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Ageing Factors of Insulation Materials with a Focus on Moisture-Induced Degradation in Automotive Applications

Master's Degree Thesis

Siddhali Rahul Parbhane

Master's Programme in All-Electric Propulsion Systems

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Ageing Factors of Insulation Materials with a Focus on Moisture-Induced Degradation in Automotive Applications

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Abstract

This study explores the impact of different ageing factors on the condition and reliability of insulation materials of electric machines in automobile applications. Insulation degradation is an inevitable process that affects the core functioning of an electric motor and its longevity. Hence, the research involves designing a test and performing a series of experiments in controlled environments to simulate worst case scenarios of real word conditions, with a focus on humidity and temperature variation in order to observe their impact on the insulation. It is estimated that high relative humidity under varying temperature conditions will degrade the insulation materials and the cooling oil of the electric machine irreversibly. These results provide a valuable insight into what ageing factor is dominant in the real world and help us improve our current testing methods in order to improve insulation performance to provide durable and efficient electric machines.

Faculty of Science and Technology

Uppsala University, Uppsala, Sweden

Supervisor: Axel Andalen, Henrique Cunha Subject reader: Mats Leijon

Examiner: Valeria Castelucci

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LIST OF ABBREVIATIONS

- **HVAC Systems**- Heating, Ventilation and Air Conditioning Systems
- **UV**- Ultraviolet
- **PD**- Partial Discharge
- **PDIV**- Partial Discharge Inception Voltage
- **RPDIV**- Repetitive Partial Discharge Inception Voltage
- **HV**- High Voltage
- **PLC**- Programmable Logic Controller
- **DC**- Direct Current
- **AC**- Alternating Current
- **FTIR**- Fourier Transform Infrared Spectroscopy
- **HiPot AC-** High Potential (High Voltage) Alternating Current Test
- **PD Surge-** Partial Discharge Surge Test
- **PD HiPot-** Partial Discharge High Potential Test
- **PD Phase to Phase-** Partial Discharge Test Between Phases
- **PD Phase to Ground-** Partial Test Discharge Phase to Ground

1
Introduction

1.1 Background

The demand for electric vehicles has skyrocketed as the world is leaning towards all electric propulsion systems. This entails further work and advancements in electric motor technologies to ensure durability and high reliability. Insulation is a vital part of any such electrical system. Insulation materials (Plastic, fiberglass, ceramic, rubber, etc.) function as a barrier between electrical systems and components by preventing the flow of high and low voltage live electric current running through them. They are a critical safety feature that prevents electrical hazards and protects both the electrical systems and the users. A fault in the insulation could lead to exposure of components to voltage levels higher than expected leading to unpremeditated current paths causing life threatening shock circuits and electrical fires. Therefore, good insulation health is crucial. However, insulating materials in normal operation degrades over time due to several factors like electrical, mechanical, thermal, and chemical stressors, this is called insulation ageing.
This thesis project focuses on investigating various ageing factors and the behaviors of insulating materials of electric machines after being exposed to them through designing testing and verification methods to simulate real-world worst-case scenarios that lead to insulation material degradation. Understanding what ageing factor is dominant is important to be able to amplify electric machine durability and to increase its operational efficiency[1].

1.2 Objective

As mentioned before, insulation materials degrade over time due to various ageing factors. In a real-world scenario, a motor may be exposed to more than one ageing factor that could amplify the effects of one another and cause severe damage, not only to the insulation but also other components of the electric motor. The main objective of the project is to design a test with a combination of some of these ageing factors to study the combined effects of them on the insulation and other components of an oil cooled electric motor. Keeping that in mind, operational and environmental stressors such as relative humidity and varied temperature cycles have been considered in order to identify degradation mechanisms such as moisture absorption and mechanical deterioration that may compromise the motor's effectiveness during real world operations in environments subject to fluctuating temperatures and high relative humidity. It would also be interesting to note what effects relative humidity and varying temperature has on the oil of the electric motor since it is an oil cooled system. The project also aims to find out whether the water content in the oil has increased due to this sort of exposure or not.

[1] 'What's The Importance Of Electrical Insulation? | MatsDirect UK'. Accessed: May 06, 2025. [Online]. Available: https://www.matsdirect.co.uk/blog/the-importance-of-electrical-insulation

1.3 Problem Description

The thesis has the following target goals:

- Design a humidity and thermal cyclic test to evaluate the behaviors of insulation materials of an electric machine aged by a thermal cyclic test.
- Measure the water content in the oil as it is one of the parameters that humidity could affect.
- Take electrical and physical degradation measurements to assess the health of the insulation materials of the test object.

1.4 Limitations

Given below are some of the estimated limitations that we will face during the execution of the project:

- As some ageing tests take a long time to get viable results, time will be one of the major limitations we will face during the conduction of this test when in comparison with the thesis timeline. To avoid this and still get a viable result, artificial ageing methods such as supplying electricity through a power supply and increasing the temperature using the Arrhenius law will be used to reduce testing duration and speed up the testing processes.
- Another estimated limitation is potentially having to adjust the temperature parameters to comply with what the rig set up can accommodate. The temperature limitations beyond which the individual components such as end windings, and mid stator will be damaged will also have to be considered leading to motor air temperature range adjustments as the end windings and mid stator components get hot easily as compared to the motor air.

Literature

2
Fundamentals of Stator Insulation in Electric Machines

2.1 Electric Machines

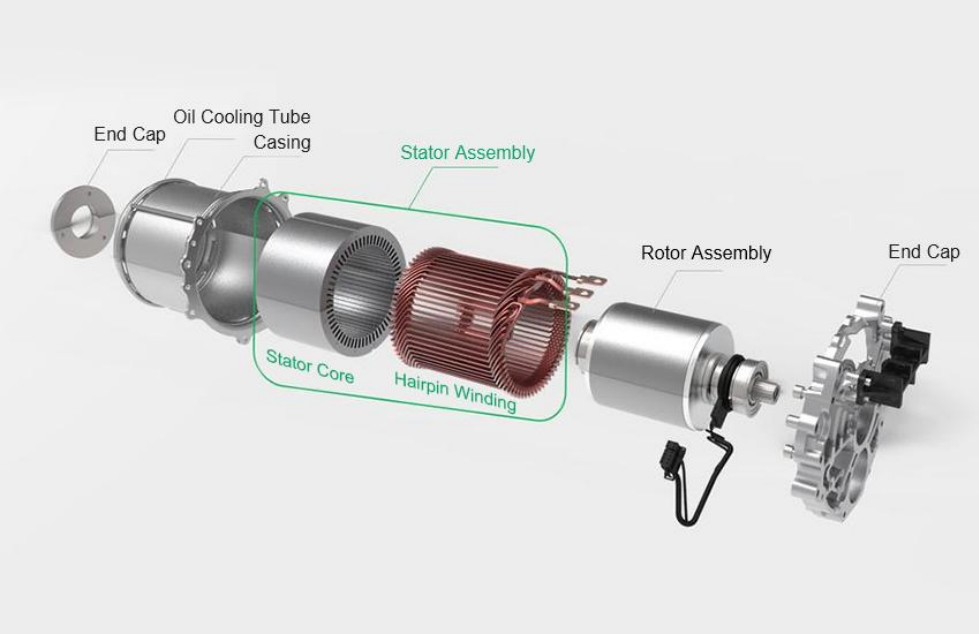

Figure 1 Interior of an electric motor[2]

An electric motor is a machine that converts electrical energy to mechanical energy.
It consists of two main parts:

- The stator, which is the stationary part. It consists of the stator core with hairpin copper windings, an outer frame, and an electrical insulation system which protects the machine from short circuits by acting as a barrier between components.
- The rotor, which is the rotating part placed inside the stator. It consists of permanent magnets.

Working principle: The permanent magnets located on the rotor produce a magnetic field which interacts with the rotating magnetic field of the stator thus creating torque which causes the rotor to rotate[3][1].

[2] 'Hairpin Motor Solutions | CH Laser Precision Laser Cutting, Ablating & Welding'. Accessed: Sept. 19, 2025. [Online]. Available: https://www.chlaser.com/hairpin-motor-solutions.html
[3] 'Permanent Magnet Synchronous Motor'. Accessed: May 06, 2025. [Online]. Available: https://about-motors.com/motorcontrol/pmsm/

2.2 Stator Components

In this project, the primary focus is on the insulation of the stator. Therefore, it would be interesting to study a few components that make up the insulation system in a stator winding. Stator winding components are a critical part of an electric motor. They help generate rotating magnetic fields that interact with the rotor's magnetic field to produce torque. Therefore, it is very important that the components of the stator windings are able to withstand various stresses including thermal, electrical, mechanical, and environmental in order to ensure the smooth operation of a motor. The components contributing to the insulation are hairpin coating, slot liner, and resin.

2.2.1 Windings

Windings are coils that generate magnetic fields when an electric current flows through them. These magnetic fields help rotate the rotor during the operation of an electric motor[4].

Two principal types of windings are commonly employed in electric machines:

- **Round wire windings**

  Among motor winding types, round wire windings are the most traditional and remain prevalent due to their simplicity and versatility. This technology involves multiple thin copper wires wound into the stator slots in order to create electromagnetic coils. Round wire windings are well suited for general purpose applications such as home appliances, HVAC systems, and budget friendly electric vehicles owing to their simplicity and adaptability[5].

Figure 2: Round wire windings[6]

[4] 'Are copper or aluminium windings better for electric motors?' Accessed: May 06, 2025. [Online]. Available: https://www.fisherpaykeltechnologies.com/knowledge-hub/are-copper-or-aluminium-windings-better-for-electric-motor

[5] Judy, 'Round Wire vs. Hair Pin Motor Winding Guide 2025'. Accessed: Sept. 04, 2025. [Online]. Available: https://www.grwinding.com/round-wire-vs-hair-pin-motor-winding/

[6] Judy, 'Round Wire vs. Hair Pin Motor Winding Guide 2025'. Accessed: Sept. 04, 2025. [Online]. Available: https://www.grwinding.com/round-wire-vs-hair-pin-motor-winding/

- **Hairpin windings**

Hairpin windings represent modern technology increasingly adopted in electric machines. It uses thicker, flat copper wires shaped like hairpins and inserted into stator slots. Unlike the conventional round wire windings, rectangular conductors can be packed more densely within the slot, which improves slot fill factor and overall electrical performance.

