the figure 5.2-b, the switch S is closed during the discharge when the current $i_c(t)$ is flowing.

Current $i_c(t)$ here is the discharge current and exists in a short time, for this reason it is very difficult to measure but there is a test circuit that is based on another quantity which makes it possible to detect the discharges [37].

The test circuit is shown in the figure 5.3. The test object is simulated by C_x and C_k shows the coupling capacitor connected in series with detection impedance which is also called as quadripole. According to standard IEC 60270 [38], the capacitance of C_k should be higher than the capacitance of the test object C_x. Purpose of the coupling device is to separate the PD current pulses from the applied voltage frequency to the test circuit. Impedance Z is impedance of filter and according to the IEC 60664 [31], there is no obligation to use it but in the case of using the filter it is required that its impedance be high enough for the measuring frequency.

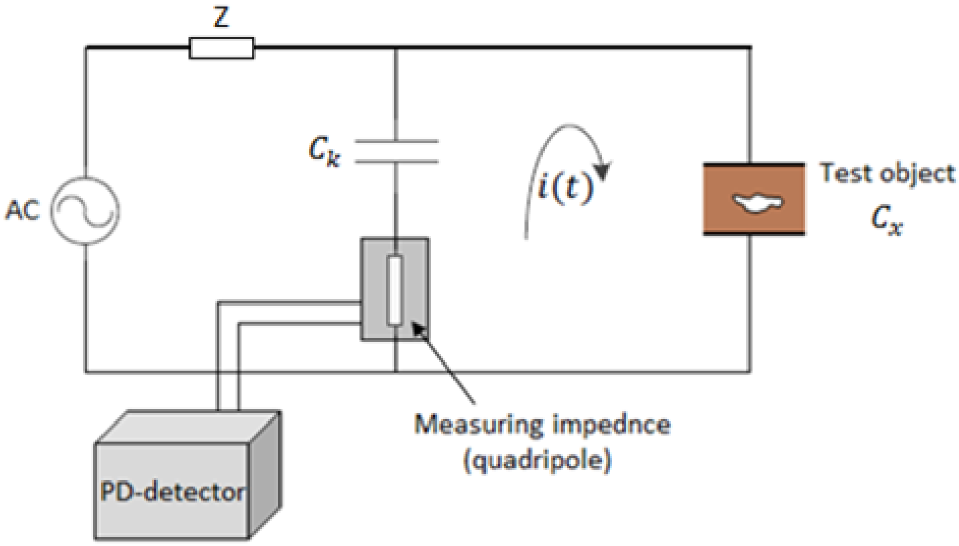


Figure 5.3: Measurement of apparent charge.

The PD-current induced from the test object, flowing between C_x and C_k, is integrated by quadripole in order to achieve apparent charge which is a quantity to determine the amount of charge released from discharge. According to the IEC 60664 [31], the apparent charge is measured at the terminal of the specimen under test. The equation 5.1 is showing the charge transfer by the current pulse $i_c(t)$,

$$q = \int i(t)dt, [pC] \tag{5.1}$$

Result of the integration above is the apparent charge which is the measured discharge magnitude and can be read directly from PD-detector [37].

The supplied voltage is shown by U and the number of discharges that can happen is directly depending on the type of the applied voltage. The amount of the discharges in a chosen time interval is higher for AC voltage. When the applying voltage is AC, discharges are happening several times in the both positive and negative cycle. Figure 5.4 shows the sequence of cavity breakdown exposed to high alternating voltage. In this figure, V_a is the applied voltage across the insulation and V_c which is a fraction of the applied voltage is the voltage across the cavity. U^+ and $U^-$are the breakdown voltage of the cavity. When the voltage V_a reaches U^+, a discharge occurs and the voltage across the cavity decreases to V^+. Meanwhile the applied voltage still is increasing which corresponds to increasing on the V_c and another discharge takes place. By decreasing the applied voltage, the voltage across the cavity increases in the reverse polarity. Another discharge occurs when the voltage reaches U^- and the V_c drops to V^-. This procedure happens several times during each cycle [39]. For this reason, performing the PD test with the AC applied voltage gives more information about the insulation.

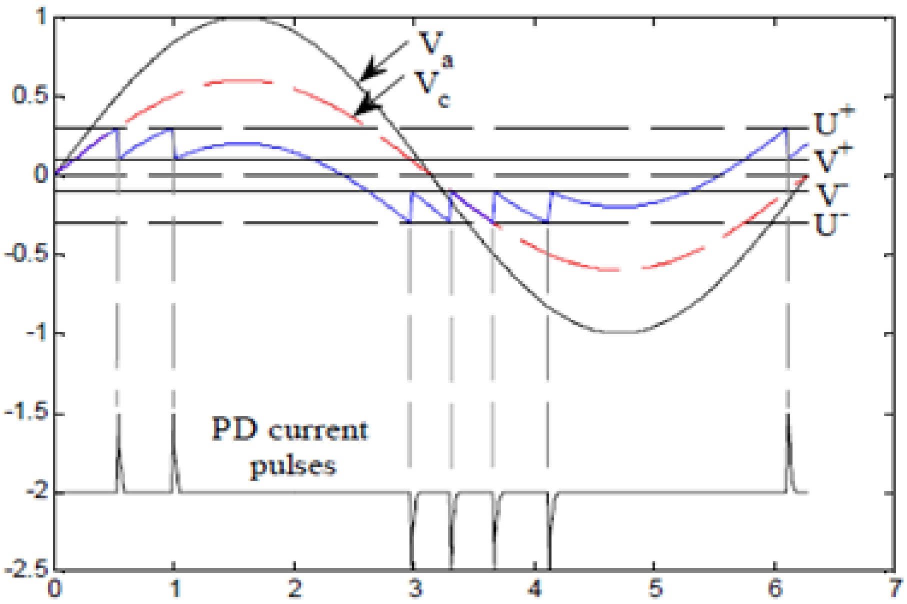


Figure 5.4: Sequence of cavity breakdown and PD current pulses [39].

When the applying voltage is DC, one or few number of partial discharges can be recorded only at the rising time part of the voltage. But when the DC applied voltage remains constant at a specific voltage, no partial discharges can be recorded until the surface charges around the walls of the cavity diffuse into the surrounding dielectric [37]. According to the ISO 6460 and IEC 60664 [31], it is specified that applied voltage is AC with a maximum distortion of 3 %.

5.3.2 Calibration of PD detector

Calibration of PD measurement is an important part of the PD test. According to IEC 60270 [38], the purpose of the calibration is to verify that the PD detector, measuring system, can measure the PD magnitude correctly. Calibration should be done for each new test object due to capacitive characteristic of the test object according to IEC 60664 [31]. As it was mentioned earlier, the test object has a capacitive behavior and represented by C_x in the figure 5.3. This capacitance affects the circuit characteristics and changes the scale factor for the measurement of the PD magnitude. Thus it is recommended to calibrate the measurement for each new object unless the test is done on a similar test object with capacitance values within 10 % of the mean values.

The calibration is made by injecting current pulses across the terminals of the test object generated from a PD calibrator and in absence of supply voltage. These pulses have short duration with known charge magnitudes q_0. These current pulses are derived from a calibrator that comprises a generator producing step voltage pulses of amplitude V_0 in series with capacitor C_0. In this way calibration pulses with charge magnitudes of $q_0 = V_0.C_0$ are injected to the PD detector. The value of the charge magnitude can be selected from the setting of the calibrator [37]. The charge magnitude can be checked by the PD detector screen and can be adjusted by "Display ADJ". As long as the value shown by PD detector is not the same as calibrator value, the system is not calibrated and when the apparent charge is adjusted to the same calibrator magnitude the calibration is successfully attuned.

Figure 5.5 shows a usual circuit for calibration of a PD measuring system. As it can be seen from the figure, a calibrator is connected across the terminals of the test object. The capacitance of the calibrator is simulated as C_0 in series with step voltage pulses of amplitude V_0 marked with G [37].

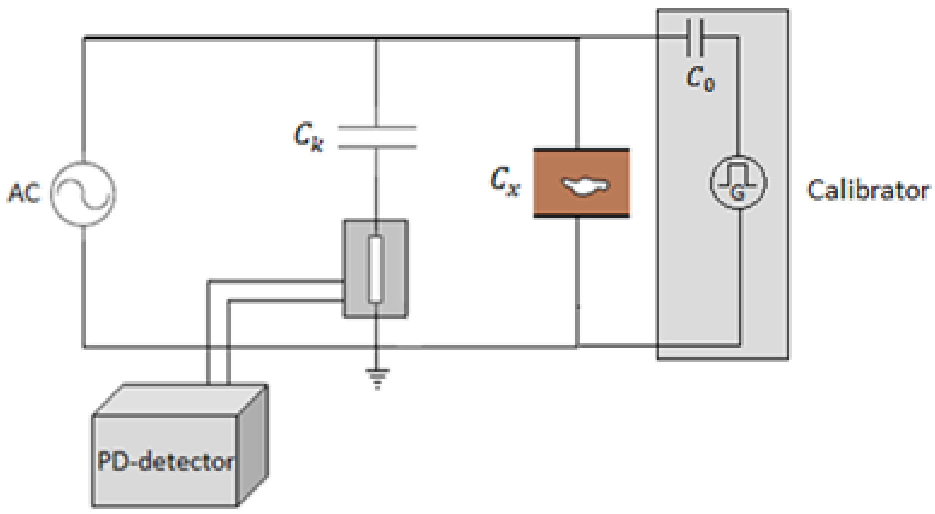
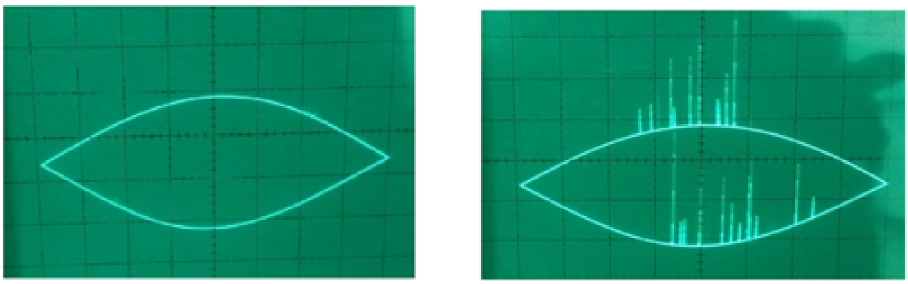


Figure 5.5: Circuit for calibration of PD measurement.

5.3.3 Typical PD results and terms

The results of the PD pulse measurements are widely presented by the phase-resolved PD pattern. These patterns can be seen directly from PD detector and has an elliptical shape. An example of typical result from PD measurement can be seen in the figure 5.6. As long as the discharges are not happening, the elliptical shape remains unchanged without any disturbances on the line figure 5.6-a. When the voltage across the insulation is increased enough, the discharges starting to appear on the shape as disturbances or sparks. The minimum voltage that leads to the partial discharges is called inception voltage. According to the IEC 60664 [31], inception voltage is the lowest peak value of the applied voltage that the apparent charge becomes greater than the specified discharge magnitude. At this voltage, disturbances are a few numbers and the magnitude of them is low. By increasing the voltage above the inception voltage the amount of amplitude of the disturbances also increased figure 5.6-b.

Each discharges can have a special pattern, for example disturbances caused by corona discharges can be recognized by its disturbances that occur in the middle of the positive cycle at the 90 phase. However, the interpretation of PD pattern is not always straightforward due to vast number and type of discharges that can happen in the insulation system [41].



(a) (b)

Figure 5.6: Eliptical display. a) Without partial discharge. b) With partial discharges.

6

High voltage test

High voltage test also referred to as hi-pot or dielectric strength test is a test carried out on electrical components to verify that the state of its electrical insulation is strong enough to protect operators from hazardous electric voltage [44]. The hi-pot test also provides a way to detect manufacturing faults between high potential points and ground in insulation materials or physical space between conductors. Normally, a hi-pot test involves applying a high voltage between the component's current-carrying point and the ground/ metal shielding [44].

There are three commonly used types of hi-pot tests that include the insulation resistance test, dielectric withstand voltage test and the dielectric break down test. The recommended tests for a battery pack in the standard UL 2580 [21] is the insulation resistance and the dielectric withstand voltage test and emphasis has been placed on these two in this section. A description of how the insulation resistance and dielectric withstand voltage tests are performed and the instruments are used is given. The criteria for passing and failure for the dielectric withstand test will be discussed. Additionally, the factors that affect the measurement of insulation resistance are presented.

6.1 Dielectric withstand voltage test

The dielectric withstand voltage test involves subjecting the insulation of an electrical component to a test voltage below the component's specified break down voltage but above operating voltage level for a specified period of time. This means the insulation experiences electrical stresses higher that it would under normal operating conditions. The insulation part that is of most interest is that which isolates the current-carrying points and the ground. Typically, the purpose of this test is not to cause break down of insulation but to prove that the tested electrical component is able to function safely at its rated voltage and can also withstand sudden voltage spikes resulting from surges or switching operations. When a high-voltage is applied and it does not cause the insulation to break down, it is safe to conclude that the component will be safe to operate under normal operating conditions [42].

This test can be performed with either AC or DC high voltage values ranging from hundreds of volts to kilo-volts but the choice of test voltage used on a device under test is determined by standards pertaining to it. In the cases when there are no standards the thumb of rule followed is that the test be performed with voltage of the same kind as that which the test object operates [43].

According to UL2580 [21] it is recommended that the dielectric withstand test be performed on batteries in electric vehicles to evaluate the electrical spacing and insulation at hazardous voltage (high voltage) circuits of the battery. During this test it is required that a DC potential test voltage of 1.414 times twice the rated voltage be applied to the device under test for a minimum duration of 1 minute. Using this standard, the test voltage used when performing the test on the battery is given by equation 6.1;

$$U_{dc,test} = 1.414 \times 2 \times U_{dc,rated} \tag{6.1}$$

The different areas to which the test voltage should be applied according to [21] are:

- Between the high voltage circuits of the test object and the non-current carrying parts which can be accessed easily or connected to accessible areas of the vehicle.
- Between the high voltage charging circuit and charging connections of the test object and the enclosure or the non-current carrying conductive parts of the DUT

It is also recommended that in order to avoid short circuiting of the positive and negative terminals of the battery, the test voltage should be applied to the positive or negative terminals and the non-current carrying parts one at a time. The criteria for passing the dielectric voltage withstand test on a battery in an electric vehicle is that there should not be breakdown of insulation or arcing over electric spacing resulting from the applied voltage [21].

An instrument known as a hipot tester is often used in carrying out the dielectric withstand test. The hipot tester monitors the leakage current flowing through the insulation when the test voltage is applied [44]. The leakage current is due to the parallel arrangement of insulation resistance and capacitance formed by two conductors separated by an insulator [44]. The hipot tester's trip leakage current limit is typically set by the user depending on the test object characteristic between the range of $0.5 - 20$ mA to avoid false tripping and minimize damage to the device under test in case of a breakdown. The device under test meets the dielectric withstand test requirement if the leakage current flowing through it is lower than the specified limit at a specific test voltage.

Failure of the dielectric withstand voltage test is evidenced by a sudden increase in leakage current flowing due to the applied test voltage and is a result of breakdown of insulation (dielectric failure or manufacturing defects) [42]. A breakdown is sometimes seen as an arc or just heard however, it may not be seen or heard but may be indicated by the hipot tester as a failure [44]. In the event of test failure, the failure voltage and the leakage current should be noted.

The difference between using DC and AC in a dielectric voltage withstand test is most significant when the Device Under Test (DUT) that is the insulation is highly capacitive. When a DC voltage is used, the capacitance of the DUT will be charged such that on initial application of test voltage there is an inrush current which gradually dissipates as the capacitive DUT is charged. However, when an AC voltage is used the capacitive DUT is not charged by the applied test voltage but there is an instant flow of reactive current which remains constant and is independent of the time of voltage application. Due to this phenomenon, AC and DC dielectric voltage withstand test usually give different current readings [45].

6.2 Insulation resistance (IR)

The reason to have insulation around conductive part of electrical system is to confine the current within the conductor. However as there are no ideal insulation material, there will always be a flow of current within the insulation. To test how good the insulation is tests are required and one of these tests is isolation resistance test. Isolation resistance (IR) as the name suggests is the resistance of the insulation when it is subjected to a high voltage. According to the Ohm's law, resistance is a relation between applied voltage and the current flowing in the system.

The ideal insulation is the insulation with infinite resistance but there are no such materials in reality which means there are some current flows through the insulation to the ground or along the insulation [46]. However, the isolation resistance should be high enough to avoid any appreciable leakage current. According to the ISO 6469 [22] and UL 2580 [21], the minimum isolation resistance shall be at least 100 Ω/V for applied DC voltage and at least 500 Ω/V for AC applied voltage. These values are the minimum acceptable values, for this reason it is not design target due ageing mechanism and also other effect like environmental stresses that can reduce isolation resistance. The environmental effects are explained in details in the next section. Since these values are the final isolation resistance value for whole the system, isolation resistance of each component is required to be a higher value than the resistance of the whole system. For these reasons, having reasonable marginal is highly recommended.

6.2.1 IR test

The purpose of insulation testing is to specify the current condition of the insulation and to identify if the insulation has been degraded. Changes in the value of the IR indicate that the insulation has been deteriorated or it is in direct influence of other factors as described in section 3.1.1. Furthermore in the research activity, IR test has been used to identify influence of various stresses on the insulation and to determine life time of the insulation. Causes of ageing mechanism on a specific product can be determined by using IR test by analyzing the result of the initial resistance value with the test result after applying the stresses [47].

Measuring isolation resistance can be done by two different methods; by direct connection of insulation tester between the two conductive parts or with help of known resistance and measuring difference in voltage distribution. In this part only the first method will be discussed. Measuring IR by using insulation tester is fairly straightforward and quicker method, the only thing that is needed is to find two conductive parts to measure the insulation between. According to the standard [19], the isolation resistance shall be measured for each part of the vehicle with help of the test instrument capable of applying a DC voltage higher than the rating of the device.

For measuring the isolation resistance of the battery system, a test instrument shall be connected between the live parts and the electrical chassis. Then, the isolation resistance is measured by applying a DC voltage. The applied voltage normally is higher than the operating voltage, specifically for the test on the vehicle; this voltage shall be at least half of the working voltage of the high voltage bus according to [19]. According to the IEC 61851[48], measurement of the insulation resistance test shall be done after applying voltage during 1 min.

According to the Ohm's law, the resistance is the relation of the applied voltage divided by the measured current. There are four different currents in the insulation system that measured as total current by the test instrument. These currents may flow when the applied voltage is a DC voltage. These currents are capacitive current (I_C), conduction current (I_R), surface leakage current (I_L) and polarization current (I_P) [49]. The total measured current (I_t) is the sum of these four different currents as shown in equation 6.2.

$$I_t = I_L + I_C + I_R + I_P \tag{6.2}$$

Figure 6.1 shows the equivalent circuit of the four currents during the insulation resistance test.

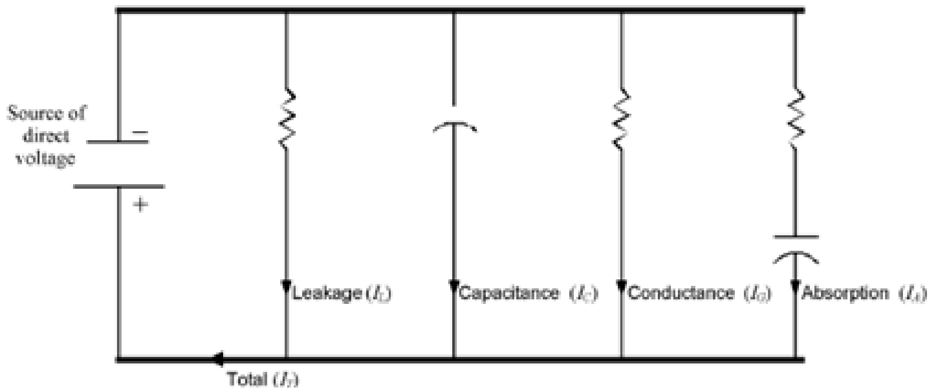


Figure 6.1: Different following currents during insulation resistance test [49].

Capacitive current (I_C)

When a DC voltage is applied to an insulator, the insulator behaves as a capacitor. Since the applied voltage is DC, first a high charging current flows to the insulation and then it decreases exponentially to a value close to the zero. Due to diagnostic information of the capacitive current, the IR measurement shall be done after that the current effectively decays to zero. In this case, the IR measurement is better to be done after a time interval of one minute to avoid influence of this current on the result [46].

Surface leakage current (I_L)

Surface leakage current is a constant current that flows over the surface of the insulation. This current is directly depended to the amount moisture or other conductive contamination on the surface of the insulation. This current has a direct effect on the results of the isolation resistance measurement and can be terminated with help of "guarding" terminal of the measurement instrument [49]. The guarding function is a shunt circuit that eliminates the surface current from the measurement and presents a more precise result of the IR test [47].

Polarization absorption current (I_P)

The result of the IR test is also dependent on the polarization current and decays at a decreasing rate to a value close to zero. The polarization current is time dependence current and can be described as the power function in equation 6.3:

$$I_A = Kt^{-n} \tag{6.3}$$

Where the I_A is the polarization current, K is a function of the insulation system and applied test voltage, t is the time and n is a function of the insulation system.

The polarization current consists of two components. The first one is the effect of the polarization of the impregnating materials in presence of the direct electric field. Since it takes time for the molecules in the insulation material to align with the electric field, it also takes time for the current-supplied polarizing energy to be decreased. The second component is due to general drift of the free electrons in presence of the direct electric field which will drift until they become trapped at the surface of the insulation [49].

Conduction current (I_R)

Conduction current flows through the insulation. This current is resisted with insulation resistance and does not depend on time; i.e. this current is steady through insulation. This is the current that is aim of IR measurement. However, the measured current is the sum of all currents and to separate the conduction current, the insulation needs to be fully charged to eliminate the capacitive current and full polarization taken in place to eliminate the polarization current and surface leakage current should be excluded by "guarding" the surface leakage current [46]. However in practice, it is not so straightforward to eliminate effect of all currents and this problem will be more significant when there are moisture and contamination on the test object.

Figure 6.2 shows the change in different currents in relation to time when the insulation is exposed to DC voltage. As shown in the figure, the total current is decreasing by time with the reduction of polarization current and is higher than the conduction current mainly due to surface leakage current. The amount of time is needed for the total current to be stabilized is mainly dependent on the accuracy and precision of test instrument and the full polarization time in the insulation material. For this reason it is not possible to fully specify how long time is needed to execute the test. However, according to the IEC 61851 [48], measurement of the insulation resistance test shall be done after applying voltage during 1 min. For more advanced instruments such as electrometer with very high current accuracy, measurement time can be varied to several hours.

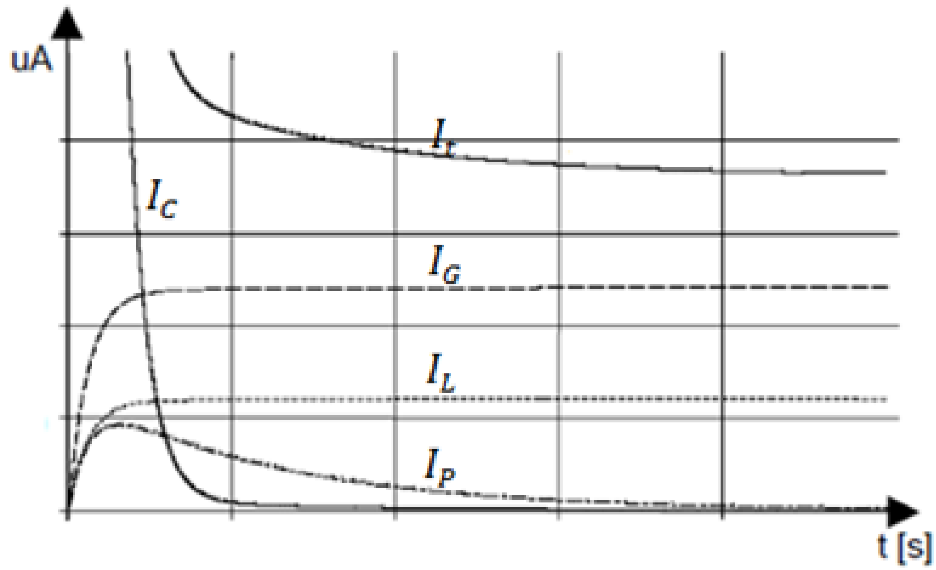


Figure 6.2: Relation between currents flowing in the insulation with time [28].

7

Tests and Results

In order to study the insulation of the battery pack, two tests were selected and performed; partial discharge test and insulation resistance test. Environmental tests that involved varied combinations of temperature and humidity were also performed to determine how they influenced the insulation resistance. This section describes the tests that were performed on the different parts that make up the battery pack. The tests are presented according the purpose for which they were performed. Additionally, the test setup and results obtained from each test are also presented in this section.

7.1 Partial discharge test

As explained in the chapter 5, the purpose of partial discharge test is to control the quality of the insulation system. Furthermore, it is possible to some level localize the weak points of the insulation and parts that are mainly on stress can be recognized by this test. This thesis is mainly focused on insulation of the battery system after assessment of the high voltage system of the vehicle.

Battery system can be categorized and seen as several subsystems consisting of cabling system, electronics, battery modules and cooling system. Figure 7.1 below shows a simplified model of the battery system in the battery pack. The cabling system and the modules are connected together to the output cables through five contactors. These contactors are placed in the battery system to open and close the current flow. Two of these contactors are the main contactors that connect the high voltage cables to the battery pack and the rest are used for controlling the pre-charging system and charging the battery. The main contactors are shown by C1 and C2 for respective positive and negative main contactors in the figure 7.1.

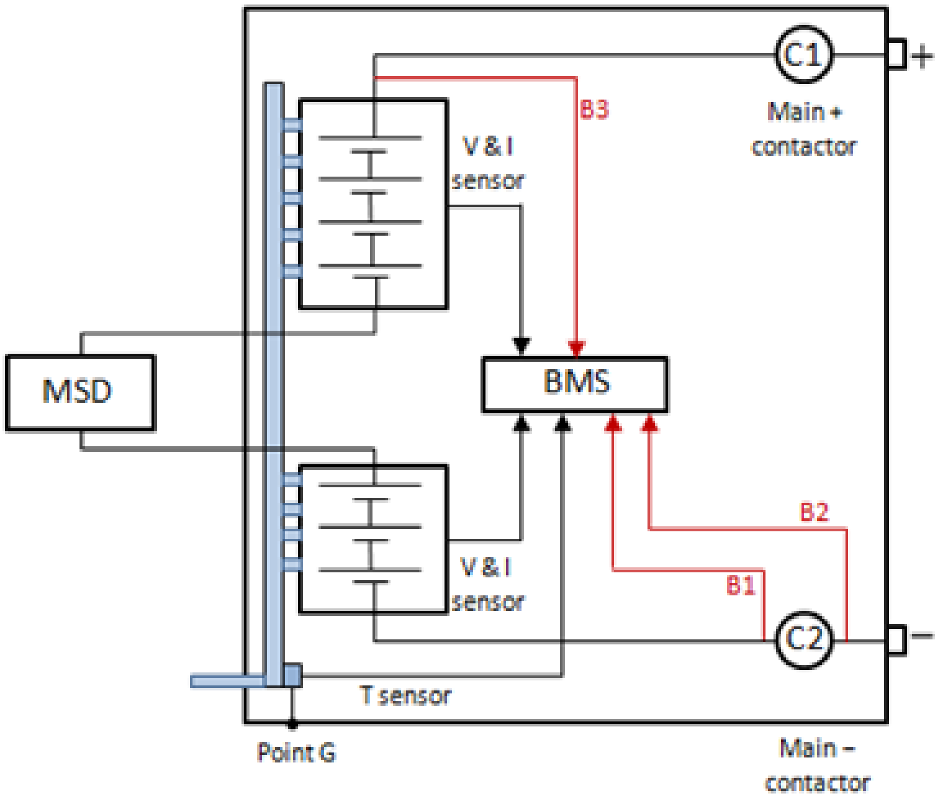


Figure 7.1: Simplified model of the battery system.

As it was explained in the section 2.2, the cabling system of the battery connects all the battery modules through a Manual Service Disconnect (MSD) and is connected to the high voltage cable outside the battery through contactors. By opening the MSD the connection between the modules is interrupted and the battery converts to two sections, positive and negative poles. Each end of the battery terminals is connected to the main contactors which are bridge between the batteries to the output cables.

The full battery system is controlled by electronics through several sensors. All sensors such as current, voltage, temperature, etc. have connection to an electronic device called battery management system (BMS). Except sensors, some resistances are situated on the BECM to ground which called bleeder resistance. There are totally three bleeder resistances in the battery pack that used for this thesis. Two of these resistances are connected to the both terminals of the main negative contactor marked with B1 and B2 in the figure 7.1 and the last one, resistance B3, is placed on the first battery module from positive side.

The cooling system in the pack is illustrated with the blue color in the figure 7.1. The cooling system is of type water cooling and cools the battery cells with help of aluminum fins which is placed between the cells, see figure 2.2. The cooling system has a direct connection to the battery pack with purpose of grounding. The connection is managed with a conductive wire directly to the liquid through the temperature sensor. The connection point is presented by point G in the figure 7.1.

Partial discharge tests are performed on the battery system with purpose of finding weak points where highest stress is induced in the cabling system and battery modules. Except finding weak points, finding the level of inception voltage was another aim to investigate the quality of the insulation and to verify the starting voltage of the discharges by the normal operating condition. Furthermore, another important aspect that was studied in this project was to find out influence of the grounding of different floating parts such as cooling system and the battery modules. In specific focus was on the effect of grounding the cooling system. In the following, each test is presented and the results of them can be found directly after each test.