This winding method is engineered for high power and efficiency applications such as electric vehicles, industrial automation, and aerospace[7].

Figure 3: Hairpin windings[8]

- **Winding Coating**

The winding coating is a thermoplastic substance. It is applied to industrial equipment such as wires and liners in the form of a powdered or aqueous material coating. It is also known to be highly resistant to both heat and chemical exposure and is used to enhance the durability of the equipment and resist degradation via water, humidity, steam, electricity, salts, radiation etc.[9]

[7] Judy, 'Round Wire vs. Hair Pin Motor Winding Guide 2025'. Accessed: Sept. 04, 2025. [Online]. Available: https://www.grwinding.com/round-wire-vs-hair-pin-motor-winding/

[8] Judy, 'Round Wire vs. Hair Pin Motor Winding Guide 2025'. Accessed: Sept. 04, 2025. [Online]. Available: https://www.grwinding.com/round-wire-vs-hair-pin-motor-winding/

[9] P. Martucci, 'What are PEEK Coatings? Uses, Process, Application | Orion Industries', Orion Industries, Ltd. Accessed: May 06, 2025. [Online]. Available: https://orioncoat.com/blog/peek-coatings-faqs/

Figure 4 Completed stator winding with coated magnet wire[10]

2.2.2 Slot Liner

Slot liner is a type of insulation material whose main purpose is to insulate the motor windings from the laminated core. They are typically made from high temperature films or paper that are cut in order to fit into the slots of motors[11].

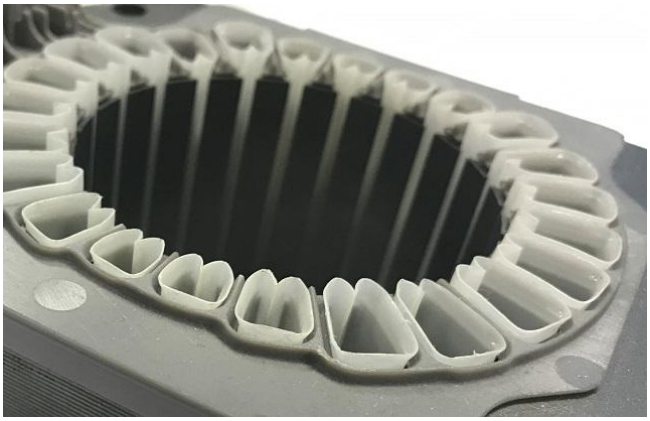

Figure 5 Slot Liner[12]

[10] 'Motor Rewind Using Zeus PEEK Insulation Products'. Accessed: May 06, 2025. [Online]. Available: https://www.azom.com/article.aspx?ArticleID=13041

[11] 'Use of Thermally Conductive Electrically Insulative (TCEI) Materials in E-Motor Slot Liner Applications'. Accessed: May 06, 2025. [Online]. Available: https://www.sae.org/publications/technical-papers/content/2022-01-0198/

[12] 'Slot Insulation', Elmotec Statomat. Accessed: Aug. 04, 2025. [Online]. Available: https://www.elmotec-statomat.eu/en/manufacturing-process/slot-insulation/

2.2.3 Impregnating resin

Impregnating resin is an insulation material which is used to fill in the gaps between the windings of components of an electric motor. Impregnation process improves the reliability of the electrical components and increases their durability[13].

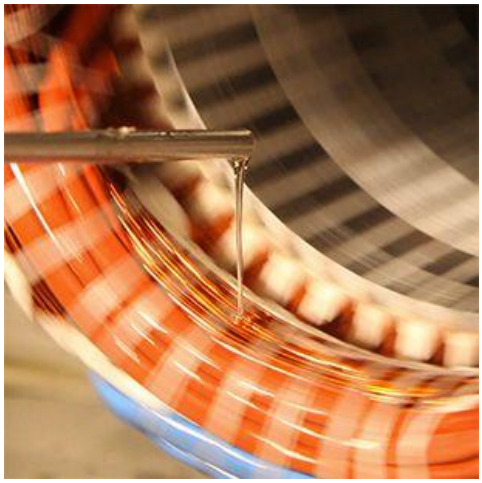

Figure 6 Impregnating the motor by trickling in resin[14]

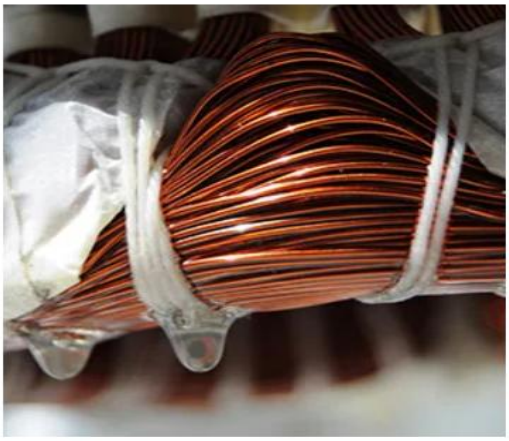

Figure 7 Motor after the impregnating process[15]

2.2.4 Powder Coating

Powder Coating is a type of coating that is applied as a free flowing, dry powder unlike conventional liquid paint coating, which is delivered via an evaporating solvent, powder

[13] 'The importance of motor impregnation & resin - PROSTECH'. Accessed: May 06, 2025. [Online]. Available: https://prostech.vn/what-is-impregnating-process-and-impregnating-resin/

[14] 'Impregnation', Tecnofirma S.p.A. Accessed: Sept. 24, 2025. [Online]. Available: https://www.tecnofirma.com/en/impregnation

[15] 'The importance of motor impregnation & resin - PROSTECH'. Accessed: May 06, 2025. [Online]. Available: https://prostech.vn/what-is-impregnating-process-and-impregnating-resin/

coating is typically applied electrostatically and subsequently cured under heat or UV (ultraviolet) light. The powder may either be thermoplastic or thermosetting polymer. Powder coating is mainly used to provide a thick, tough finish for high durability to metal objects, particularly those subject to rough use[16][2].

Figure 8: Powder coating for hairpin windings[17]

[16] 'Powder coating', *Wikipedia*. June 21, 2025. Accessed: Sept. 04, 2025. [Online]. Available: https://en.wikipedia.org/w/index.php?title=Powder_coating&oldid=1296650406

[17] 'Powder Coating', Tecnofirma S.p.A. Accessed: Sept. 24, 2025. [Online]. Available: https://www.tecnofirma.com/en/impregnation/machinery/powder-coating

3
Ageing Factors and Insulation Degradation

As the electric machine operates, insulation materials degrade over time due to various ageing factors they come into contact with during their normal life span.

The causes that determine the breakdown of insulation systems can be divided into 7 different groups however it is found that insulation ageing is the most important factor besides partial discharge and winding contamination that contributes to insulation degradation [3].

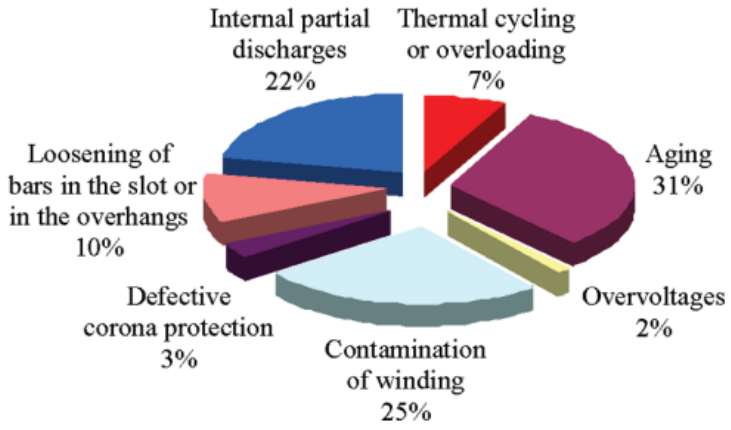

Figure 9: Causes of insulation system damages (CIGRE Study Committee 2003) [3]

As a reference, given below is an image of an unaged motor with a stator insulation system in a good condition.

Figure 10 Motor with stator insulation in good condition [4]

The effects the ageing factors have on the insulation materials and how they cause degradation is mentioned as follows:

3.1 Thermal ageing

Thermal stress is unarguably one of the most significant factors contributing to the ageing of insulation materials. There are two types of thermal ageing, one where there's varying temperatures and one where there's constant high temperatures. Repeated heating and cooling cycles during the operation of electric machines lead to expansion and contraction of the insulation materials causing delamination and microcracks while constant high temperatures can cause materials to degrade, lose strength or become more brittle. This is because high temperature accelerates chemical degradation processes like hydrolysis and oxidation which leads to cracking and embrittlement which can reduce the insulation resistance and the dielectric strength causing electrical degradation[18] [19].

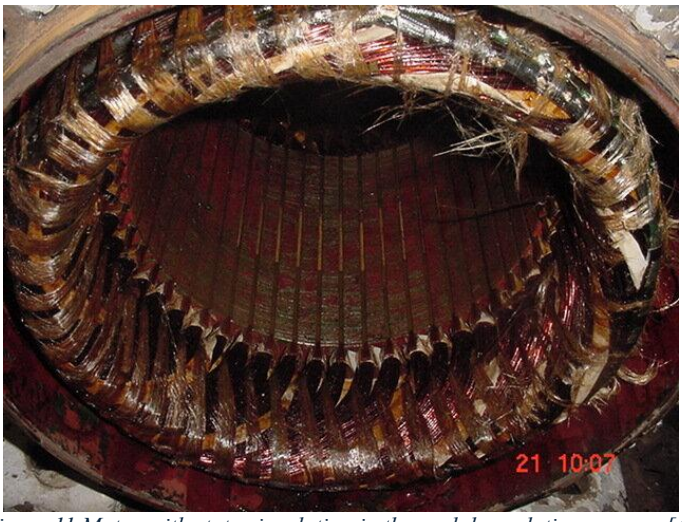

Figure 11 Motor with stator insulation in thermal degradation process [4].