7.1.1 PD measurement on cabling system

PD measurement on the cabling system is performed in order to determine the quality of the insulation of the cable and also localizing the weak points in term of discharges indicated by lower inception voltage. The cabling system consists of wires, contactors, Y-capacitors, relays bleeder resistances and other low voltage connections to the BECM. Test on the low voltage cable is excluded from the test as the main focus was on the high voltage system. Since the applied voltage is AC, all capacitive components effect on the final result. For this reason, both the Y- caps were excluded from the both negative and positive sides during all PD measurement.

The purpose of this test was to determine influence of the bleeder resistance (BECM) on the partial discharges and also to determine that the inception voltage of the cabling system including contactors is higher than operational voltage.

The procedure following was done to perform the test:

- First step was to disconnect the battery modules from the cabling system. It was done by disconnecting the cable connections to the main terminals of the battery modules. A wire was used to connect the main positive contactors to the main negative one as it is shown in the figure 7.2 by color blue.
- A wire was used to manually short-circuit the terminals of the contactors.
- The test was performed first on pure cables including contactors and relays. For this reason, all the bleeder resistances were disconnected from cables. figure 7.2-a, shows connections for this test.
- In the second test, the bleeder resistance B1 was connected to the circuit in order to find the influence of this connection to the BECM. This connection can be seen in the figure 7.2-b.
- In the third set-up, the bleeder resistance B2 was only connected to the test circuit according to the figure 7.2-c. In the same way at the fourth attempt, the bleeder resistance B3 was only connected to the test circuit according to the figure 7.2-d.

– In the final test on the cabling system all resistances were connected for the testing

– According to the test setup for PD measurement as stated in section 5.3, the voltage applied across the point A and B and the battery pack was grounded from its connection point to the chassis.

– The applied voltage across the test object was at maximum 1.25 kV peak value when there was connection to the BECM in order to avoid of damaging to the electronics. However, the maximum applied voltage was maximum at 2 kV peak value when there were no bleeder resistance connected on the test circuit.

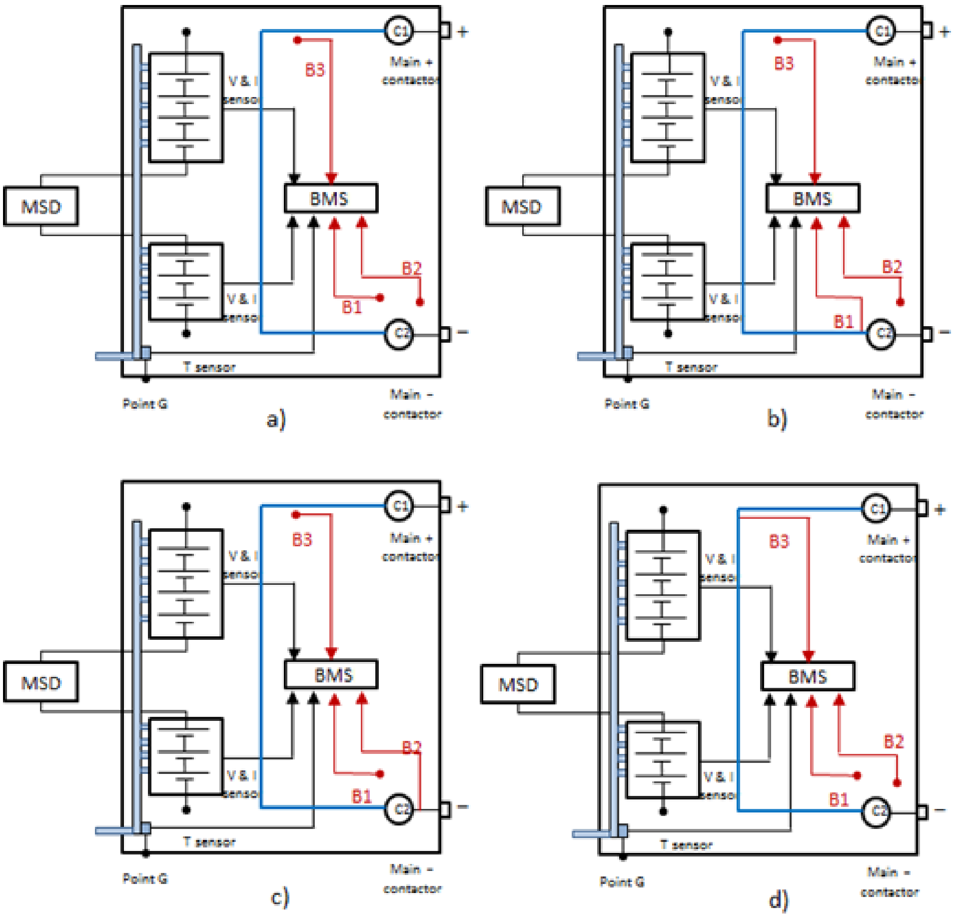


Figure 7.2: PD measurement on cabling system. a) Without bleeder resistances. b) Bleeder resistance B1 connected. c) Bleeder resistance B2 connected. d) Bleeder resistance B3 is connected.

Table 7.1 shows the result of PD when the applied voltage was at max 1.25 kV peak voltage. As it can be seen from the table, partial discharges take place only when the resistance B1 is connected to the test circuit. In the other cases when resistances B2 and B3 were connected, no partial discharges were detected until 1.25 kV peak voltage. During measurement on the cabling system with connection of bleeder resistances, the test voltage kept lower down 1.25 kV in order to avoid any damages to the electronics.

However the inception voltage was much higher when there was no connection of the bleeder resistances on the test circuit which shows the influence of the BECM on the discharges. The inception voltage without any connection of the bleeder resistances was at 1.99 kV peak AC voltage. This voltage is much higher than when the bleeder resistances are connected. This indicates that the connection to the BMS influencing the PDs. However, this influence is constant for all the connections.

Table 7.1: Results of PD measurements on the cabling system.

Resistor	Inception voltage [peak V]	Extinction voltage [peak V]
All resistances	965	895
B1	875	850
B2	No PDs	No PDs
B3	No PDs	No PDs

7.1.2 Influence of the grounding on the partial discharges

In order to having better understanding of the influence of the grounding system on the partial discharges, test on two different parts are performed. The first part was a single battery module and the second was doing on the single module while it is grounded through cooling system. The purpose of dividing the test on these parts is to find out the difference when the grounding is a pure ground connection and when the grounding has a resistive difference.

Test on single module
With this test purpose is to evaluate the places on the module that is required to be grounded and also to check the effect of having a resistance between the cooling fins and ground.

There are designed grounding spots on the module and these parts are the outer plate of the module and cooling fins. The effects of grounding of these parts are different and will be presented in the following. Figure 7.3 shows places that grounding test has been checked.

Set-up configuration:

The first test was done on the module when both the outer plate and cooling fins were grounded. Outer plates were grounded with help of grounding the two screws on the module. Since the outer plate is a conductive material and screws are going through the plates and passing the painted surface, the plates can be grounded via the screws. To ground the cooling fins, the ”terminals” of the cooling fins were short-circuited with a wire and then direct connection to the ground. Figure 7.4-a is showing this connection.

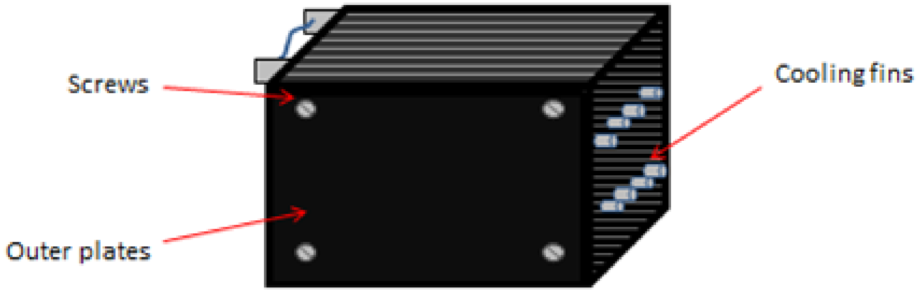


Figure 7.3: Favorite grounding places on the module.

Next test has been done when only outer plates were grounded. This connection is shown in Figure 7.4-b. In the same the next test was done when only the cooling fins was grounded, see Figure 7.4-c. The final test was done when both the cooling fins and the plates were grounded with one difference that the cooling fins were grounded via a 4.9 $M\Omega$ resistance according to Figure 7.4-d. The purpose of this test was to determine the influence of pure and resistive grounding.

Test procedure:

The voltage on whole of these tests was applied on the terminal of the module while the positive and negative terminals were short-circuited. The maximum applied voltage for this test was at 750 V peak AC voltage. The applied voltage on the terminal of the module was slowly increased until the partial discharges occurred. This voltage is recorded as inception.

After reaching the inception voltage, the applied voltage was decreased again slowly to record the extinction voltage. After each test the device under test was grounded to eliminate the accumulated charges in the module and also to discharge the coupling capacitor for safety reason.

Results of the test on the single module are presented in the table 7.2. Sparks and noises were clearly heard close to the inception voltage. The origins of this discharges was heard mainly between the cells. Since the amount of discharges are dependent to the applied voltage, by increasing the voltage more than that inception voltage more and more sparks was observed.

Table 7.2: Results of PD measurement on the single module.

Grounding places	Inception voltage [peak V]	Extinction voltage [peak V]
Outer plates and cooling fins	770	705
Only outer plates	515	494
Only cooling fins	485	470
Cooling fins with 4.9 $M\Omega$ resistance	505	485

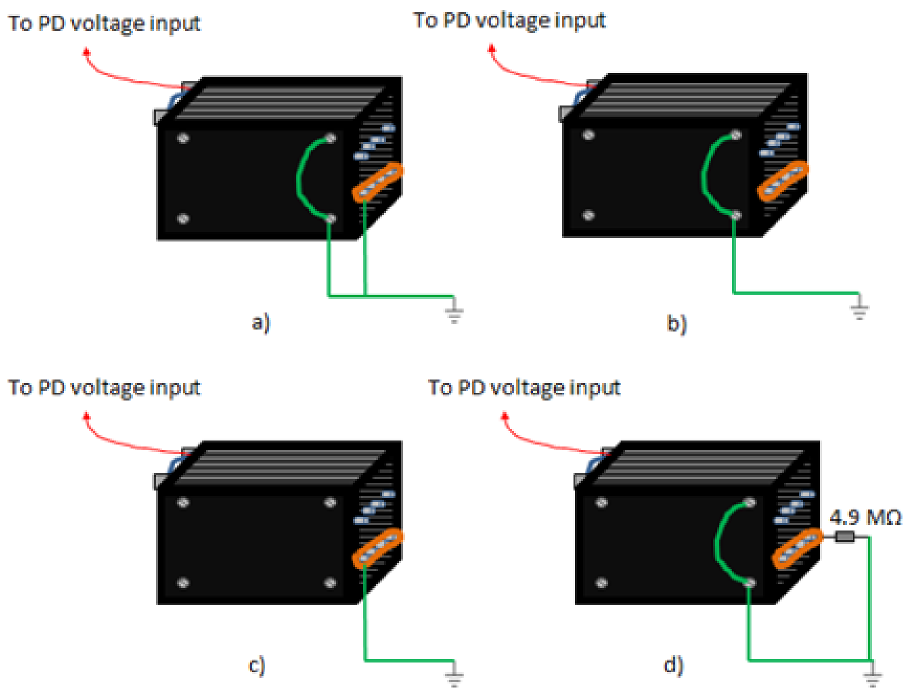


Figure 7.4: PD measurement on the single module. a) Both other plates and cooling fins grounded. b) Only outer plates grounded. c) Only cooling fins grounded. d) Outer plates grounded and cooling fins grounded through 4.9 $M\Omega$ resistance.

Test on single module with coolant

The purpose of this test was to gain a better understanding of grounding through the coolant of the cooling system. This test was performed on a single module inside the battery pack. For this test several measurements with the same connection were repeated to make sure that the result is steady. The important point for doing this test, all of the capacitances connected to the battery pack are required to be disconnected in advanced prior doing the test. If not done, the result of these capacitances will decrease the inception voltage and yield false information. One way to make sure that these capacitances are disconnected during the test is to control the amount of current that the test device is providing for the device under the test. When the current is significantly high, it is an indicator of having a high capacitor.

The procedure of this test is as following:

– The module close to the temperature sensor was selected for the test. All the connection from other module to the terminal of the test object was disconnected.

– The first test was done with ground connection through the temperature sensor.

– The second test was done without ground connection. The ground point can be disconnected by opening the connection of the ground wire of the temperature sensor from the battery pack as it shows in the figure 7.5.

– During the entire test, the voltage was applied to the terminal of the module where the positive and negative terminals were short-circuited.

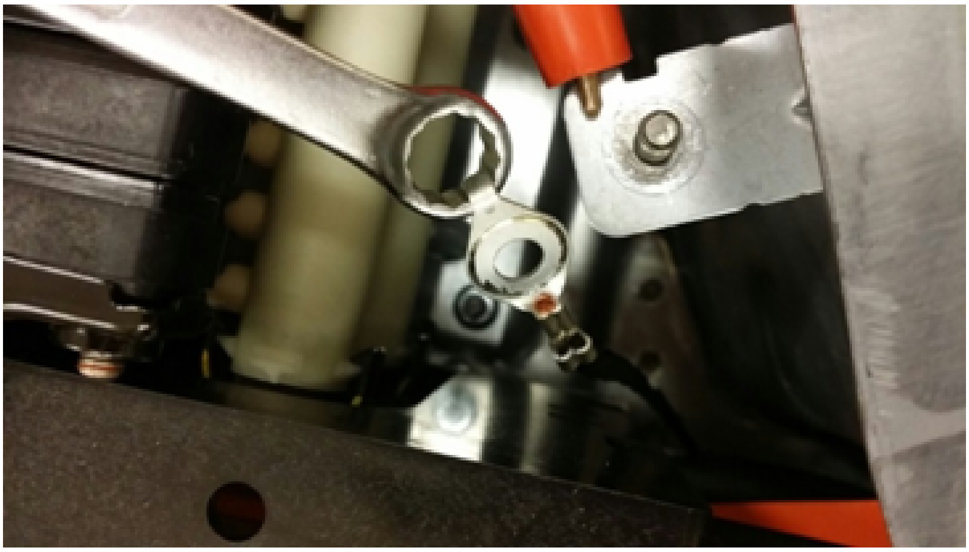


Figure 7.5: Disconnecting the ground connection of the cooling system.

The inception and extinction voltage of each test was recorded after performing the test. These results are presented in the table 7.3. Like previous test, test on the stand alone module, noises and sparks was observed also around the inception voltage. This noises itself are proof of having discharges in the pack and this can result in long term effect of the surrounding insulation.

Table 7.3: Results of PD measurement on the single module inside the battery pack.

Test	Inception voltage [peak V]	Extinction voltage [peak V]
With grounding	675	581
Without grounding	650	610

Test on whole battery modules

After first two conditions, one test has proposed to test on whole the battery modules with purpose of having real situation in the normal operation. In order to find the information about the cooling system, all connections to the cabling system were disconnected and bleeder resistances were completely sealed to eliminate any effect on the results.

In this experiment like the single module test, the experiment was performed once with ground connection and once without the ground connection. Table 7.4 shows the results. In this test, the amount of sparks and noises were more than previous two tests. The reason of this increase can be extra numbers of the modules. These noises were heard mainly from inside the module and mainly between the cells and cooling fins.

Table 7.4: Results of PD measurement on the entire battery modules full with coolant.

Test	Inception voltage [peak V]	Extinction voltage [peak V]
With grounding	550	466
Without grounding	472	449.5

Figure 7.6 shows results of PD tests of this section which is a comparison between when test has been done on a single module, on the single module inside the battery pack and when it was performed on whole the pack. The comparison of the test result shows clearly the importance of the grounding to increase the level of the inception voltage.

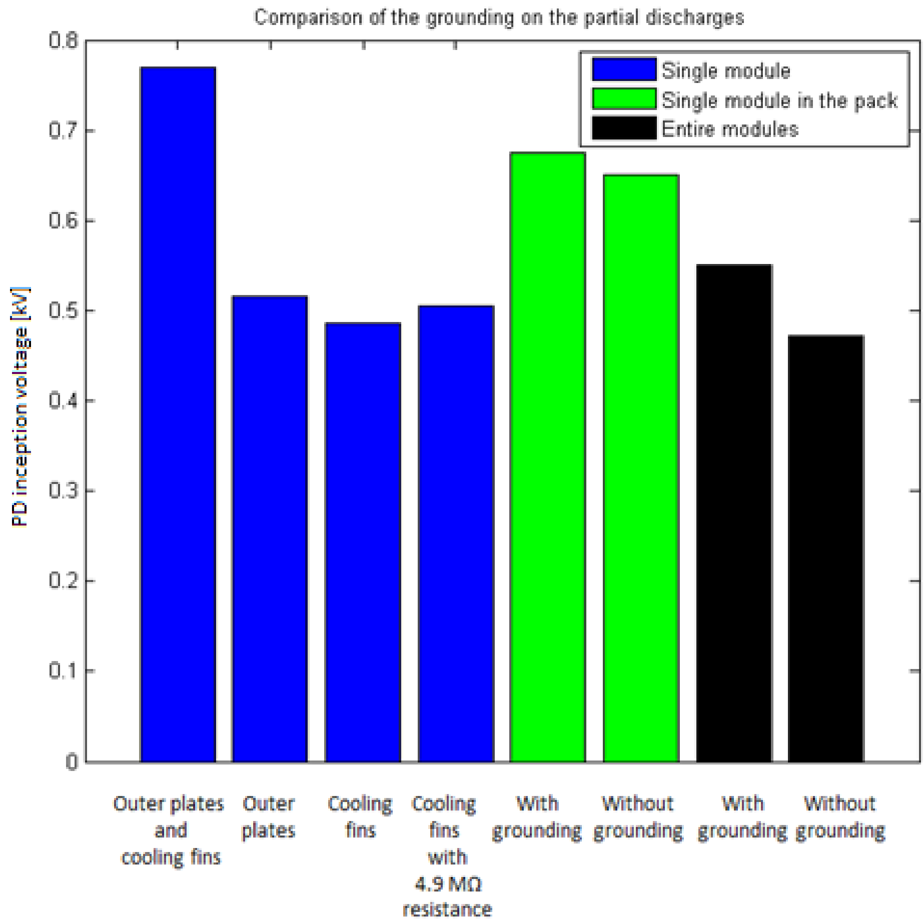


Figure 7.6: PD result respective grounding connection.

7.1.3 High stress points in the battery modules

All the performed measurements have shown that in that the partial discharges origins are mainly due to the insulation in the battery modules, more specifically between the cells and cooling fins. This was studied further by more experiment on the insulation and improvement in the places that most of the discharges are suspected to happen.

This test mainly was directed to the one section of battery module including two cells with the cooling fin between them and the black plastic holder, see figure 7.7. The purpose was to identify the place inside module that causes the PDs and is normally on a higher stress level than rest of the battery pack.

Figure 7.7: One section of the battery module.

The first part of this test was about measurement on existing section without any changes. The test object was connected to the measurement device with connection in figure 7.8. As it can be seen from the figure, the measurement voltage is applied to the both terminals and the device under the test is grounded from the one pin of the cooling fin. In the beginning and end of the measurement, when the voltage applied to the test object was in form of the impulse voltage, few clear sparks where observed which are mainly due to charging and discharging the cell at a quick time. These sparks are also observed when the applied voltage was DC voltage during the isolation resistance measurement. These sparks were mainly occurred around the edges of the cells which are surrounded with insulation tape but more often and stronger at the corner of the cells where the insulation is uncovered.

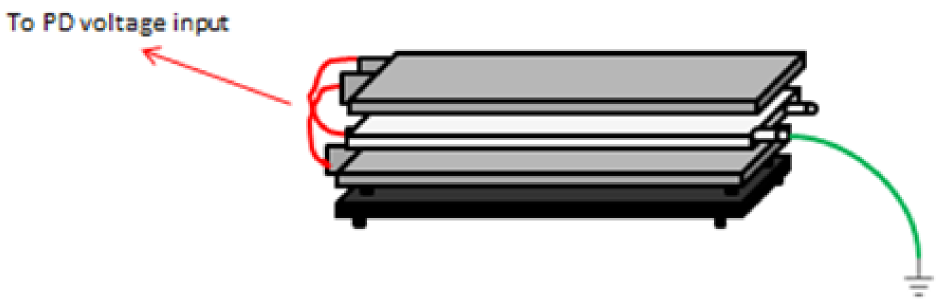


Figure 7.8: Connection for the PD measurement on the cells.

After several tests on the same cells and connection and after recording the results, focus was moved to investigate improvement of the insulation to check at what places the reinforcement of insulation is needed. These tests were done in different places as following:

1. Reinforcement around the edges of the cell
2. Reinforcement around the edges of the cell plus adding insulation between the terminals of the cells
3. Adding insulation around the cooling fin
4. Putting an insulation paper between the cells and cooling fin

During these tests for reinforcement of the cells and cooling fins, a black color self-adhesive tape was used. These changes were added to the original section without changing any other part to find out exact influence of these changes on the results. The result of these tests and also test of the original section are presented in the table 7.5.

Table 7.5: Result of PD measurement on the cells with different improvement.

Test	Inception voltage [peak V]	Extinction voltage [peak V]
Test on the original case	715	700
Test number 1	735	690
Test number 2	860	800
Test number 3	735	690
Test number 4	No PDs	No PDs

Figure 7.9 shows the comparison between the results of the PD test on the cells.

7.2 Insulation resistance test

The purpose of performing the insulation resistance tests was to determine the current condition of the insulation for different parts of the battery pack and the single stand-alone battery module with respect to ground (chassis). The test was performed on a discharged battery pack and a discharged single stand-alone module. The tests performed on the battery pack involved testing the battery pack as a whole as well as separately testing different parts of the battery pack. Two types of instruments were used when measuring the insulation resistance, the Fluke 1587 Insulation Multimeter also known as the megger and the Keithley model 6517A electrometer/ high resistance meter. The megger offers insulation test voltages of 50 V, 100 V, 250 V, 500 V and 1000 V and insulation resistance measuring range from 0.01 $M\Omega$ up to 2 $G\Omega$. The electrometer offers insulation resistance measuring range from 50 Ω to 106 Ω at calibratible insulation test voltages. The electrometer has low current sensitivity and a built-in 1kV voltage source with sweep capabilities which simplifies performing leakage, breakdown and high resistance testing as well as surface resistivity measurement on insulating materials. When using the megger the

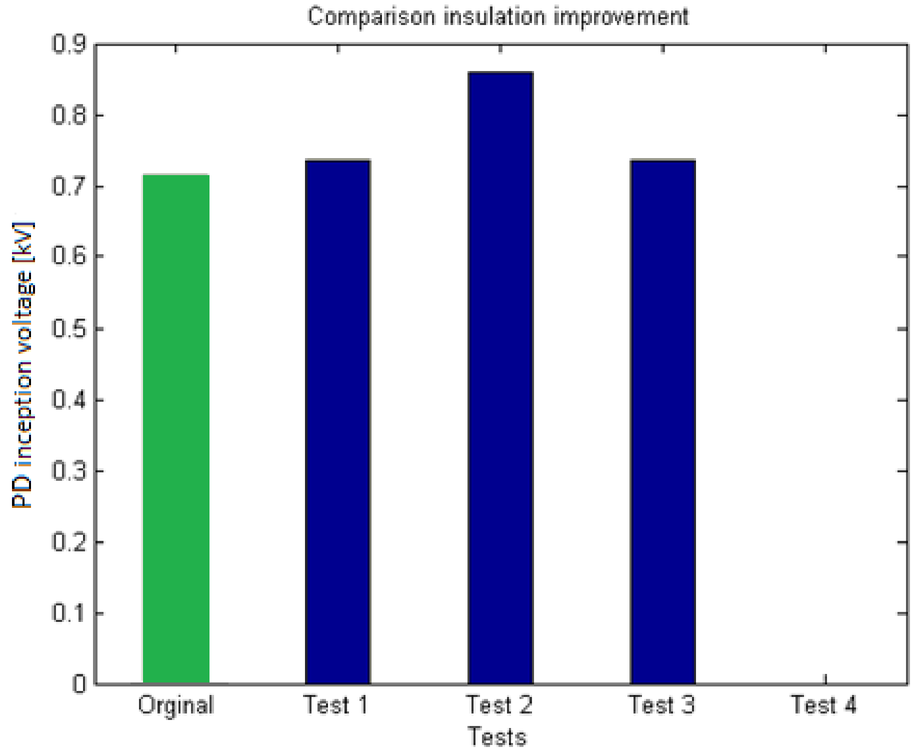


Figure 7.9: PD results respective changes in the insulation.

test was performed for 60 seconds in order to reach a stabilized value and the maximum and minimum values were recorded. When using the electrometer the insulation resistance test was performed for at least 4 hours before a stable reading was obtained, however the readings is highly accurate.

These tests were performed before the battery was subjected to any other DC or AC tests that had been planned. The tests were performed by connecting the test instrument between the high voltage points in the battery pack and the chassis (body of the battery enclosure) as stated in section 6.2.1.The voltage levels that were selected as applied tests voltages during the tests were 50, 100 V, 250 V and 500 V. Some tests were also performed using 1000 V test voltage but for purposes of safety testing at 1000 V was later excluded. All tests were performed at room temperature of 22.5 °C. The battery was short circuited during all the tests performed to eliminate the chances of charging up the battery again. The battery pack voltage was maintained at approximately 27 mV during testing.

7.2.1 Evaluating current insulation of battery pack

In order to determine the condition of the insulation in the battery pack, insulation resistance test was performed on both the positive and negative polarities of the battery including the cables and the batteries with respect to ground (chassis). The test was also then performed on separate parts of the battery pack, specifically the high voltage bus bar cables (both the positive and negative side) and the series connected battery modules inside the battery pack.

Measuring insulation resistance of the positive side of battery pack
In order to determine the condition of insulation resistance of the positive side of the battery pack with respect to ground (chassis) both the megger and electrometer were used. When using the megger for testing the bleeder resistors were left connected. And so the results obtained reflected the bleeder resistors. To perform the test, the measurement instrument was connected between the positive current carrying cable and the chassis as shown in figure 7.10. The setup used when using the megger was the same as when the electrometer was used.

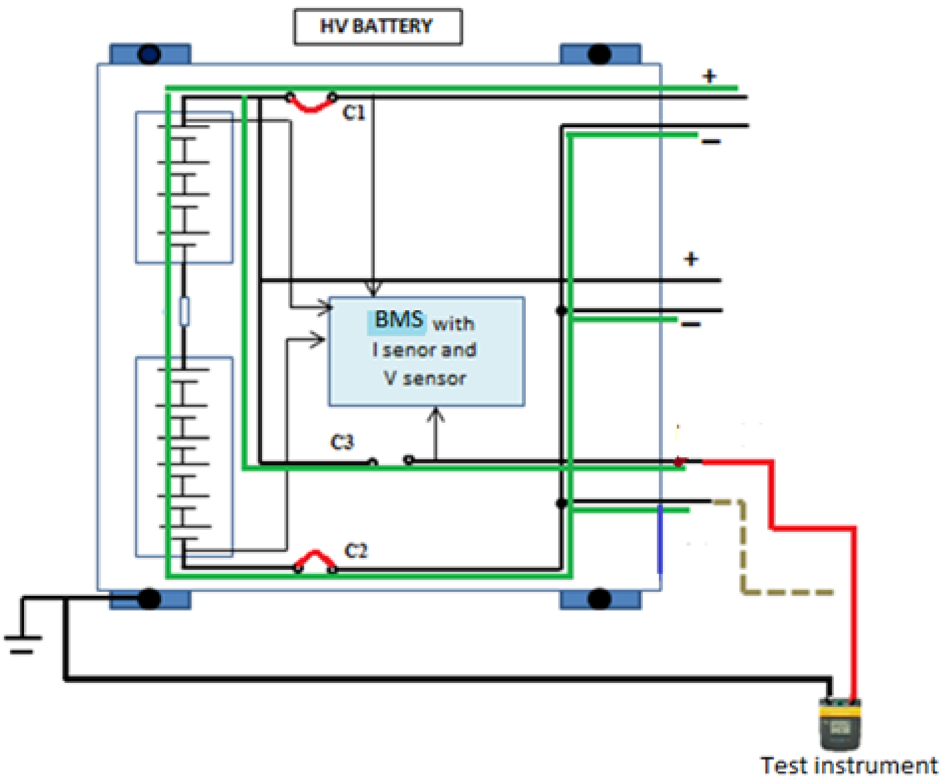


Figure 7.10: Test setup for measuring insulation resistance for the whole battery pack.

Using the megger, the insulation resistance test was performed at test voltages 50, 100, 250, 500 and 1000 V for 60 seconds for every applied voltage after which the minimum and maximum values were recorded. The results obtained are presented in table 7.6. At test voltage of 1000

V, sparking was heard when applying and disconnecting the DC voltage.

Table 7.6: Insulation resistance test results for positive side of battery pack using the megger.

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

Using the electrometer, the insulation resistance test was performed on the whole battery pack using an applied voltage of 500V. During this test the bleeder resistor were excluded to determine the condition of the insulation without the influence of the bleeder resistors. Two settings were used: one test was conducted with cooling system connected to ground and the other without grounding the cooling system. The test was performed for about 5 hours before a stable result was reached. The test results in table 7.7 show that the insulation resistance value measured is higher when the cooling system is grounded than when it is not grounded. The significant difference between the results when an electrometer is used for measurement can be attributed to the electrical properties of the coolant through which the battery pack is connected to ground.

Table 7.7: Insulation resistance test on battery pack using the electrometer.

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

Measuring insulation resistance of the negative side
To determine the condition of insulation resistance of the negative side of the battery pack with respect to ground the megger was used. When using the megger for testing, the bleeder resistors were left connected and the results reflect them. The test instrument was connected between the negative current carrying cable and the chassis. The test setup was as shown in figure 7.10 with the test instrument connected to the MAIN (-).

The insulation resistance test was performed at voltages 50, 100, 250,500 and 1000 V and the maximum and minimum results obtained after every 60 seconds are presented in table 7.8. At test voltage of 1000 V, sparking was heard when applying and disconnecting the DC voltage.