3.2 Electric Ageing

As an electric machine continues operating, it is very common for it to be exposed to electric stress due to constant exposure to high voltages. High electric potential accelerates insulation ageing by triggering phenomenon such as partial discharge and electric treeing, which physically and chemically degrade the dielectric unit and the insulation material leading to a dielectric breakdown[20] [21].

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[18] 'Building Materials and High Temperature: Failure Isn't an Option', Advanced Architectural Products. Accessed: Aug. 14, 2025. [Online]. Available: https://greengirt.com/articles/building-materials-endurance-to-prolonged-high-temperature-exposure-failure-isnt-an-option/

[19] 'Thermal stress', *Wikipedia*. Oct. 24, 2024. Accessed: May 06, 2025. [Online]. Available: https://en.wikipedia.org/w/index.php?title=Thermal_stress&oldid=1253165344

[20] 'Insulation System and Aging Phenomenon'. Accessed: May 06, 2025. [Online]. Available: https://encyclopedia.pub/entry/35867

[21] 'Partial discharge', *Wikipedia*. June 27, 2025. Accessed: Aug. 14, 2025. [Online]. Available: https://en.wikipedia.org/w/index.php?title=Partial_discharge&oldid=1297626389

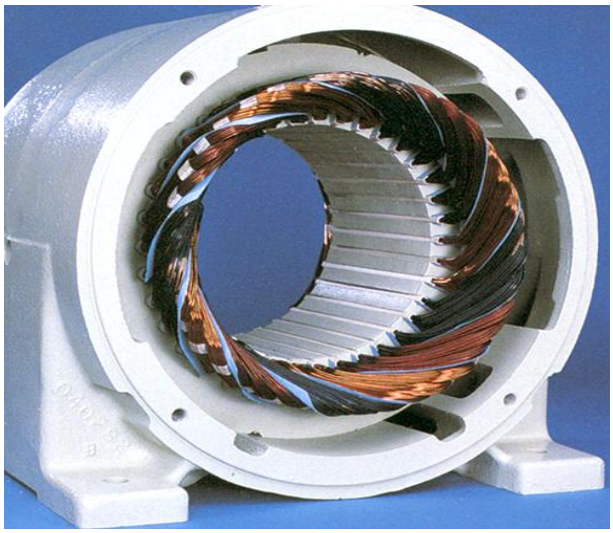

Figure 12 Insulation damage due to unequal voltage between phases[22]

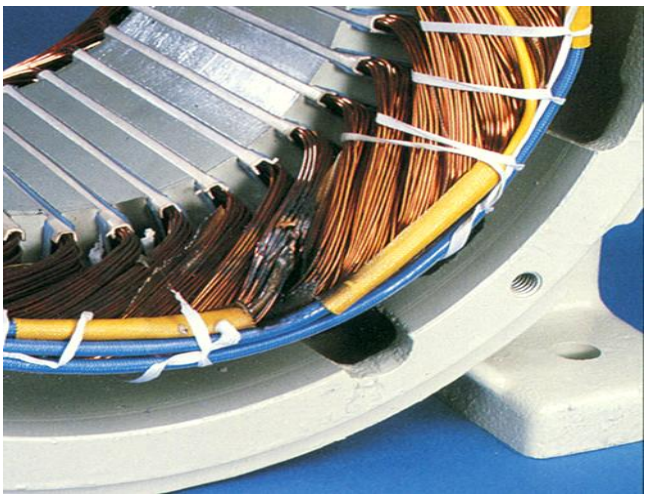

Figure 13 Winding failure due to voltage surge[23]

3.2.1 Dielectric Breakdown

A dielectric breakdown is when a dielectric medium starts conducting and a current flows through it due to being subjected to high voltage. All insulation materials undergo dielectric breakdown when an electric field caused by the voltage applied exceeds the material's

[22] ip-admin, '3-phase stator winding failure [With examples]', Duke Electric. Accessed: Aug. 14, 2025. [Online]. Available: https://www.dukeelectric.com/blog/3-phase-winding-failure-examples/

[23] ip-admin, '3-phase stator winding failure [With examples]', Duke Electric. Accessed: Aug. 14, 2025. [Online]. Available: https://www.dukeelectric.com/blog/3-phase-winding-failure-examples/

dielectric strength. This voltage at which the insulation material becomes conductive is termed as breakdown voltage[24].

Dielectric breakdown is often preceded by partial discharge. It is one of the main causes of insulation breakdown of high voltage motor stator windings. It is a localized dielectric breakdown of a small portion of a solid or liquid electrical insulation system under high electrical potential stress (High voltage stress). Partial discharge occurs in different insulation mediums such as solid, liquid or gas. It often begins with gas voids such as bubbles in the machine oil or voids in solid epoxy insulation which leads to the erosion of insulation leading to a breakdown[25] [26].

Partial discharge inception voltage (PDIV) is the lowest value of voltage at which partial discharge occurs. It is often measured for insulation health checks because it gives the exact measurement of the point where the partial discharge occurs, i.e. when the insulation degradation begins[27].

Repeated partial discharge activity can initiate electric treeing. Electric treeing in insulation materials is a degradation phenomenon due to partial discharge when tree like structures form and grow under high electric stress which gradually erode leading to a dielectric breakdown[28].

The aforementioned processes collectively reduce the insulation resistance, which provides an early indication of ageing before dielectric breakdown occurs. Insulation resistance is the ability of an insulation material to resist the flow of an electric current. Higher the insulation resistance, the better the insulation material performance as it prevents electricity from leaking out of the conductor into the motor housing or the environment which would be a safety hazard[29].

3.3 Mechanical ageing

Mechanical ageing is a kind of ageing that may occur from structural defects such as microcracks and microcavities [5] as well as continuous vibrations and friction in the electric vehicle since the electric motors are subjected to constant motion. Insulation material which

[24] 'Electrical breakdown', *Wikipedia*. June 18, 2025. Accessed: Aug. 14, 2025. [Online]. Available: https://en.wikipedia.org/w/index.php?title=Electrical_breakdown&oldid=1296245398

[25] 'Partial discharge', *Wikipedia*. June 27, 2025. Accessed: Aug. 14, 2025. [Online]. Available: https://en.wikipedia.org/w/index.php?title=Partial_discharge&oldid=1297626389

[26] ip-admin, '3-phase stator winding failure [With examples]', Duke Electric. Accessed: Aug. 14, 2025. [Online]. Available: https://www.dukeelectric.com/blog/3-phase-winding-failure-examples/

[27] 'PARTIAL DISCHARGE Understanding PD – Combined Cycle Journal'. Accessed: Aug. 07, 2025. [Online]. Available: https://www.ccj-online.com/4q-2014/partial-discharge-understanding-pd/

[28] 'Electrical treeing', *Wikipedia*. Mar. 11, 2025. Accessed: May 06, 2025. [Online]. Available: https://en.wikipedia.org/w/index.php?title=Electrical_treeing&oldid=1279941510

[29] A. McDonald, 'The Basics of Insulation Resistance Testing and Why It's So Important', Vitrek. Accessed: May 22, 2025. [Online]. Available: https://vitrek.com/the-basics-of-insulation-resistance-testing-and-why-its-so-important/

cannot withstand this motion and vibration break down due to frequently being exposed to these conditions. Insulation material cracking, delamination, loss of adhesive between layers and wear are some noticeable indications of damage due to mechanical ageing. Mechanical ageing can also be accelerated by thermal stress as heating and cooling insulation materials can make them expand and contract due to temperature variations.
Mechanical ageing of insulation materials is often assessed through vibration and durability tests under real world conditions[30].

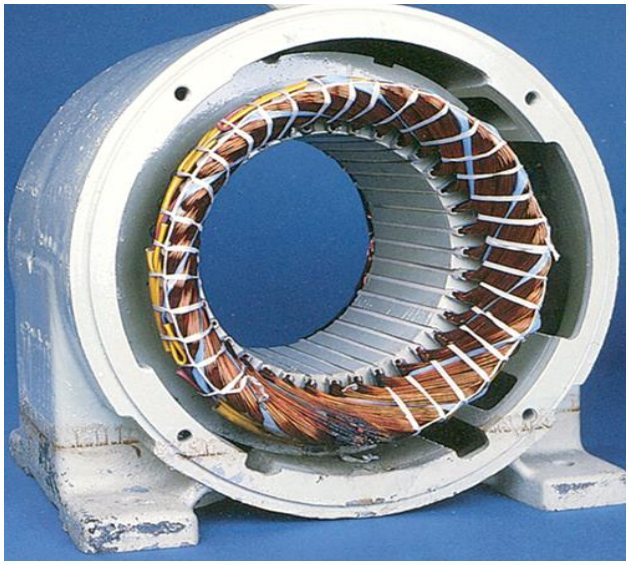

Figure 14 Winding with shorted connection; Insulation failure due to contaminants, abrasion, vibration or voltage surge[31]

3.4 Moisture ageing

Humidity, water ingress and condensation causes moisture related ageing. If insulation materials are exposed to moisture of any sorts, they end up absorbing it which leads to hydrolisys, material swelling, reduced insulation resistance, and risks of short circuits. Therefore, continuous exposure to humidity can be very damaging for the insulation materials as it leads to their breakdown. Moisture is a very common ageing factor due to the presence of relative humidity in the air which can lead to water content in the electric motors and lubrication systems to the point corrosion is almost unavoidable[32].

[30] 'Insulation System and Aging Phenomenon'. Accessed: Aug. 07, 2025. [Online]. Available: https://encyclopedia.pub/entry/35867

[31] ip-admin, '3-phase stator winding failure [With examples]', Duke Electric. Accessed: Aug. 14, 2025. [Online]. Available: https://www.dukeelectric.com/blog/3-phase-winding-failure-examples/

[32] 'Moisture ingress reduces insulation effectiveness | Armacell'. Accessed: Aug. 07, 2025. [Online]. Available: https://www.armacell.com/en-GB/moisture-ingress-reduces-insulation-effectiveness

Figure 15 Motor with stator insulation in moisture contamination process[4].