Table 7.8: Insulation resistance test results for negative side of battery pack using the megger

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

Measuring insulation resistance of the HV bus bar (cable)
It was important to determine condition of the insulation of the high voltage bus bar (cable) with respect to ground on its own since it carries all the voltage delivered by the battery. To perform the insulation resistance test all the cables to the battery (the battery modules) were disconnected. Separate tests were performed for the positive cable and the negative cables. The test instrument was connected between the current carrying parts of the cable and the chassis. The test setup used for measuring the insulation resistance for the positive and negative cables (solid line for positive and dotted line for negative) is shown in figure 7.11. Tests were performed using both the megger and electrometer. Using the megger the test was conducted for 60 seconds at the selected test voltages of 50, 100, 250, 500 and 1000 V. The test performed on the positive side did not have the bleeder resistors connected at the contactor while the test conducted on the negative side had the bleeder resistors connected. Table 7.9 and table 7.10 give the results obtained from the insulation resistance test on the positive and negative cable respectively. The results in table 7.10 are an indication of the influence of the bleeder resistors present on the negative cable and in table 7.9 the values obtained were much larger than the megger's measurement range. The difference between the results in table 7.9 and table 7.10 is due to the influence of the bleeder resistors present on the negative cable during the insulation resistance measurement.

Table 7.9: Insulation resistance test results for the positive HV cable excluding bleeder resistor using the megger.

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

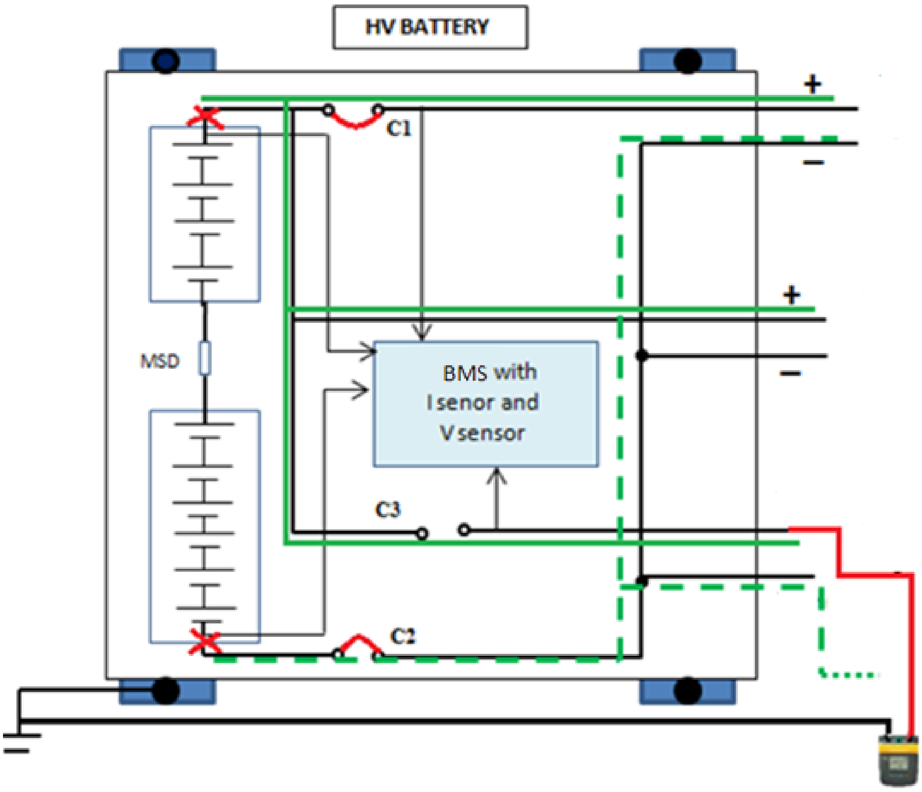


Figure 7.11: Test setup for measuring insulation resistance for the cables only.

Table 7.10: Insulation resistance test results for the negative HV cable including bleeder resistor using the megger.

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

In order to determine the actual insulation resistance of the HV cables without the influence of the bleeder resistors a new test was performed using the electrometer on both the negative and positive cables with all the bleeder resistors disconnected. This test was conducted using a test voltage of 500 V and was performed for 4 hours before a stable value was reached. The results obtained from this test are presented in table 7.11. According to the results shown, the negative cable had a slightly higher insulation resistance compare to the positive cable.

Table 7.11: Insulation resistance test result for cables using the electrometer.

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

Measuring insulation resistance of the battery modules
Since the battery modules are the source of stored energy used for propulsion, it was important to determine the condition of its insulation resistance with respect to ground as well. All the cables connecting the battery modules to other systems were disconnected to ensure that the insulation resistance test was conducted only on the series connected battery modules inside the battery pack. The positive and negative terminals of the battery modules were short-circuited in this test. Only the megger was used to conduct this test and it was connected between the short-circuited positive and negative terminals and the chassis.

The test was performed at the test voltages of 50 V, 100 V. 250 V, 500 V and 1000 V and the results are shown table 7.12. The values of insulation resistance obtained from this test were larger than the measurement range of the megger. To get more exact values an electrometer was used to measure the insulation resistance of a single module and the results are given in section 7.2.2.

Table 7.12: Insulation resistance test result for 10 battery modules using the megger.

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

7.2.2 Determining insulation resistance of single battery module

When the insulation resistance test was conducted with respect to ground on a single stand-alone battery module using the megger, the results obtained were the same as in table 7.12 when the test was performed on series connected battery modules. In order to have more accurate results, the electrometer was used to conduct the test on a single battery module to determine the condition of its insulation.

The test setup used for the test was as shown in figure 7.12. The electrometer was connected between the short-circuited terminals and the cooling fins. The test was performed at voltage levels of 400 V and 1000 V and high values of insulation resistance were obtained in this test

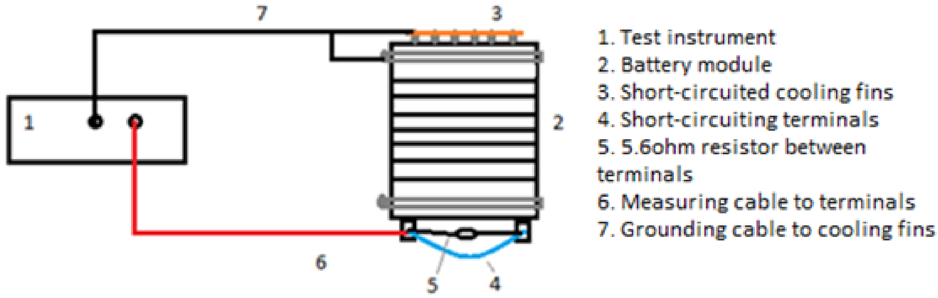


Figure 7.12: Test setup for measuring insulation resistance for the battery module.

Table 7.13: Insulation resistance test on single battery module using the electrometer.

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

as shown in table 7.13. The significant fall in insulation resistance when the test voltage was increased from 400 V to 1000 V could be as a result of insulation problems resulting from imperfections or fractures in the insulation worsened by the presence of moisture or dirt [49].

7.3 Environmental test

The purpose of these tests was to simulate the environmental conditions of the battery pack and to determine how the effect on the battery's insulation resistance with respect to ground. The environmental tests were performed under controlled temperature and humidity conditions inside a climate chamber combined with the use of ionized water. During the experiment the greatest concern was the amount of condensation that accumulated on the battery modules when temperature and humidity changes take place in the battery pack and how the insulation resistance is affected by this. For purposes of simplicity the tests were performed on a stand-alone discharged battery module whose positive and negative terminals were short circuited.

During each of the environmental tests the module was placed in the climate chamber which had the functionality to cycle temperature and humidity following the specified profile. The temperature of the battery module and that of the climate chamber were monitored throughout the testing period. In addition, the insulation resistance with respect to ground of the battery module was measured in five minute intervals. In order to measure the insulation resistance a megger was used. The positive cable of the megger was connected to the short-circuited battery module terminals and the negative cable to the short-circuited cooling fins assumed to be at ground potential. The test setup for the environmental test is shown in figure 7.13.

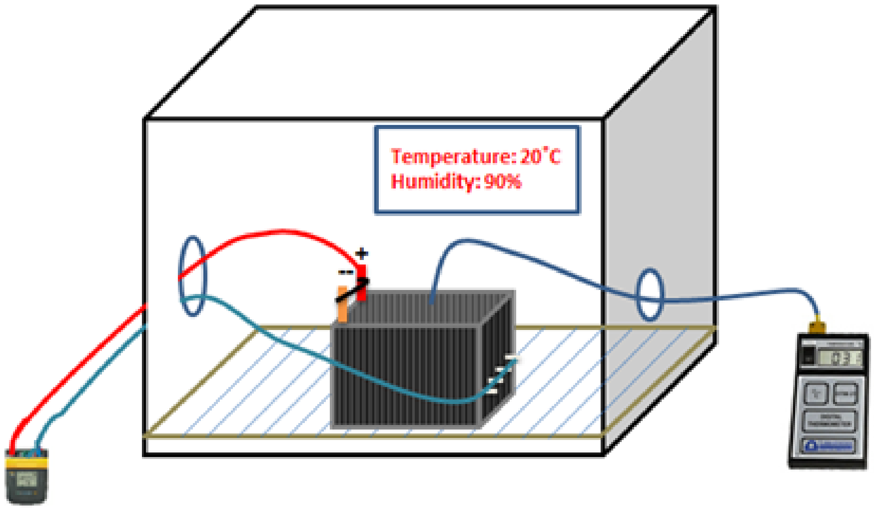


Figure 7.13: Test setup for environmental test.

Three ambient profiles were chosen to determine the influence of environmental conditions on the insulation resistance of a battery module. The tests involved subjecting the battery module to varied levels of temperature and humidity. The periods during which water vapour condensed on the battery module were of great interest. The conditions within which these three tests were performed as well as the results obtained from each test are detailed in the sections that follow.

7.3.1 Insulation performance under extreme temperature and humidity variation

This is a test that was chosen to replicate a worst case scenario in terms of the level of temperature and humidity a battery would be exposed to within a vehicle. In addition, the amount of moisture build-up within the climate chamber was not controlled as would be in the battery pack this meant that the amount of water condensing on the module keeps on accumulating.

The purpose of this test was to determine during which periods of temperature and humidity cycling does condensation occurs on the battery module and how its insulation resistance is affected by extreme temperature and humidity cycling and uncontrolled water content (moisture) in air. The temperature ranges selected for the climate chamber were between $-20\,^{\circ}\mathrm{C}$ and $60\,^{\circ}\mathrm{C}$ and the relative humidity range was from 0 % to 93 %. The climate chamber was responsible for maintaining the set temperature and relative humidity conditions. A sensor was inserted in between the cells of the battery module and connected to a thermometer to monitor the temperature of the battery module.

The temperature and humidity profile for the climate chamber during this test is as shown in figure 7.14. This is an extreme test and does not represent what would normally happen in a battery pack. With reference to the expected temperature ranges from 15 °C to 32 °C in a sealed battery pack, the very low temperatures, high temperatures and high humidity levels combined with the unlimited amount of moisture in air to which the battery module was exposed in this test were classified as extreme.

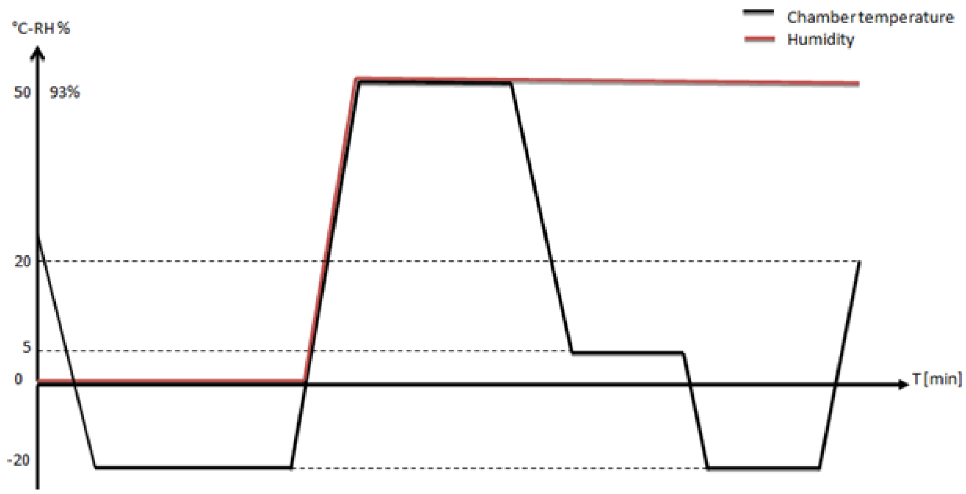


Figure 7.14: Humidity and chamber temperature profile.

Test procedure
The procedure followed when performing this test was as follows:

- The battery module was placed in the climate chamber. The chamber temperature was set to −20 °C and the relative humidity 0 %. In order to the lower temperature of the module the chamber temperature was maintained for a period of approximately 3 hours since the temperature of the climate chamber changes faster than that of the module.
- After the 3 hours the module temperature was −12 °C. The chamber temperature was then ramped up to 60 °C and the relative humidity set to 93 %. With these values of temperature and humidity the dew point was determined as 59 °C using the psychometric chart (below the dew point water vapour in air is expected to condense on the cooler surfaces).
- The temperature of the battery module increased due to increased air (chamber) temperature, however it increased slower than the chamber temperature as depicted in figure 7.15 and consequently condensation (water vapour) collected on the battery module at temperatures (of the module) below 59 °C.
- When the module temperature reached 30 °C, the chamber temperature was ramped down to 5 °C and later on to −20 °C and the relative humidity maintained at 93 %.

Result
Figure 7.15 shows the measured profile of the humidity, module and chamber temperature over a time period of approximately 6 hours during the test. Condensation started to accumulate on

and within the battery module at the point when the chamber air temperature became higher than the module temperature and it continued to accumulate as long for as this condition was met. The condensation was seen on the module surface and was dripping from inside the module as well.

Since the air in the chamber heated up faster than the battery module, the warm air in the chamber absorbed moisture. The warm air immediately surrounding the cold battery module was cooled on contact with the cool surfaces and turned to liquid to form condensation. The dew point is when the air is completely 100 % saturated with moisture and is dependent on relative humidity and air temperature. Below the dew point condensation will occur and the period when condensation accumulated has been marked as the area of condensation. However, when then battery module the same temperature as the air in the chamber, the condensed moisture started to evaporate into the air again.