3.5 Chemical ageing

Apart from thermal, electric, mechanical and moisture ageing, chemical ageing also plays an integral role in the ageing of insulation materials. When the insulation materials come into contact with substances such as corrosive vapors, dirt, oil, salts, or other substances especially in industrial environments, there's a chemical reaction that causes the insulation material to break down, making it less effective at preventing the electric current from escaping. For example, oil or dirt on an insulation surface creates pathways for unwanted electrical current flow. This unwanted current is called leakage current. Prolonged exposure to these chemical reactions can cause permanent damage such as softening of insulation, embrittlement, and damage to the adhesive between layers[33].

Figure 16 Motor with stator insulation in contamination process by oil/dirt [4].

[33] 'Insulation Quality: The Five Key Causes of Insulation Degradation - Tech Library / Articles', TestGuy Electrical Testing Network. Accessed: Aug. 14, 2025. [Online]. Available: https://wiki.testguy.net/t/insulation-quality-the-five-key-causes-of-insulation-degradation/4405

4
Ageing Tests

4.1 Thermal stress test: Cyclic and Constant

Thermal stress test is a type of testing method that is used to verify the reliability and functionality of a test object over a particular temperature range, usually higher than the operational temperature range expected to be seen during real-world operations. It is applied during the design or production phase of most electrical components, in our case to test the durability of insulation materials since reliability is important[34].

Thermal stress tests come in two different variants, Thermal Cyclic and Thermal Constant.

- Thermal Cyclic: In this type of insulation test, the temperature is cycled between a predetermined temperature range, for example between negative and positive temperatures with a big temperature difference between them. The cycles are repeated for a certain period of time which gives a good idea of one of the real-world conditions when there's varying temperatures in the components due to the operation of the electric vehicle[35].
- Thermal Constant: As the name suggests, this is a test that is designed to have a constant high temperature which is slightly more severe than the real-world operation in order to assess whether the test object can handle being heated up to a certain degree of temperature[36].

[34] admin, 'Thermal Stress Testing', Total Temp Technologies. Accessed: Aug. 22, 2025. [Online]. Available: https://www.totaltemptech.com/thermal-stress-testing-2/

[35] admin, 'Thermal Stress Testing', Total Temp Technologies. Accessed: Aug. 22, 2025. [Online]. Available: https://www.totaltemptech.com/thermal-stress-testing-2/

[36] admin, 'Thermal Stress Testing', Total Temp Technologies. Accessed: Aug. 22, 2025. [Online]. Available: https://www.totaltemptech.com/thermal-stress-testing-2/

Figure 17: Thermal cycling testing set up[37]

Normally, insulation material degradation at normal operating temperatures takes a very long time to take place. The rate of ageing could be several months or years. Therefore, to make thermal stress tests quicker and more efficient in order to study the effects of thermal ageing, an accelerated ageing method is used which ages the material in less time as compared to the normal ageing pace. This technique follows the Arrhenius law.

- ## Arrhenius Law

The Arrhenius law equation states that an increase in temperature significantly speeds up the insulation degradation process. It is very useful when you want to artificially age your material in a shorter period, and it is a principle that will be applied in the project to shorten the length of cycles to get ageing results quicker[38][1].

Arrhenius law equation:

$$k = Ae^{\frac{-Ea}{RT}}$$

k = Rate constant
A = Pre-exponential factor
Ea = Activation energy (in the same units as **R*T**)
R = Universal gas constant
T = Absolute temperature (in Kelvin)[39] [1]

[37] gd-admin, 'News - Thermal cycle test of hub motor', https://www.robotmotor.com/. Accessed: Aug. 29, 2025. [Online]. Available: https://www.robotmotor.com/news/thermal-cycle-test-of-hub-motor/

[38] 'Arrhenius equation', *Wikipedia*. Apr. 10, 2025. Accessed: May 06, 2025. [Online]. Available: https://en.wikipedia.org/w/index.php?title=Arrhenius_equation&oldid=1284878921

[39] 'Arrhenius equation', *Wikipedia*. Apr. 10, 2025. Accessed: May 06, 2025. [Online]. Available: https://en.wikipedia.org/w/index.php?title=Arrhenius_equation&oldid=1284878921

4.2 Temperature humidity stress test

Temperature and humidity testing is useful for evaluating the performance of electronic, plastic and metal products in environments with humidity. High temperature and humidity are commonly identified as the primary cause of product failures because if insulation materials are exposed to moisture for too long the insulation can absorb the moisture and this leads to hydrolysis, corrosion, material swelling, reduced insulation resistance, the wear of moving parts and a risk of short circuits.

During this test, test object samples are subjected to temperature-humidity stress for periods of time, up to 10 to 95% relative humidity. For test durations as long as 1000 hours, it is common to remove the samples for electric health inspection[40].

Figure 18: Vötsch climate chamber[41]

4.3 Voltage endurance test

High voltage (HV) stress contributes to the occurrence of ageing of the stator winding insulation which eventually leads to insulation failures. Therefore, voltage endurance testing serves as a benchmark for assessing insulation quality by applying a much higher normal operating phase to ground voltage (3.76 times higher) to the coils within a short period of

[40] 'Temperature Humidity Testing', Oneida Research Services, Inc. Accessed: Sept. 05, 2025. [Online]. Available: https://orslabs.com/services/environmental-testing/temperature-humidity-testing/

[41] 'Temperature Humidity Testing', Oneida Research Services, Inc. Accessed: Sept. 05, 2025. [Online]. Available: https://orslabs.com/services/environmental-testing/temperature-humidity-testing/

time in order to accelerate insulation ageing which occurs during the operation of the electric motor[42].

Figure 19: Voltage endurance testing set up[43]

In conjunction with a voltage endurance test, the following diagnostic tests may be performed to assess the condition and quality of the insulation system[44]:

- Partial discharge.
- Insulation resistance and polarization index.
- Power factor.
- Insulation breakdown.
- Dissection and microscopic examination[45].

4.4 Vibration stress test

Vibration testing is a diagnostic test approach that is used to measure and analyze oscillations in different planes in motor components in order to detect hidden electrical and mechanical faults before they cause component failures. Devices such as a motor vibration tester or a vibration meter are used[46].

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[42] H. Zhu, 'Voltage Endurance Tests on Stator Coils and Bars', Doble Engineering Company. Accessed: Aug. 29, 2025. [Online]. Available: https://www.doble.com/voltage-endurance-tests-stator-coils-bars/

[43] 'Experimental methods in chemical engineering: Karl Fischer titration - Rivera-Quintero - 2024 - The Canadian Journal of Chemical Engineering - Wiley Online Library'. Accessed: May 06, 2025. [Online]. Available:

[44] H. Zhu, 'Voltage Endurance Tests on Stator Coils and Bars', Doble Engineering Company. Accessed: Aug. 29, 2025. [Online]. Available: https://www.doble.com/voltage-endurance-tests-stator-coils-bars/

[45] H. Zhu, 'Voltage Endurance Tests on Stator Coils and Bars', Doble Engineering Company. Accessed: Aug. 29, 2025. [Online]. Available: https://www.doble.com/voltage-endurance-tests-stator-coils-bars/

[46] 'Vibration Test In Electric Motors | Motor Vibration Analysis'. Accessed: Aug. 29, 2025. [Online]. Available: https://mme-ae.com/vibration-test-in-electic-motors/

Mechanical stress (Vibrations) is a common factor that a motor may undergo under operating conditions. Some of the sources that lead to abnormal vibrations are:

- Rotor imbalance: Uneven mass distribution in the rotor that causes imbalance.
- Shaft misalignment: Improper alignment between the motor and driven equipment.
- Electrical issues: Loose windings in the motor or magnetic imbalances.
- Bearing faults: Worn out or damaged bearings can generate abnormal vibrations[47].

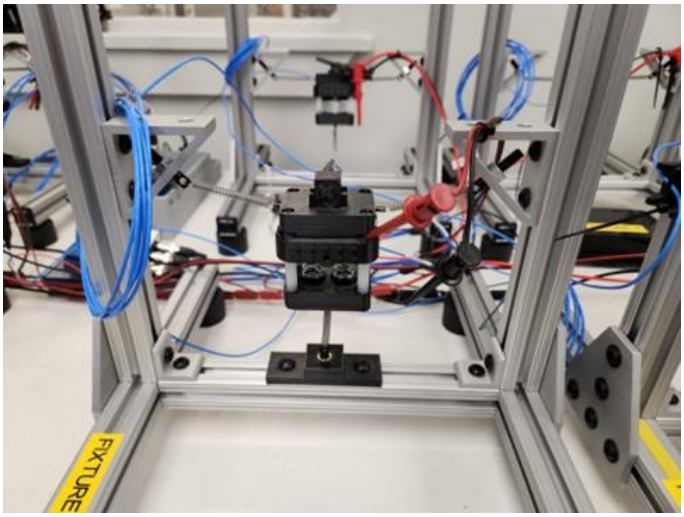

Figure 20: Test apparatus suspended by springs[48]

[47] 'Vibration Test In Electric Motors | Motor Vibration Analysis'. Accessed: Aug. 29, 2025. [Online]. Available: https://mme-ae.com/vibration-test-in-electic-motors/

[48] 'Refining a Haptic Motor Vibration Test with ObserVIEW Analysis', Vibration Research. Accessed: Sept. 05, 2025. [Online]. Available: https://vibrationresearch.com/resources/refining-haptic-motor-vibration-test-obserview-analysis/

Project

5
Design of Test Method

5.1 Test Overview

Considering the ageing factors that influence the performance of insulation materials as well as the different types ageing tests used to assess their effects, this study focuses on moisture and temperature cycling as the primary focus for designing the test method due to the practicality of carrying it out using the available test equipment and materials.

Given below is an overview of the general procedure of the humidity and temperature cycling test that has been designed along with its specifications and the reasoning behind why particular values have been selected.