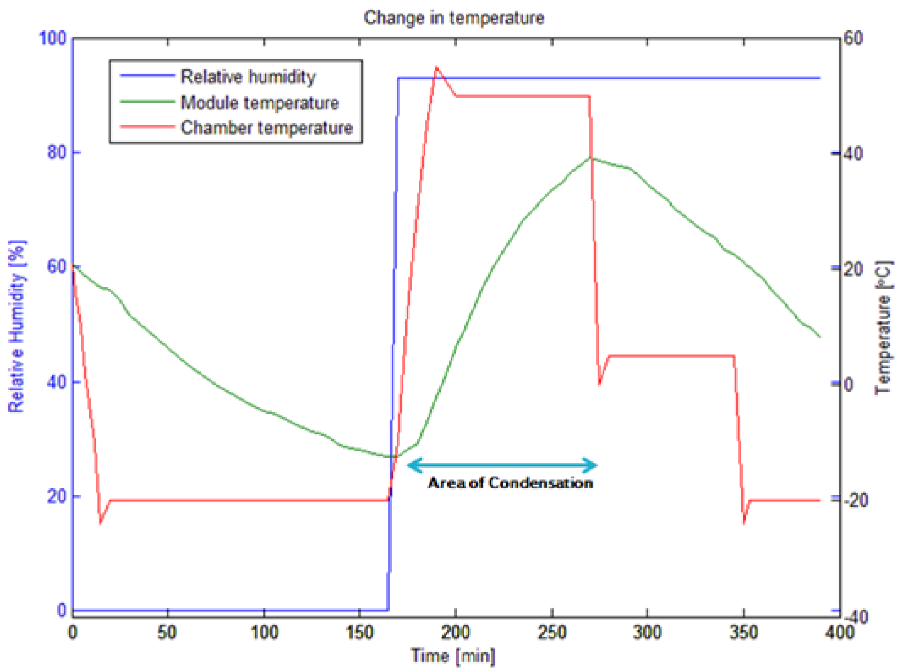


Figure 7.15: Extreme humidity and temperature variation.

During the test the insulation resistance of the battery module was measured in 5 minute intervals at DC voltage levels of 100 V, 250 V and 500 V using a megger. Before condensation started (area of condensation is indicated in figure 7.16) to accumulate on the battery module, the insulation resistance measured at 100 V test voltage was high; greater than 110 $M\Omega$ (the measuring limit of the megger at 100 V). However, when condensation started to collect on all cold surfaces of the battery module, low values of insulation resistance were measured. It can be seen in figure 7.16 that there was a sudden drop in insulation resistance as a result of accumulated condensation on the battery module and it remained very low as long as condensation was present. The lowest insulation resistance value recorded at test voltage of 100 V was 1.8 $M\Omega$ as shown in figure 7.16.

When the chamber temperature was reduced and equal to the module temperature the condensation on the battery module stopped. The condensation on the battery module slowly evaporated into air (dried up) as the chamber temperature reduced further. As a result, the values of the insulation resistance started to increase as the condensation dried up. The increase in insulation resistance was slow at first but a sudden rise occurred at the same instant that condensation stopped. The battery module's insulation resistance was restored to the original values (when most of the condensation had evaporated) i.e. >110 $M\Omega$.

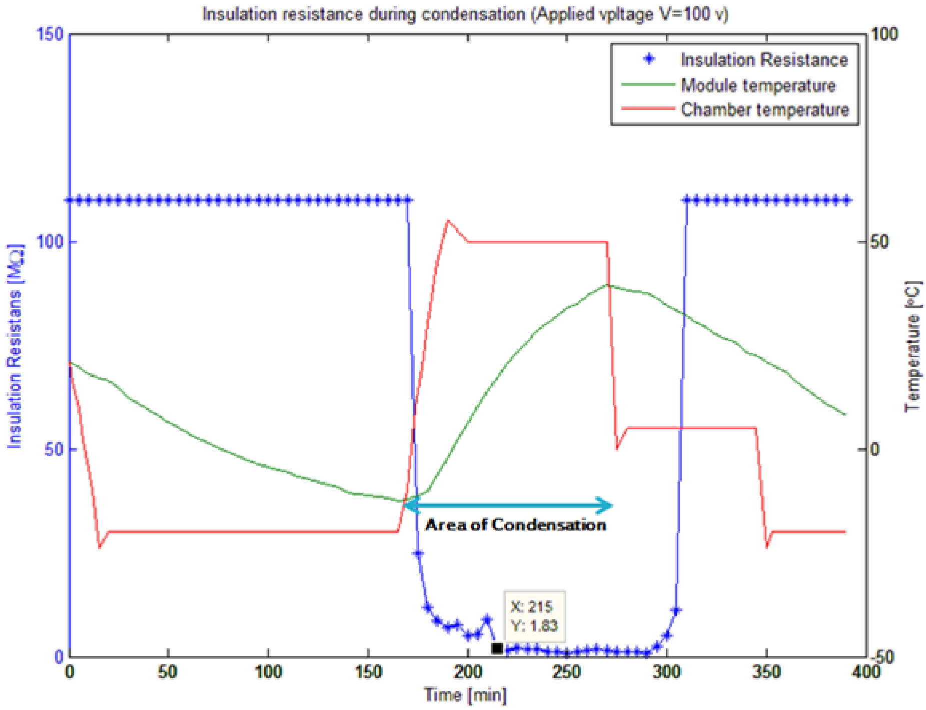


Figure 7.16: Effect of uncontrolled condensation on insulation resistance at 100 V in extreme case.

The insulation resistance of the battery module measured at different test voltages of 100 V, 250 V and 500 V is shown in figure 7.17. When no condensation is taking place during the first 3 hours, the insulation resistance measured very high at values greater than scale of the measuring device (megger), at 100 V insulation resistance was >110 $M\Omega$, at 250 V insulation resistance was >275 $M\Omega$ and at 500 V insulation resistance was >550 $M\Omega$.

The sudden decrease in insulation resistance resulting from accumulation of condensation on the battery module was noted at all the three test voltages. The lowest insulation resistance value measured was 1.2 $M\Omega$ at 500 V test voltage. The insulation resistance values followed the same profile during condensation regardless of the level of test voltage; the values were low. A slower more gradual increase in insulation resistance is evidenced at the different test voltages during the period when condensation does not accumulate on the battery module but evaporates into the air. The insulation resistance of the module was restored to the initial measured value for all three test voltages.

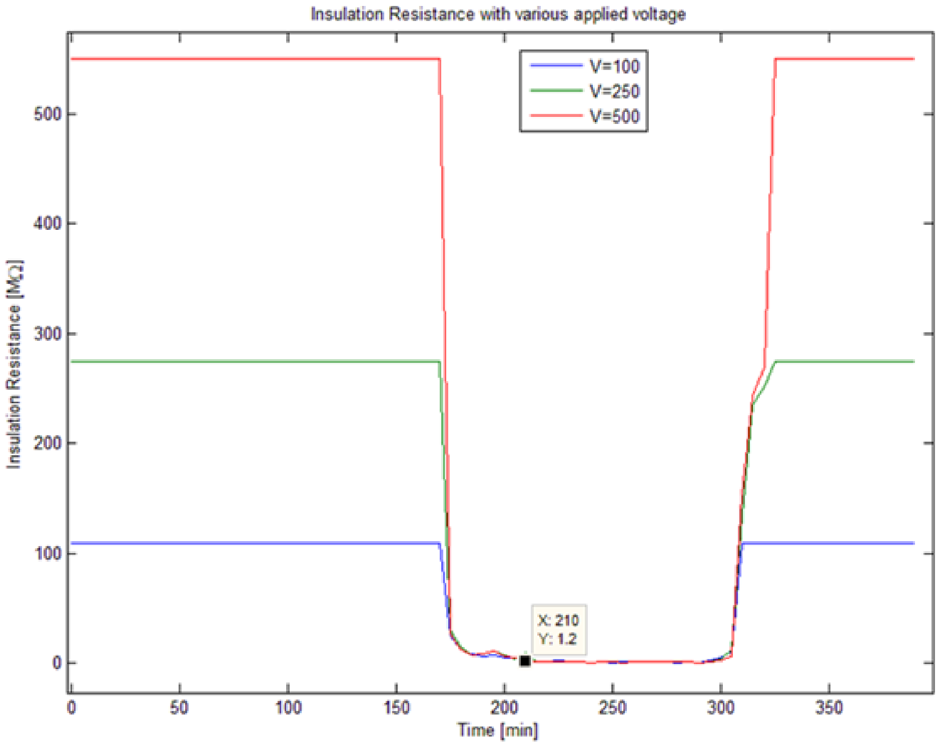


Figure 7.17: Insulation resistance at different test voltages in extreme case.

7.3.2 Insulation performance under realistic temperature and humidity variation

A second test was performed to reflect more realistic temperature and humidity levels that a battery pack would be exposed to inside a vehicle. There was no limit on the amount moisture in the air within the chamber where the tests were done as in section 7.3.1. The difference between this test and the previous was the use of lower temperature and humidity values. Although the selected values of temperature and humidity were closer to those the battery pack is exposed it, this test did not depict the conditions inside the battery pack where the amount of moisture in air is controlled by the battery pack enclosure.

The purpose of this test was to determine how condensation would affect insulation resistance when more realistic temperature and humidity values were used in an environment with uncontrolled build-up of moisture content. The temperature ranges selected for the climate chamber were between −20 °C and 32 °Cand the relative humidity range was from 0 % to 85 % to depict the temperature and humidity conditions characteristic of those a battery pack is subjected to during operation. This test was performed with the same setup as described in the first test in 7.3.1. The temperature and humidity profile for the climate chamber during this test was as given in figure 7.18 below. The test was performed at temperature and humidity levels closer to those that would be found in the battery pack but under conditions of uncontrolled moisture. It represents a case where there is a constant humidity source inside the battery pack.

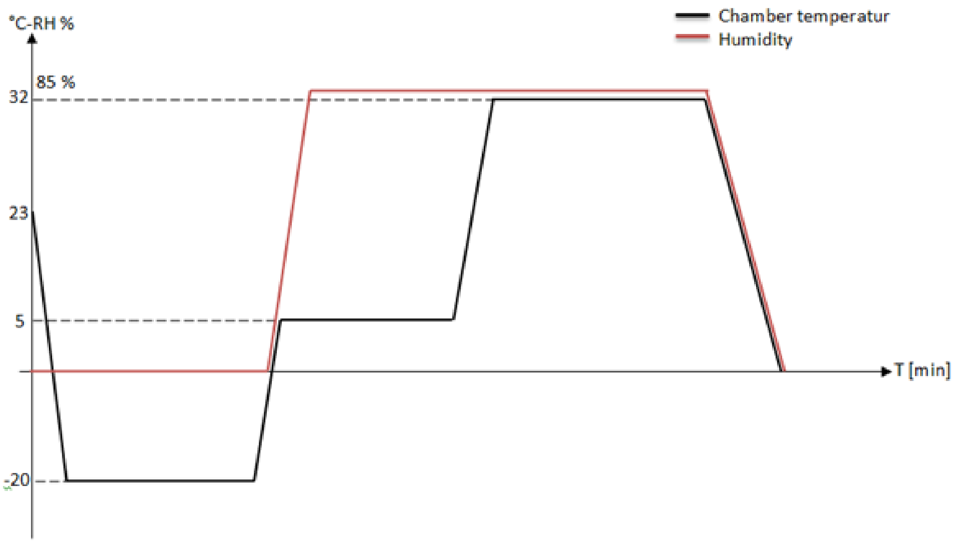


Figure 7.18: More realistic chamber temperature and humidity profile.

The procedure when performing this test was as follows:

– The battery module was placed in the climate chamber. The chamber temperature was set to $-20\,°C$ and the relative humidity set to 0 %. In order to the lower temperature of the module the chamber temperature was maintained for a period of approximately 3 hours.

– As shown in figure 7.19, when the module temperature reached $8\,°C$, the chamber temperature was ramped up to $5\,°C$ to stop the module temperature from falling any further and then to $32\,°C$ and the relative humidity set to 85 %. The dew point at $32\,°C$ and 85 % relative humidity was determined as $28\,°C$.

– The period when the temperature of the battery module was lower than that of the chamber condensation accumulated on the battery module for temperatures below the dew point of $28\,°C$.

– When the module temperature reached $28\,°C$, the chamber temperature was ramped down to $5\,°C$ and the relative humidity set to at 0 %.

Result
Figure 7.19 shows the actual profile of the humidity, module and chamber temperature through-

out the testing period. As in 7.3.1 condensation started to accumulate on and within the battery module (all surfaces of the module) at the point when the chamber air temperature became higher than the module temperature and it continued to accumulate as long for as this condition was met. The condensation was seen on the module surface and was dripping from inside the module as well. The period when condensation took place is indicated in figure 7.19.

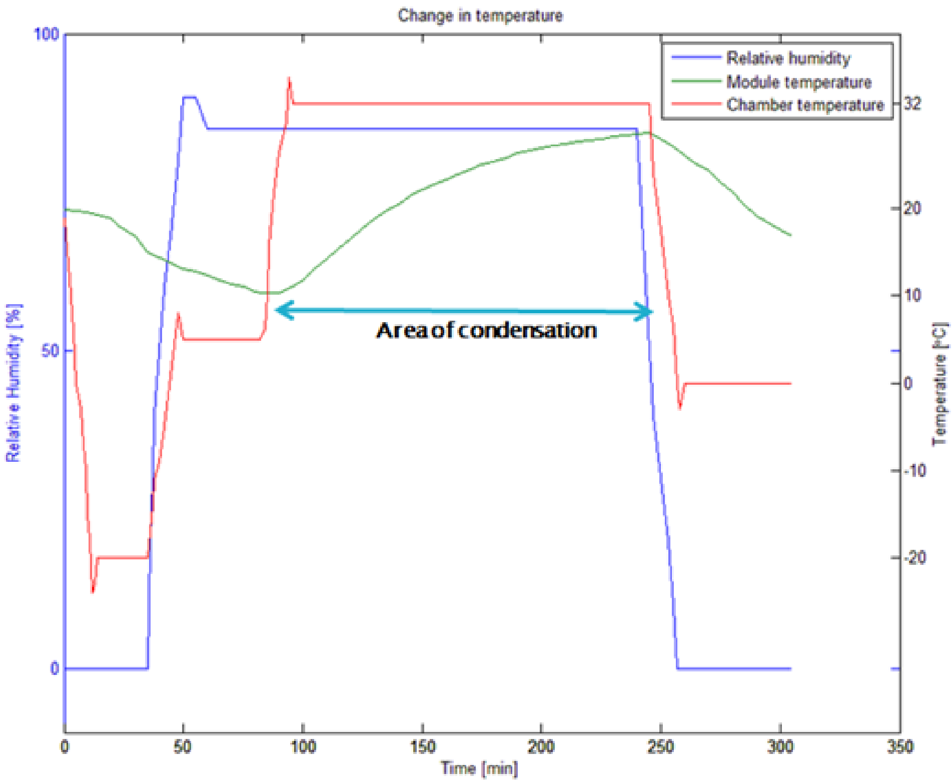


Figure 7.19: Variation of module and chamber conditions in a more realistic case.

The results obtained from the insulation resistance tests are shown in figure 7.20 and figure 7.21. The insulation resistance values behavior in the same way as the previous test in 7.3.1. Prior to the period of condensation the insulation resistance measured at 100 V test voltage was very high; greater than 110 $M\Omega$. As in the previous test, when condensation started to collect on all cold surfaces of the battery module, there was sudden fall in the insulation resistance measured. At a test voltage of 100 V, the lowest insulation resistance measure was 1.7 $M\Omega$ as shown in figure 7.20.

Once the chamber temperature was reduced from 32 °C to 5 °C, the module followed and at the point when the module and chamber had equal temperatures, the condensed liquid started to evaporate into the air. As a result, the insulation resistance value started to increase first slowly and then quickly with a sudden rise to extremely high values. When most of the condensation had evaporated the insulation resistance of the battery was restored as in the beginning of the test. The insulation resistance of the battery module measured at different test voltages of 100

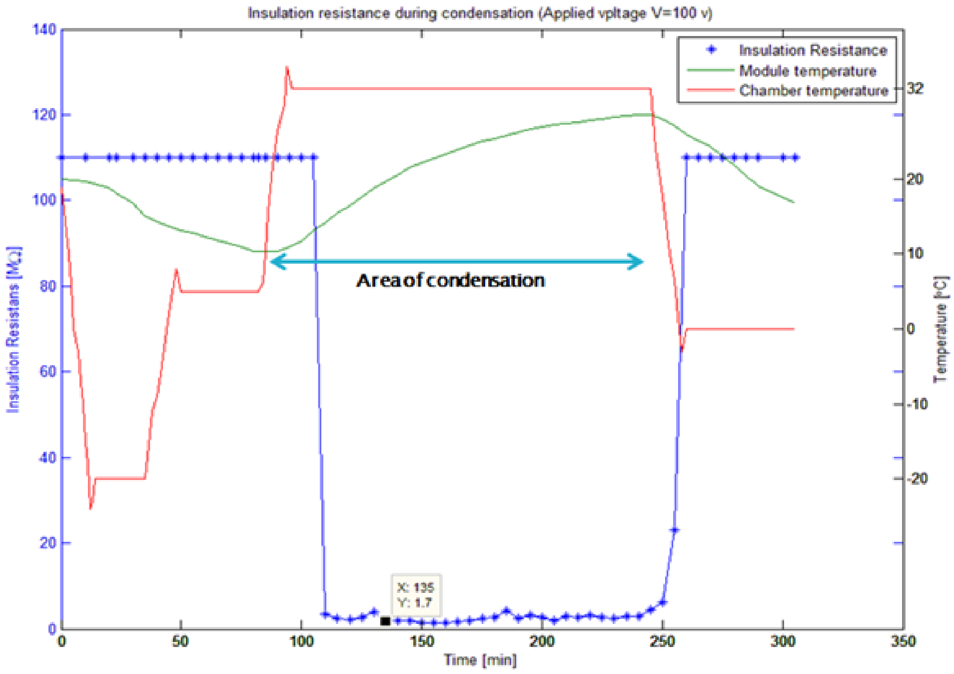


Figure 7.20: Effect of condensation on insulation resistance at 100 V in a more realistic case.

V, 250 V and 500 V for this test is shown in figure 7.20. The insulation resistance values are still similar to those in 7.3.1 such that the low insulation resistance values were recorded in the area of condensation for all three test voltages. Before condensation happened, the insulation resistance measured was very high at values greater than scale of the measuring device. The sudden fall in insulation resistance resulting from accumulation of condensation on the battery module was noted at all the three test voltages. The lowest insulation resistance value measured was 1.3 $M\Omega$ at 500 V test voltage. A slower more gradual increase in insulation resistance was evidenced at the different test voltages during the period when condensation does not accumulate on the battery module but evaporates into the air. The insulation resistance of the module was restored to the initial measured value for all three test voltages when most of the condensation evaporated.

7.3.3 Simulation of battery pack temperature and humidity conditions

Since the battery is located in an enclosure with in an electric vehicle, there is limited amount of air that the battery pack can contain. Thus a limited amount of humidity is contained in that air as long as there is no humidity source within the battery pack. An example of a humidity source could be water that could have accumulated in the bottom of the battery pack that humidifies the air when the battery is cooled down. In order to replicate the temperature and humidity conditions similar to those found inside a battery pack assuming no humidity source,

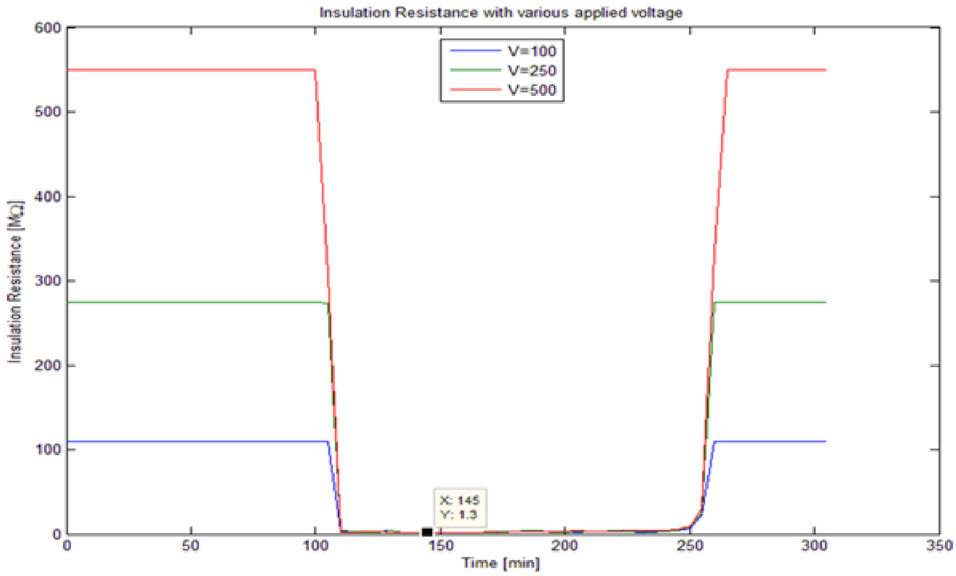


Figure 7.21: Insulation resistance at different test voltages in more realistic case.

a test where the amount of moisture within the climate chamber is limited was performed.

The purpose of this test was to determine how insulation resistance of the battery module is affected by the condensation that accumulates on it in an environment with a limited amount of moisture content. The temperature ranges selected for the climate chamber were between 8 °C and 32 °C and relative humidity ranging from 90 % to 95 %. The test setup was the same as that used in sections 7.3.1 and 7.3.2. The temperature and humidity profile used in this test is given in figure 7.22. The test tries to replicate the environmental conditions within which a battery exists inside a battery pack. The limited moisture in air, temperature and humidity levels used are similar to those in a battery pack.

The procedure when performing this test was as follows:

- The battery module was placed in the climate chamber. The chamber temperature was set to 8 °C and the relative humidity set to 95 %. The chamber temperature and humidity was maintained for approximately 3.5 hours.

- When the module temperature reached 8 °C, the chamber temperature was ramped up to 32 °C and the relative humidity set to 90 %. At 32 °C and 90 % relative humidity the dew point was determined as 29 °C.

- When the temperature of the chamber stabilized at 32 °C and the relative humidity at 90 %, the chamber was turned off to stop further moisture accumulating in the air.

- The moisture in the air settled on the cool surfaces of the battery module for the period when the temperature of the battery module was lower than that of the chamber below

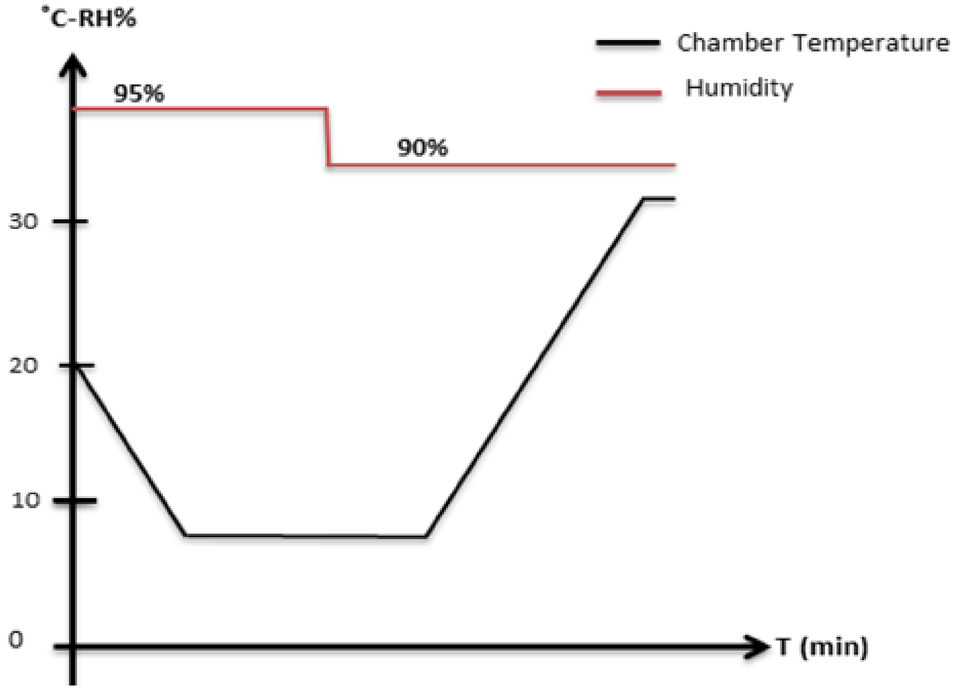


Figure 7.22: Insulation resistance at different test voltages in more realistic case.

the dew point. This is period is indicated as the area of condensation in the figure 7.23. Note: When the chamber was turned off the temperature of the chamber started to fall as that of the battery module was increasing as shown in figure 7.23.

– The insulation resistance of the battery module was measured throughout the entire experiment.

The insulation resistance of the battery module was measured in 5 minute intervals at DC voltage levels of 100 V, 250 V and 500 V in this test as well. The results obtained from the insulation resistance tests at test voltage of 250 V are shown in figure 7.24. Prior to the period of condensation the insulation resistance measured at 250 V test voltage was very high; greater than 275 $M\Omega$. However, when the climate chamber was turned off the moisture in the chamber condensed on the cool parts of the module. Additionally, the low temperature of the battery module caused the temperature in the chamber to start dropping as well.

Due to controlled amount of moisture content in the chamber, the amount of condensation observed on the battery module was less than the previous two tests. In addition, the insulation resistance did not drop as much as in sections 7.3.1 and 7.3.2 during the period of condensation. The test lowest insulation resistance measured at test voltage of 250 V was 90 $M\Omega$ (much higher value than in 7.3.1 and 7.3.2 as shown in figure 7.25.

With the climate chamber closed and turned off the battery module was left inside it for 6 more hours. After the 6 hours it was observed that the condensed liquid on the battery module had

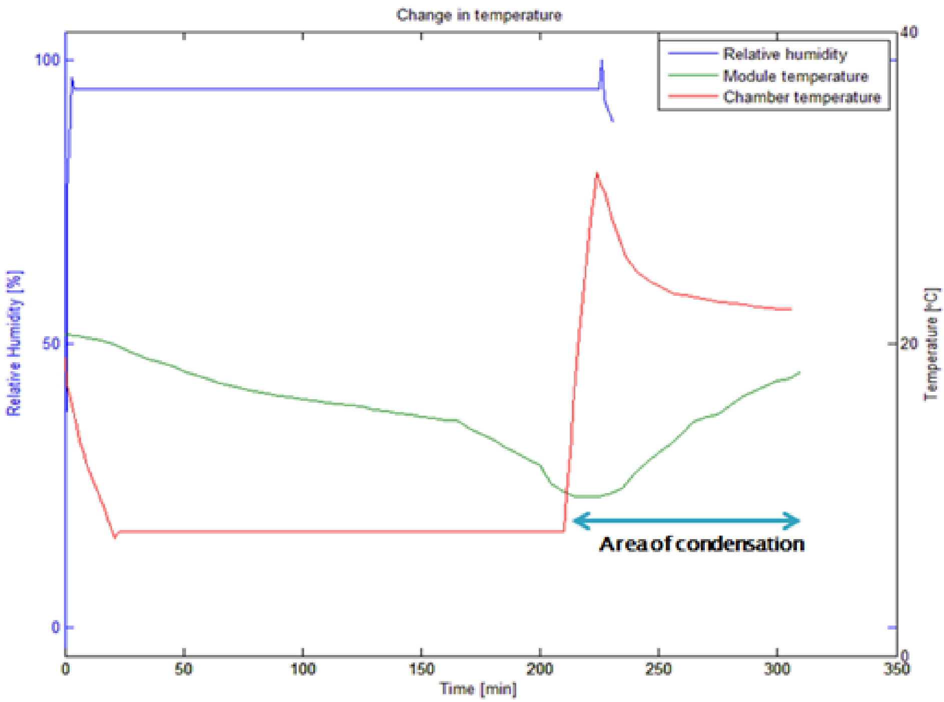


Figure 7.23: Variation of temperature and humidity conditions similar to those in a battery pack.

not evaporated even though the temperature of the module and the chamber were almost the same, 19.1 °C and 20 °C respectively. The reasons why the condensation did not dry up when the module and chamber temperature were equal can be explained by the ambient conditions in the chamber when it is turned off which is outside the scope of this study. The insulation resistance of the battery module was measured as 90 $M\Omega$ at 100 V, 88 $M\Omega$ at 250 V and 41.5 $M\Omega$ at 500 V. These values were lower than those at the beginning of the test but still higher than the values obtained in 7.3.1 and 7.3.2 when there was condensation.

Figure 7.25 gives a comparison between the insulation resistance result obtained at test voltages of 100 V, 250 V and 500 V. At 500 V test voltage the insulation resistance measured dropped suddenly from a value greater than 550 $M\Omega$ (prior to condensation) to 200 $M\Omega$ and continues to drop gradually with time during the period of condensation. At 250 V test voltage the insulation resistance measured quickly dropped from greater than 275 $M\Omega$ (prior to condensation) to 190 $M\Omega$ after which it continues to drop gradually during condensation. At 100 V test voltage the megger is designed to measure up to 110 $M\Omega$. Hence, the drop in the measured value of insulation resistance at 100 V is not very large since the lowest measured value was 90 $M\Omega$.

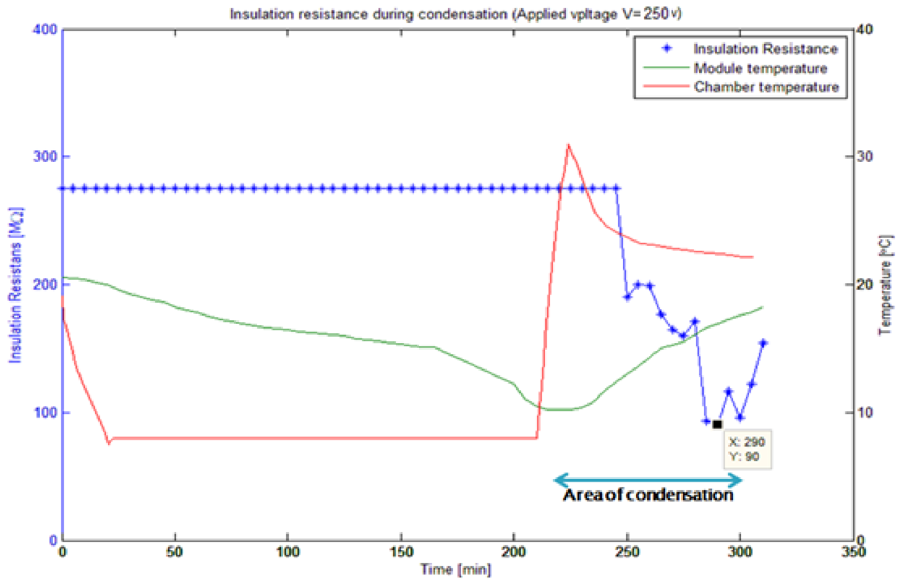


Figure 7.24: Effect of condensation on Insulation resistance under controlled moisture at 200 V.