5.1.1 Methodology

This section describes the experimental approach used to investigate the effect of humidity and thermal cyclic conditions on an electric machine. As the name of the test suggests, a test object is exposed to high relative humidity under varying temperature conditions.

The test object will be subjected to heating up to a predetermined temperature and subsequently cooled. This process of heating and cooling will be repeated per cycle to simulate condensation in the presence of relative humidity since moisture is a known contaminant and can damage the insulation if not kept in check [6].

The effect of high relative humidity on the electric motor also depends on the dew point temperature, which is when the temperature of the water vapor contained in the air is condensed into moisture [7]. If the machine is operating above the dew point temperature, humidity doesn't affect the insulation. Similarly, if the motor temperature during operation drops below the dew point temperature, water vapor condenses into moisture, and it tends to stick to the components as well as dissolve in the oil [7]. Therefore, it is reasonable to infer that simulating constant exposure to high relative humidity and varying temperatures will increase the water content in the oil that is used to lubricate and cool the electric machine as well as potentially degrade the insulation materials of the stator windings.

This is an attempt to replicate the worst-case scenario for this condition in the real world. We will further investigate the rate at which the water level rises. The amount of water content in the oil will be measured by collecting oil samples from the oil sump after a certain number of cycles. The method that will be used for this process is the Karl Fischer titration method.

- **Karl Fischer titration:**
  Karl Fischer titration method is classic titration method used in both volumetric and coulometric titrations. It is used to estimate the amount of water in a given sample. In this method, the water is titrated in the presence of an organic base and sulfur oxide.

$H_2O + I_2 + SO_2 + CH_3OH + 3\ RN \rightarrow [RNH]SO_4CH_3 + 2\ [RNH]I$ [49]
The acids Hl and H_2SO_4 which are formed during titration reaction are neutralized with the help of pyridine.

Karl Fischer titration method involves dissolving a liquid or solid sample into a water free solvent like methanol. The Karl Fischer titrant, which contains iodine, after being added by a burette reacts with water in the sample and is consumed by it. Once all water has reacted with iodine, free iodine remains in the solution which is then detected electrochemically using platinum electrodes for volumetric indication[50].
In this project, the Karl Fischer titration will be done with an automated titrator.

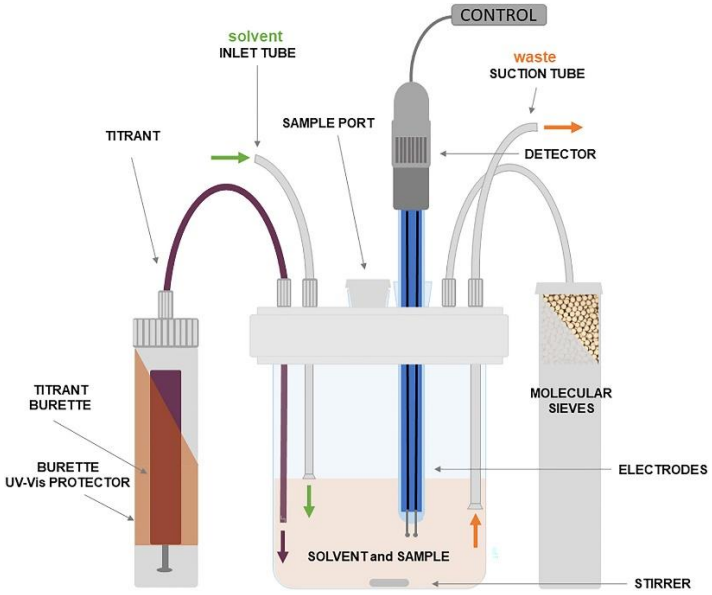

Figure 21 : Titration cell of a standard volumetric Karl Fischer (KF) automatic titrator[51]

Various other electrical measurements will also be conducted during oil sampling in order to assess the insulation material's health, for example partial discharge inception voltage, insulation resistance, and overvoltage apart from the visible physical degradation checkups.

[49] M.-T. I. I. all rights reserved, 'What Is Karl Fischer Titration?' Accessed: May 06, 2025. [Online]. Available: https://www.mt.com/sg/en/home/applications/Application_Browse_Laboratory_Analytics/Application_fam_browse_main/kf-titration-principle.html

[50] M.-T. I. I. all rights reserved, 'What Is Karl Fischer Titration?' Accessed: May 06, 2025. [Online]. Available: https://www.mt.com/sg/en/home/applications/Application_Browse_Laboratory_Analytics/Application_fam_browse_main/kf-titration-principle.html

[51] 'Experimental methods in chemical engineering: Karl Fischer titration - Rivera-Quintero - 2024 - The Canadian Journal of Chemical Engineering - Wiley Online Library'. Accessed: May 06, 2025. [Online]. Available: https://onlinelibrary.wiley.com/doi/full/10.1002/cjce.25295

5.2 Test Object

The test object is a permanent magnet synchronous motor with a stator with hairpin windings and an oil cooled system. It is a fully functioning motor with minor ageing due to a thermal ageing test, but the electrical functionality is up to par with an unaged motor.

Parts such as rotor, inverter, and transmission have been removed in order to comply with the rig test object weight limitations and for the focus to be on the stator winding insulation.
The motor also contains 6 temperature sensors to get precise measurements of the temperature conditions of the end windings, inside of the motor and the middle of the stator respectively.
Other components present in the electric machine include a breather (a device that allows air to flow in and out of a closed system) which allows flow of relative humidity into the cavity of the motor, and a cooling circuit which consists of a heat exchanger, an oil pump, sump and oil channels to circulate oil through the machine.

5.3 Test set-up

The testing rig for the humidity and thermal cyclic test is a climate chamber that can reach up to varying levels of negative and positive temperatures.
The set up will have different values of temperatures for different parts and purposes as shown in the diagram below.
T1 represents the ambient air temperature, which is the temperature of the climate chamber, and it will be constant but small amounts of variations may be observed.
T2 represents the varying temperature values different components of the electric machine will be exposed to, for example the end windings, middle of the stator, oil, all have different temperature limitations going above which would be damaging to them individually.
T3 represents the air connected to the breather, the value of which varies between a certain range of temperature.

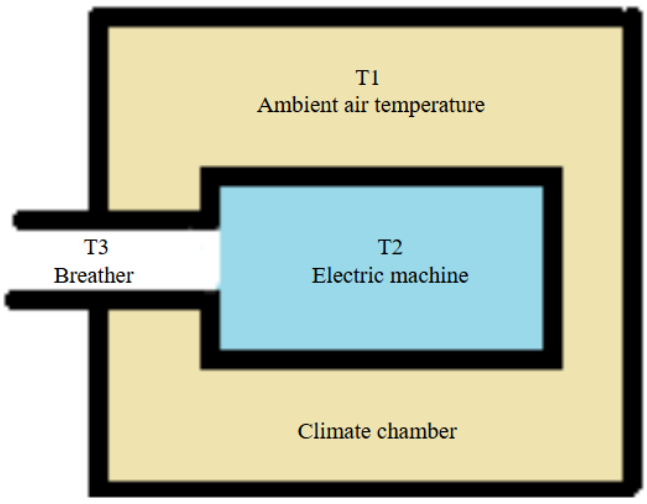

Figure 22 Temperature strategy of the test set up

The brain of the test is a programmed PLC (Programmable logic controller) that has been set up to perform different tasks required during the operation of the test.
The PLC operates and makes decisions based on the outputs it gets from the mid stator temperature sensor connected to a temperature measurement system to provide ON and OFF control signals to start or stop the operation of the following components that are a part of different processes in one cycle:

- The oil pump, the PLC turns it ON and OFF at a certain temperature. This in turn controls the flow of oil in the test object making the cooling process faster. The cooling circuit also consists of a heat exchanger to help with fast cooling since cooling takes longer time than heating.
- The PLC turns ON and OFF the main power supply that provides 450 A current and DC power to test object during the heating stage for a faster heating process and turns it off during the cooling stage.
- The PLC also controls the magnet valves which turn ON the humidifier which is connected to the breather of the electric machine through which the test object is exposed to relative humidity.

These control signals have been programmed into the PLC for one cycle which will be repeated throughout the test for other cycles.
Given below is a visual representation of the system layout and control flow chart which would give a better understanding of the set up and how the PLC operates during each cycle:

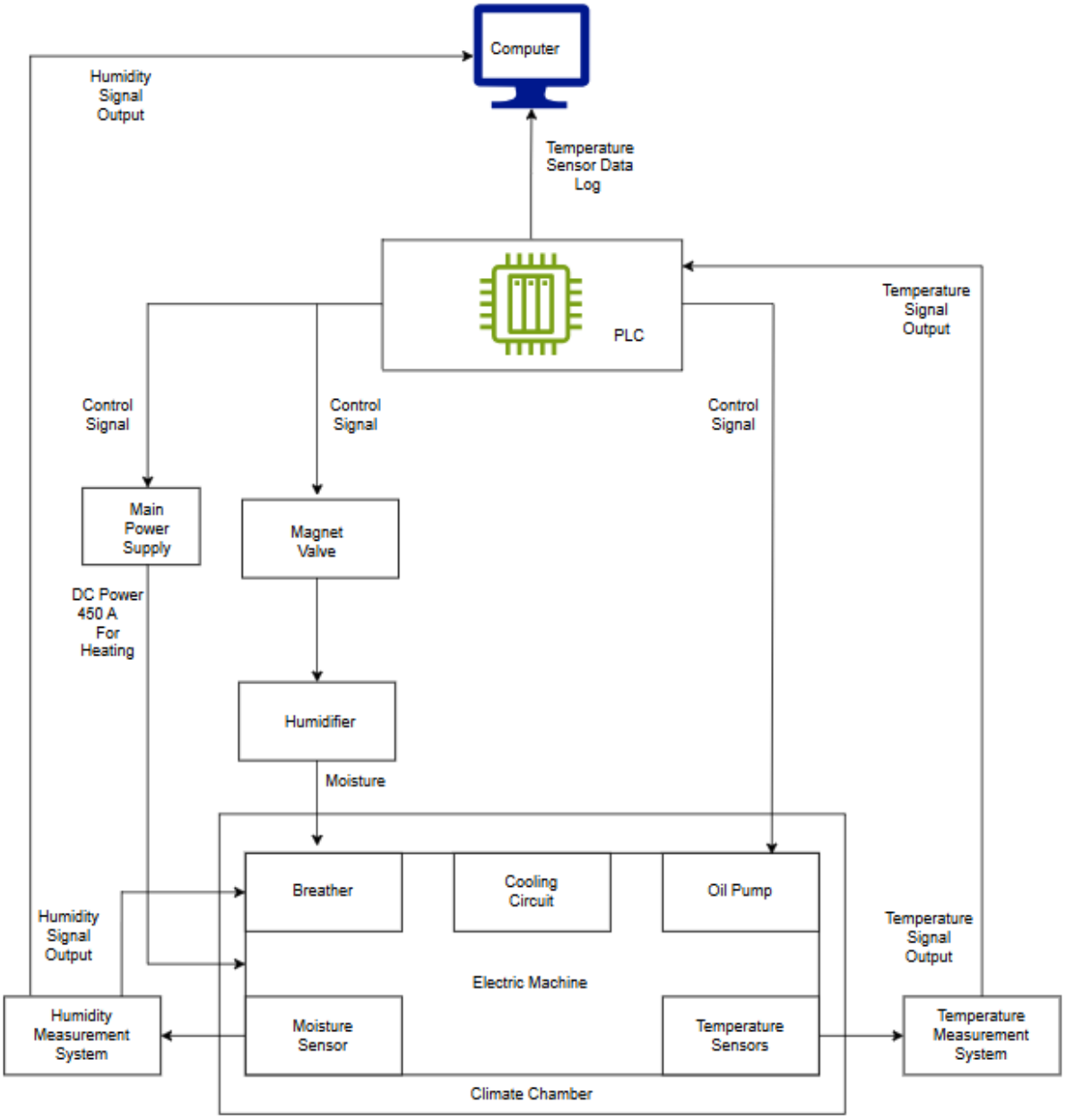

Figure 23: System Layout Flow Diagram

External DC power supplies have also been utilised for powering multiple components such as the oil pump, magnet valve, PLC and temperature probes besides the main power supply which is used for speeding up the heating process.
The power requirement for each apparatus is outlined below:

- 4.5V for the remote function of the main power supply.
- 12.4V supplied to the oil pump.
- 24V supplied to the magnet valve connected to the humidifier.
- 12.4V for the PLC.
- 22.1V for the Analog temperature measurement system.

5.4 Oil Sampling Strategy

The electric machine will be filled with roughly 3.5 L of oil at the beginning of the test. Roughly 5 to 10 ml of oil samples will be collected after a certain number of cycles for them to undergo Karl Fischer titration method in order to estimate the amount of water in the oil. It is important to note that there is no fixed permitter on what the reasonable content of water in the oil would be that would cause damage to the insulation; However, the goal is to simulate a scenario which exposes the electric machine to high relative humidity which is a way to incorporate water in the oil by having varying temperature cycles as a combinational stressor [7].

5.5 Development of the test method

As we know, the main goal of the project is to expose the test object to condensation under varying temperatures through a series of repeating cycles.

In this case, the air inside the motor (breather temperature) will be exposed to low temperatures, then heated to a maximum temperature of 50°C. It is important to note that the air holds higher amount of water vapour at higher temperatures so ideally, a temperature higher than 50°C would ramp up the ageing test by a lot but it is the highest motor air temperature attainable in the current testing set up limitations without causing damage to other components due to them having a specific set of limitations as well [8].

The end windings are being used as a heating source to increase the breather air temperature during the heating phase in this case. The heating phase will then be followed by the cooling phase where the breather temperature goes from 50°C to -10°C. The chamber temperature and the oil are used as a cooling source in order to decrease the breather air temperature during the cooling phase. The test object throughout the heating and the cooling phase will be exposed to high relative humidity in order to induce condensation inside the motor cavity.

As mentioned before, certain components like the middle of the stator and the end windings have temperature limitations, going above which could damage them therefore it is necessary to make sure that the components are not stressed above their maximum temperature handling capacity.

Table 1: Maximum temperature components can handle individually

Mid stator temperature limit	180°C
End winding temperature limit	150°C

The following sections will be about the conduction of multiple experimental test cycles which helped determine the concrete nature and specifications of the test before the start of the real test cycles.

5.5.1 Iteration 1:

The goal of the first experimental cycle was to determine the cycle duration during selected temperature values informed by prior testing knowledge. A lot of these temperature values as previously mentioned such as that of the end windings, middle of the stator and air in the motor have practical limitations had to also be considered to avoid component breakdown.

The temperature of the air inside the motor was heavily dependent on the temperature of the middle of the stator and the end windings. Therefore, this iteration is an attempt to play around with the temperature values of these variables in order to get a reasonably high motor air temperature.

As we know, the PLC had been programmed to operate based on the temperature sensor output from the middle of the stator. During the initial attempt, the lowest mid stator temperature was set to -10°C and it steadily rose to 120°C while the chamber air temperature remained stable between -30°C and -25°C.

It took 10 minutes to heat up to the highest mid stator temperature, and the following were the highest temperature values observed during this cycle:

Table 2: Lowest and Highest Temperature Values Recorded at Different Measurement Points in iteration 1

	Lowest Temperature Value	Highest Temperature Value
Mid stator	-5°C	120°C
End windings	-3°C	103°C
Breather air	-10°C	3.9°C
Chamber	-31°C	-31°C

A full cooling cycle wasn't run because the estimated time for cooling to -10°C was approximately 3 hours so it was more beneficial to switch to the next iteration to save time.

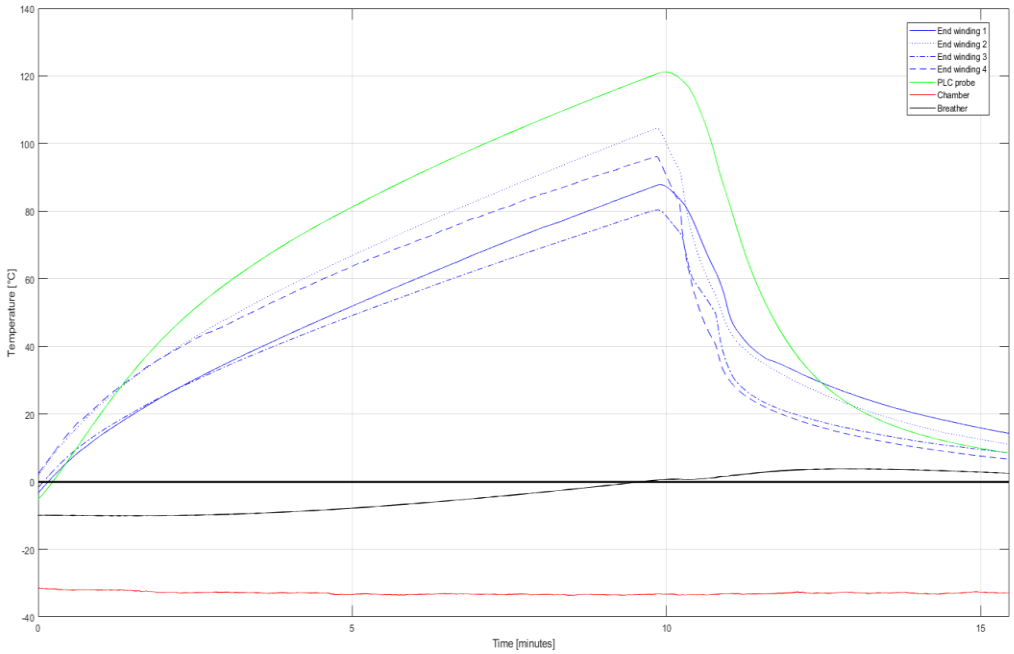

Figure 24: A graphical representation of iteration 1

Conclusion of iteration:

- The temperature of the air inside the motor (breather temp) observed was 3.9°C at it's highest which is significantly lower than the target of the breather temperature set which is 50°C. A temperature of 3.9°C is insufficient to guarantee the appropriate conditions for condensation therefore it needs to be increased.
- The cooling time was too long, approximately over 3 hours, this would mean we'd have to run fewer cycles for a longer time.
- The oil pump malfunctioned thereby increasing the cooldown time.

5.5.2 Iteration 2:

Following the first experimental cycle, the goal of the next experiment was to try and reduce the cooldown period because it would've consumed a large amount of time in the project. A solution to this was changing the chamber air temperature. Another goal was to increase the temperature of the air inside the motor which would be achieved by tweaking the mid stator temperature.

Therefore, the chamber air temperature was increased to 0°C. This helped reduce unrealistic heat losses caused by negative chamber air temperatures. The heating phase duration was increased by a minute and as a consequence we had to allow the mid stator temperature to go slightly above 120°C. So the range of the mid stator temperature was adjusted from 0°C to 123°C in the PLC program with the aim of increasing the temperature of the motor air above 3.9°C.

During the first cycle of this attempt, the following temperature values were observed:

Table 3: Lowest and Highest Temperature Values Recorded at Different Measurement Points in iteration 2

	Lowest Temperature Value	Highest Temperature Value
Mid stator	0°C	123°C
End windings	0°C	113°C
Breather air	0°C	30°C
Chamber	0°C	0°C

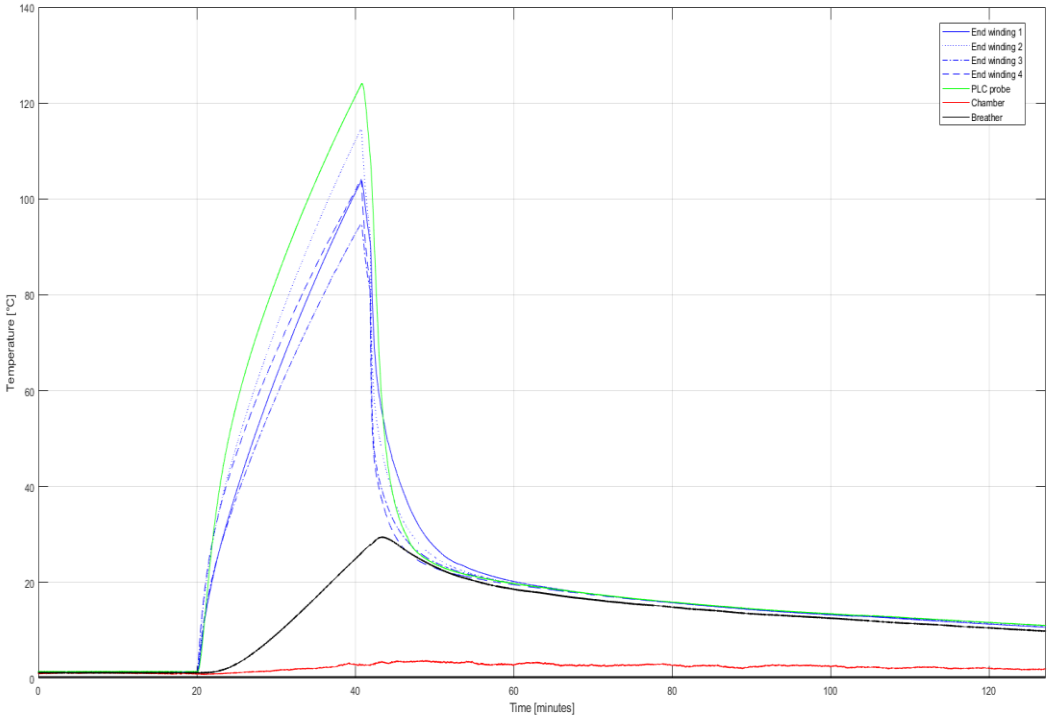

Figure 25: A graphical representation of iteration 2

Conclusion of the iteration:

- The initial idea was to let the mid stator temperature to reach 120°C and maintain the temperature for a few minutes to allow the motor air temperature to catch up. However, due to the rig limitations, it was not possible to maintain a holding period, as a result we had to increase the heating phase duration in order to increase the motor air temperature.
- The breather air temperature increased from 9.6°C to 30°C however, it was still not close to the target temperature value of 50°C therefore, the cooling phase was never completed.

5.5.3 Iteration 3:

After more series of experimental cycles, it was established that the breather air temperature needed to be further increased. This entails adjusting the chamber air and the mid stator temperature again.

During the experiments, it was observed that the end windings approached their temperature limit quicker as compared to the mid stator. This is due to the fact that the temperature of the end windings is consistently lower than that of the mid stator. Therefore, the mid stator temperature should be increased only to the point where the end windings approach their temperature limit which is 150°C.

The chamber air temperature was set to 10°C. This meant increasing the starting temperature of the cycle from 10°C to 15°C because it is necessary to have at least 5°C difference between the chamber air temperature and the component temperature in order to ensure the cooling process doesn't take longer.

There was another speculation that the timing of the activation of the oil pump plays a role in how high the motor air temperature gets. Therefore, to obtain a definitive conclusion regarding this hypothesis, two different cases of tests were conducted with the changes to the chamber air and mid stator range applied:

- **Case1:** The oil pump wasn't turned on during the cooling phase. This significantly slowed down the cooling process to about 2 hours. The mid stator temperature rose from 15°C to 154°C followed by an increase in the end windings and the motor air temperatures. Oil pump being turned off lead to a slight increase in the temperature of the motor air which appeared to be about 46.2°C now.

Table 4: Lowest and Highest Temperature Values Recorded at Different Measurement Points in iteration 3, case 1

	Lowest Temperature Value	Highest Temperature Value
Mid stator	15°C	154°C
End windings	15°C	142°C
Breather air	15°C	46.2°C
Chamber air	6°C	9°C

Table 5: Duration of Heating, Cooling, and Total Cycle Length for iteration 3, case 1

	Duration
Heating phase	≈ 15 minutes
Cooling phase	≈ 1 hour 50 minutes
Total cycle length	≈ 2 hours 5 minutes

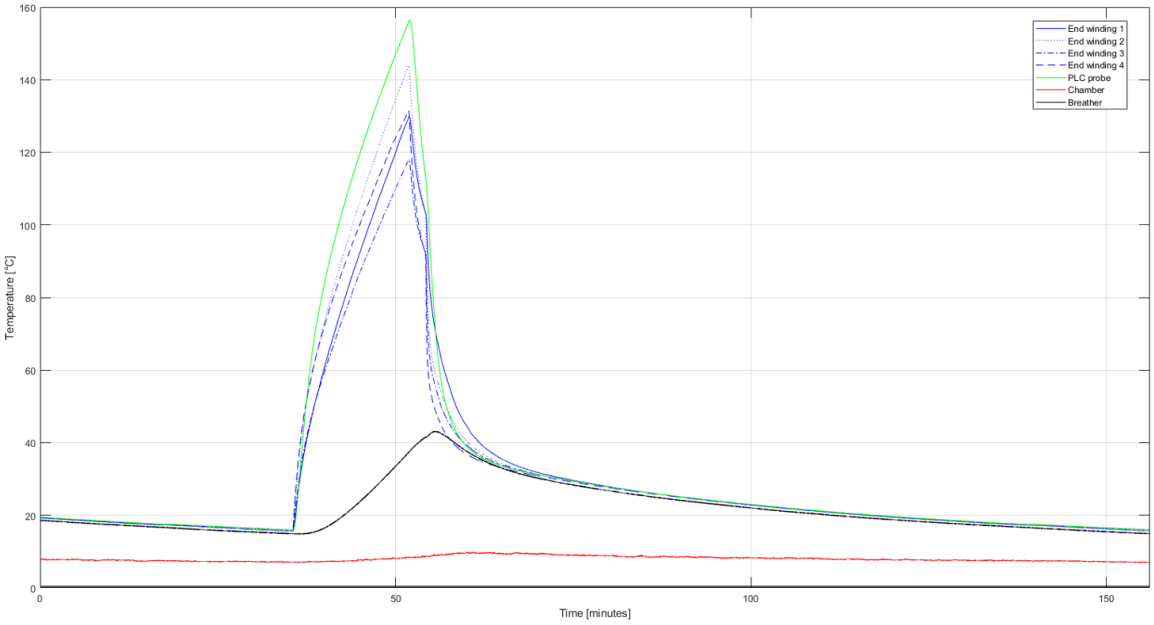

Figure 26: A graphical representation of the cycle with the oil pump turned off

Case 2: The oil pump was turned on at 130°C which was a value chosen based on previous testing experiences. The mid stator temperature then heated up from 15°C to 166°C. It was necessary to not go beyond this temperature because the end windings had reached their maximum temperature capacity. This lead to a 15 minutes heating phase and 1 hour 35 minutes cooling phase. The cooling phase was observed to be shorter as compared to the previous case because of the oil pump being turned on. The reasoning behind the oil pump turning on at 130°C was that it would give the motor air enough time to increase it's temperature as the mid stator temperature went from 166°C to 130°C, factors such as increased cooling time and evaporation of the moisture was also considered when coming to this decision in case we decided to turn on the oil pump to cool the machine any later than 130°C.

Table 6: Lowest and Highest Temperature Values Recorded at Different Measurement Points in iteration 3, case 2

	Lowest Temperature Value	Highest Temperature Value
Mid stator	15°C	166°C
End windings	15°C	151°C
Breather air	15°C	45°C
Chamber air	6°C	9°C

Table 7: Duration of Heating, Cooling, and Total Cycle Length for iteration 3, case 2

	Duration
Heating phase	≈ 15 minutes
Cooling phase	≈ 1 hour 35 minutes
Total cycle length	≈ 1 hour 50 minutes

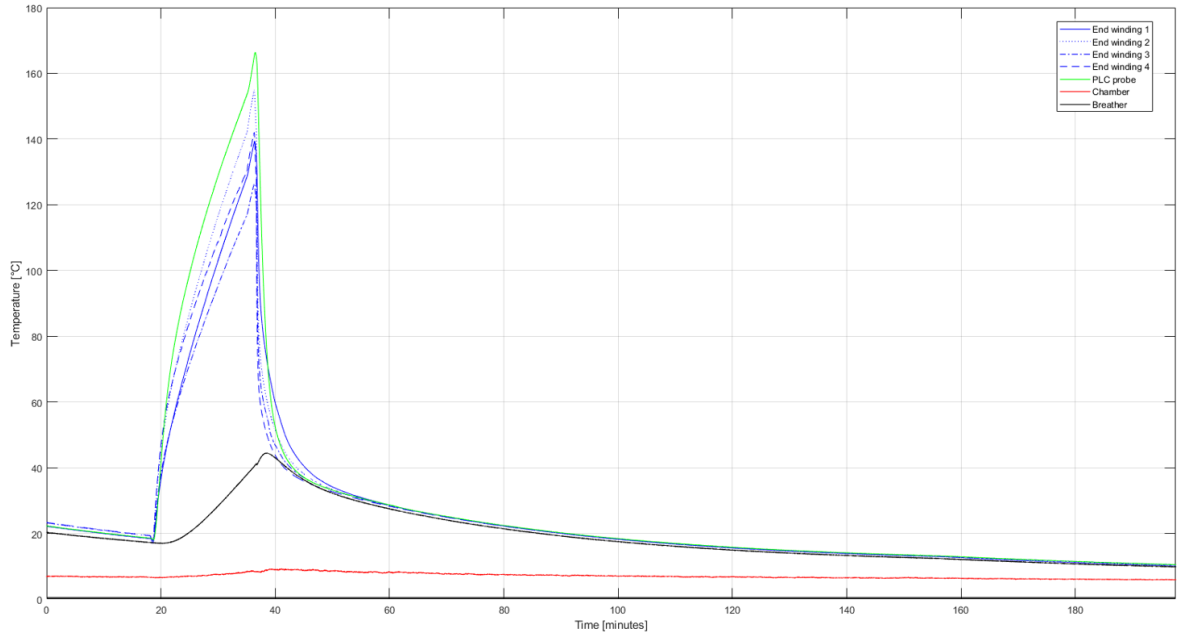

Figure 27: A graphical representation of the cycle with the oil pump turned on at 130°C

Conclusion of iteration:

- After observing both the cases, it was concluded that while turning the oil pump off did increase the motor air temperature by a couple of degrees, the deviation introduced negligible impact on the results and had a higher cooldown period.
- The breather temperature observed in both cases was a bit under the target temperature of 50°C, however it wasn't possible to achieve a higher temperature in this case without damaging other components due to test set up limitations since the end windings reached their maximum temperature limit.