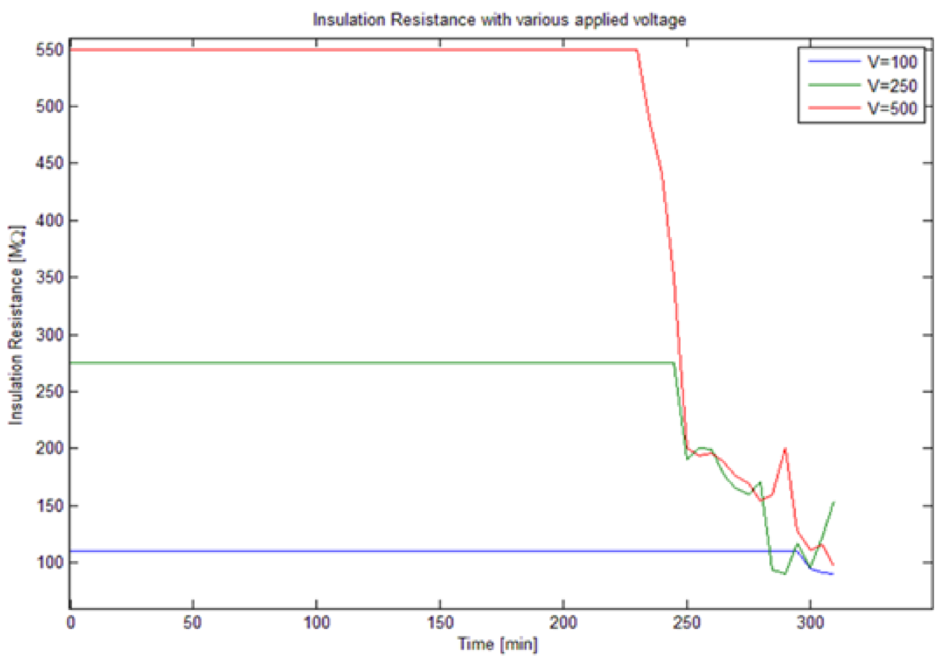


Figure 7.25: Insulation resistance at different test voltages in more realistic case.

8

Discussion

8.1 Partial discharge measurement

The results from the partial discharge measurement on the cabling system indicate that the discharges start at inception voltage of 2 kV peak AC voltage. However, this voltage is for the test when only the cables and contactors are connected in the test circuit. This voltage is reduced when test was done by including the bleeder resistances, connection to the BMS board, into the test circuit. However, all of bleeder resistances do not affect the discharges equally. The lowest inception voltage was recorded when bleeder resistance B1 was in the tests circuit, see figure 7.2. The inception voltage in this case was 875 V peak AC voltage. Despite the fact that there are discharges on this connection, still the inception voltage is much higher than the operational voltage which is at maximum 420 V DC voltage. For this reason, no potential weak points were detected on the cabling system. Note that testing with AC voltage applies higher electric field build up across the insulation and results in higher stresses to the insulation. Therefore these discharges on cabling system that starts at high enough voltage will not cause problem during the normal operation.

The result in the figure 7.6 for the grounding test performed on the single battery module stands alone shows the importance of the grounding to increase the level of the inception voltage. When test was done by grounding the outer plates and cooling fins, it results in an inception voltage at 770 V peak AC voltage. The inception voltage was 515 V peak AC voltage when only outer plates were grounded which is 33 % reduction on the inception voltage and when only cooling fins were grounded, the inception voltage reduced by 37 % to 485 V peak voltage. This comparison shows that the grounding of both outer plates and cooling fins are necessary in order to have high inception voltage. Therefore in order to minimize the probability to have discharges in the normal operation, it is recommended to ground both cooling fins and outer plates. Since the grounding through the coolant is resistive grounding, the test on single module with grounding the cooling fins through a 4.9 $M\Omega$ resistance was proposed to show the difference between pure and resistive grounding. This test shows decrease in the inception voltage. The result shows an decrease in inception voltage while the cooling fins are grounded through a 4.9 MOhm. Since the grounding the cooling system through the coolant are resistive, it is important to research on different mixture of coolant with different resistivity.

The same analysis is applicable when the test was done on the single module or entire modules inside the battery pack. In the both cases grounding the cooling fins leads to higher inception level. The only difference here is the fact that the grounding has been done through the coolant and less inception voltage in these cases can be depend on the resistive grounding.

The PD measurements on the modules indicate that the origins of the PDs are mainly located inside the battery modules. This was done by aural methods i.e. listening to the acoustics noises from the discharges. Testing on the cells shows that the weakest points are located on edges of the cells, especially on the sharp points on the corners and insulation between the terminals of the cell.

The results in the table 7.5 and figure 7.9 on the two cells and the cooling fins between them indicates that by placing a plastic film between the cells and cooling fin, it is possible to improve the insulation so that until 1.4 kV peak applied AC voltage no PDs appears. Also, adding insulation between the terminals of the cell can increase the inception level by 20 %. In the other hand, reinforcement on the insulation around the edges of the cooling fin does not significantly affect the test result and is not recommended.

It can be concluded from PD test on the cabling system that the insulation of the cables are strong and up to operational voltage which is at 420 V DC, no partial discharges are supposed to be take place. There are discharges on one bleeder resistor which mainly can be because of the placement of the resistor on the BMS board. Since the applied voltage during the discharges was at 875 peak AC voltage, it will not be any problem during the normal operation.

From the results of the test on the single module, it can be concluded that grounding the cooling fins and outer plates of the modules are required in order to reduce possibility of having discharges at lower voltages as well as not having points at floating potential. Same conclusion can be made from the PD test on the single module and whole modules in the battery pack. Since the modules are grounded through the coolant which is resistive, it is recommended to investigate different properties of the coolant.

8.2 Insulation resistance test

The results from the insulation resistance test with respect to ground on both the positive and negative side for the whole battery pack were very similar and comparable at every test voltage level. This shows that the insulation resistance on the negative and positive side is almost the same. The tests were performed with the bleeder resistors connected and the results obtained were influenced by the bleeder resistance in parallel with the insulation resistance of the battery and the cables. Without the bleeder resistor connected the insulation resistance of the whole battery measured with respect to ground was as high as $T\Omega$ (see table 7.2). This shows that the battery modules and the cables under dry conditions and room temperature have a very high insulation resistance.

The results in table 7.7 for the insulation resistance test performed on the battery modules alone confirm that the modules have distincly higher insulation resistance. In addition the insulation resistance tests performed on the cables as an individual entity in table 7.6 confirms that the insulation resistance of the positive and negative cables in the battery pack are very high in $T\Omega$ under dry ambient conditions without the bleeder resistors.

Comparing the results obtained when insulation resistance tests were performed without the bleeder resistors in 7.6 to those performed on the negative cable with the bleeder resistors connected in 7.5, the influence of the bleeder resistors on the measured insulation resistance is clearly shown. As long as no degrading of the insulation has occurred in the battery, the resistance measured will be set by the bleeder resistors in the system. However, if the insulation resistance of any of the other components in the battery pack is comparable or lower than that of the bleeder resistance then the measured insulation resistance will be affected. The intention of using a bleeder resistor is to connect the HV system to ground and give the floating voltage of the HV system a reference point.

The results in table 7.7 show that the insulation resistance of a stand-alone module is very high in $T\Omega$ at both 400 and 1000 V test voltage. In order to stress the insulation further a series of environmental tests were performed.

8.3 Environmental tests

The environmental tests were performed on a single stand-alone module. The interaction between several modules tightly packed with power cables in an enclosure was not taken into account. The effect of how the different geometries with in a battery pack would affect the measured insulation resistance has not been considered. In the battery pack the cool parts of the battery module are the cooling fins however in these tests the entire module was cooled during the test. In a battery pack mounted in a vehicle, condensation would most likely take place on the cooling fins and not on all surfaces of the battery module as in the tests performed. Since the battery is enclosed in a sealed pack, the amount of moisture in air that it is exposed to is limited. However the amount of moisture in air was not monitored in the tests performed and thus its effect on the results obtained has been not been emphasized.

The megger was used to measure the insulation resistance during the environmental tests however because of it limited measuring range it was not possible to find out how much the insulation resistance of the module was affected by temperature or humidity alone. The results obtained only show the insulation resistance as being greater than the largest value measureable by the available test instrument the megger. Although the insulation resistance is actually affected by humidity and temperature, the value of the measured insulation resistance is satisfactory since it is significantly higher than that required by the standards.

The results obtained under the extreme test conditions involving condensation show that the insulation resistance of a battery module is greatly affected by condensation that accumulates when the battery module is cooler than the air around it under the specified conditions. With 10 battery modules in series in a battery pack the value of insulation resistance under the same conditions would be lower than the recorded 1.7 $M\Omega$ in this test. Similar results were obtained in section 7.3.2 which shows that continued accumulation of condensation resulting from uncontrolled moisture build-up greatly affects the measured insulation resistance of the battery module. However, the results obtained from the test simulating the environmental conditions in which the battery operates show that under conditions of controlled moisture in air there is no continuous condensation on the surface of the module under the specified conditions.

Surface leakage is directly dependant on the amount of moisture on the insulation surface since condensation on the insulating surfaces leads to high surface leakage currents resulting in lower insulation resistance. The results in section 7.3.1 and section 7.3.2 reveal that continuous condensation build-up (providing a path for the surface leakage current) eventually leads to sudden drop in insulation resistance. However, in the results in section 7.3.3 show that if there is no condensation build-up this sudden fall in insulation resistance is not experienced. This shows that the measure of the amount of condensation on the insulation surface of the module significantly affects the surface leakage current which directly affects the measured module's insulation resistance.

According to UL2580, the measured insulation resistance divided by the maximum working voltage of the test circuit should be at least 100 Ω/V for AC circuits and 500 Ω/V for combined AC and DC circuits in insulation resistance tests [21]. The result from all insulation resistance tests including the environmental test met this requirement. But considering the environmental test on the whole battery pack with 10 modules, if each module has insulation resistance of 1 $M\Omega$ the overall insulation resistance value of all the modules will be one tenth of a single module; 0.1 $M\Omega$. This value will give 238 Ω/V which is very close to the lowest accepted value of 100 Ω/V.

9

Conclusion

From the standards that have been reviewed, it can be concluded that under the specified conditions the insulation resistance of a battery pack with respect to ground meets the stated requirements on insulation resistance in dry conditions. However, when subjected to environmental stress in the form of humidity and temperature resulting in moisture build up, the insulation resistance dropped significantly. Considering this value for 10 series connected battery modules in a battery pack the insulation resistance value is too close to the lowest accepted value which is not acceptable.

It can be concluded that the weak points of the battery is the battery modules. Specifically, the weakest point of the modules are the insulation around the corners of the cells, insulation between the cells and the cooling fins and insulation on the cells in the area between the terminals of the cells. In order to improve the insulation in the weak areas, it is recommended that all insulation around the edges of the cells completely cover all the corners. Since adding insulation between the terminals of the cells leads to higher inception voltage, it is recommended to add insulating material between the terminals of the cells. The best way of reducing probability discharges is to have insulation between the cooling fins and the cells. It is also recommended to find a way to ensure all moisture that builds up on the surface of the module is removed. Additionally, water that may accumulate in the battery pack should be drained out to eliminate continuous humidification inside the battery pack.

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Appendix

Calculating the dew point

Dew point is the temperature at which water vapor condenses as a result of air that is cooling e.g. in the event of warm moist air getting in contact with a cool surface. The moisture remains in air above the dew point but at or below the dew point, the moisture leaves the air and condenses on cooler surface it the air is in contact with. The condensed water vapor that forms on solid surfaces is dew. The dew point is dependent on relative humidity and a high relative humidity is an indicator that the dew point is close to the current air temperature.

The dew point can be calculated using the Magnus formula or a psychometric chart using values of dry-bulb temperature and relative humidity. An illustration of the psychometric chart method is shown below. The dew point is determined by finding the intersection of the vertical dry bulb temperature and the exponential relative humidity. The point where the horizontal line of this intersection point meets the last line of the relative humidity is the dew point in °C as shown in figure 9.1 below.

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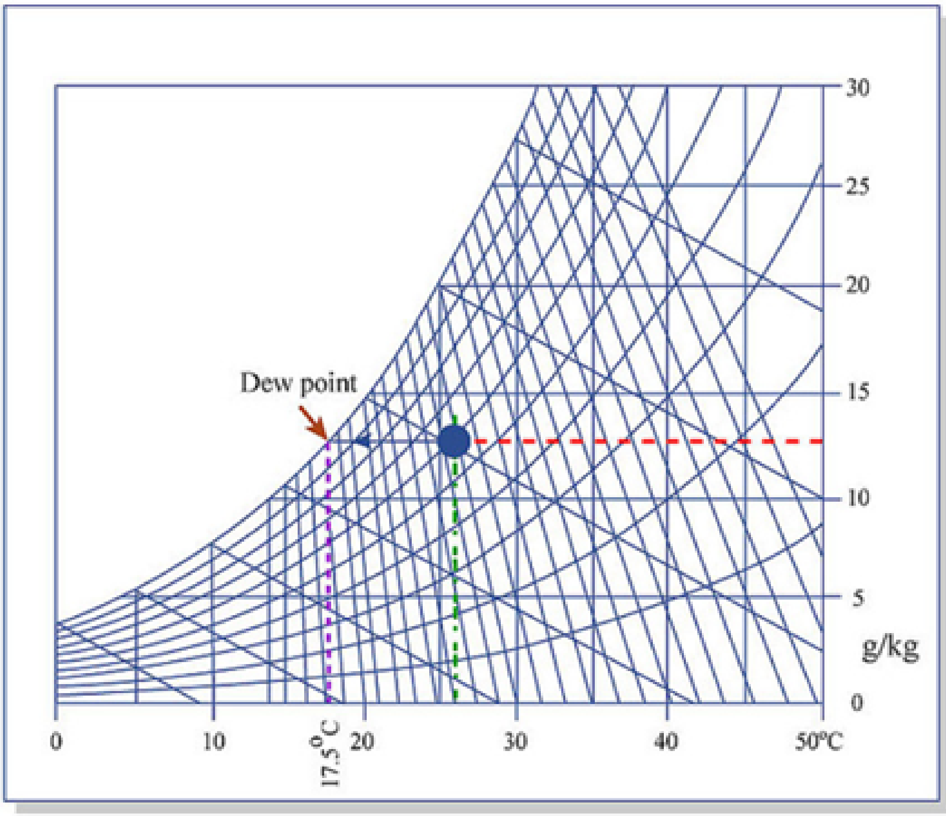

Figure 9.1: Psychometric chart (Downloaded from: MIT OpenCourseWare).