5.5.4 Finalised iteration:

The objective was to identify the specifications that would bring the breather air temperature closest to the target value of 50°C, which represents the maximum permissible motor air temperature within the rig's operational limitation, multiple experimental test cycles were completed which introduced a number of changes, commencing with an increase in the chamber air then adjusting the start point temperature value, increasing the maximum temperature limit and turning on and off the oil pump settings. Iteration 3, case 2 was then finalized since the breather air temperature achieved in iteration 3, case 2 was the closest to 50°C in comparison to the other iterations. This would enable a reasonable simulation of condensation conditions which would allow the observation of the rate at which the water content increases in the oil of the electric machine.

Therefore, the final cycle parameters look like this:

- The mid stator temperature range: 15°C to 163°C, chamber air temperature: 6°C to 9°C.
- Oil pump turns on at 130°C.
- Heating from 15°C to 166°C takes 11 mins and cooling from 166°C to 15°C takes 1h 39 mins.
- Total cycle length is 1 hour 50 minutes.

Table 8: Finalized iteration, Lowest and Highest Temperature Values Recorded at Different Measurement Points

	Lowest Temperature Value	Highest Temperature Value
Mid stator	15°C	166°C
End windings	15°C	151°C
Breather air	15°C	45°C
Chamber air	6°C	9°C

Table 9: Finalized iteration duration of Heating, Cooling, and Total Cycle Length

	Duration
Heating phase	≈ 15 minutes
Cooling phase	≈ 1 hour 35 minutes
Total cycle length	≈ 1 hour 50 minutes

Following are the highest values observed on different parts of the electric machine, keeping in mind the mid stator range and chamber air temperature:

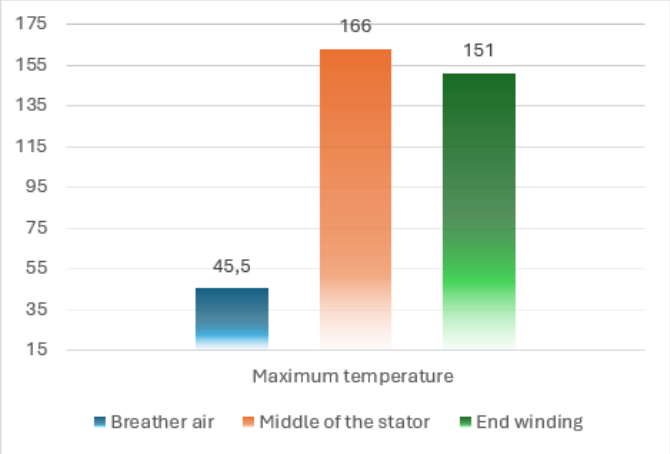

Figure 28: Highest temperature values the components reach

Given below is a table with data showing the duration of one cycle, and the total number of cycles executed over the course of the test:

Table 10: Finalized cycle duration data

Length of a cycle	≈ 1h 50m
Number of cycles in a day	≈ 20
Number of cycles in a week	≈ 70 full cycles
Number of cycles in 4 weeks	≈ 280 full cycles
Total number of cycles performed during the whole test	784 cycles

6
Results and Discussion

It is important to know that the test could not be performed as intended because a hose surrounding the cable connecting the breather to the humidifier melted into the cable, damaging it in a way that made it so the humidity couldn't be transported to the insides of the motor, therefore only the Karl Fischer result of the first oil sample measurement can be considered and the findings demonstrated an increase in water content of the oil but due to the technical error mentioned above, it is difficult to tell how much water accumulates in the oil over time.The experience provides guidance for future experiments, ensuring that such errors are avoided in similar configurations.

Figure 29: The cable defect is attributable to the melting of a hose into it.

6.1 Oil Sampling Result and Observation:

In order to assess the increase in water content of the oil, a fresh oil sample that hadn't been aged was tested for its water content using the Karl Fisher titration apparatus. The result observed was that a fresh oil sample contains approximately 109 ppm of water by default.

Table 11: Karl Fisher titration result of a fresh and unaged oil sample.

Oil sample type	Water content in oil (ppm)
Fresh and unaged	109

Following this, oil samples were collected on a weekly basis to assess the temporal increase in the water content of the oil. The results are as follows:

Table 12: Oil sampling conditions and results

Date and time of sample collection	Chamber temperature	Water content in oil (ppm)	Cycle count at oil sampling	Observations
4 June 2025	20C	186	-	Sample collected after experimental test cycles. An increase in the water content observed.
11 June 2025	23C	155	68	Water content was reduced slightly. Black residue observed in the oil.
18 June 2025	29C	170	155	Water content was increased slightly. Black residue and particles observed in the oil.
26 June 2025	16C	178	253	Black residue observed in the oil.
4 July 2025	20C	133	787	Black residue observed in the oil.

As observed, there is an increase in the water content of the oil in the first sample, but it could not be calculated for the samples that followed.

While sampling oil, another observation was made; black residue and particles were seen in the oil while collecting the samples. An FTIR spectroscopy (Fourier transform infrared spectroscopy) was carried out for the particles, and they turned out to be polyamide particles. It is reasonable to assume that the presence of these residual particles is due to the melting of the adhesive used on the temperature sensors at elevated temperatures, which then appears in the oil during sampling as the glue is made up of polyamide.

Figure 30: Black residue observed

6.2 Electrical Health Checks

A series of electrical diagnostic assessments were performed in order to evaluate the presence of electrical deterioration in the insulation system.

Insulation resistance test and HiPot AC tests were performed once every week in between the cycles in order to assess the rate of deterioration if any.

- The insulation resistance test involved feeding the insulation system with 1kV DC voltage for over 40 seconds and examining the change in the resistance if any.
- In the HiPot AC test, a voltage of approximately 2.75 kV is applied to the insulation system in order to check if it can withstand it without breakdown. A leakage current output is then measured, if it is within the limit then the test is a PASS and there's no deterioration otherwise the test is a FAIL.

Table 13: Insulation resistance and high potential AC test results

Date and time of health check	Insulation Resistance (1kV DC for 40 s)	HiPot AC 2.75kV AC)
5 June 2025	PASS	PASS
11 June 2025	PASS	PASS
19 June 2025	PASS	PASS
26 June 2025	PASS	PASS
4 July 2025	PASS	PASS
25 August 2025	PASS	PASS

As observed, the insulation resistance and high potential test results conclude satisfactory insulation performance, confirming that the insulation is in a good condition. No signs of electrical level insulation degradation has been detected throughout the operation of the 787 observed cycles and the experimental test phases. Additional electrical health checks were performed after the completion of the test cycles in order to assess the health of the insulation system. Given below is a table of comparison between the results of the electric health check performed before and after the humidity and thermal cyclic test was performed.

Table 14: Electric health check comparison

Sr. no.	Test type	Before humidity and thermal cyclic	After humidity and thermal cyclic
1.	Winding Resistance	PASS	PASS, No deterioration
2.	Insulation Resistance	PASS	PASS, No deterioration
3.	AC HiPOT	PASS	PASS, No deterioration
4.	PD Surge	PASS	PASS, No deterioration
5.	PD HiPOT	PASS	PASS, No deterioration

Table 15: Electric health check comparison, PD Phase to Phase

Phases	Before test		After test	
	PDIV (V)	RPDIV (V)	PDIV (V)	RPDIV (V)
U-V	PASS	PASS	PASS, No deterioration	PASS, No deterioration
V-W	PASS	PASS	PASS, No deterioration	PASS, No deterioration
W-U	PASS	PASS	PASS, No deterioration	PASS, No deterioration

Table 16: Electric health check comparison, PD Phase to Ground

Phases	Before test	After test
	PDIV (V)	PDIV (V)
U-Ground	PASS	PASS, No deterioration
V-Ground	PASS	PASS, No deterioration
W-Ground	PASS	PASS, No deterioration

The results indicate that there isn't much difference between the two instances. No electrical deterioration was observed due to the fact that the electric machine was not subjected to high relative humidity as intended. However, it is important to note that the parts did undergo thermal stress, the insulation system continues to demonstrate good condition.

7
Conclusion

The primary aim of this study was to determine whether a combination of ageing factors could be damaging to the insulation materials of the electric machine, therefore it ended up with the design of humidity and thermal cyclic test because the effects of humidity would be an interesting real world environmental phenomenon to test with.

While it couldn't be proven that humidity has substantial effect on the insulation because of a technical error, it can be reasonably assumed that it does increase the water content in the oil, and we know that from the first and only sample deemed relevant for analysis. This makes it completely possible that the water content in the oil increases further if the oil cooled motor is continuously exposed to high relative humidity and varying temperatures. Therefore, this document warrants further investigation and documentation because varying temperatures and humidity are a frequently observed phenomenon while driving a car.

Studying a combination of ageing factors is necessary because there are all sorts of factors leading to insulation breakdown and as insulation materials represent a fundamental part of any electrical system, it is very important that we put them through all sorts of tests to get safe and comfortable electric vehicle experience.

8
Future Scope

This project has established a solid foundation for understanding the ageing factors of insulation materials under controlled thermal and environmental conditions.
However, the insulation materials studied in this project involve multiple variables that are difficult to control, such as relative humidity, temperature and material properties. It is suggested that employing an alternative insulation system with revised temperature requirements could lead to a more stable and reproducible setup for future experimental evaluation.
On the other hand, several areas remain open for further experimentation to deepen insight and enhance practical applications:

- New combinations of ageing factors-
  Additional ageing factors beyond temperature and relative could be explored in the future individually or as combinations of electrical, mechanical and chemical factors in order to accurately simulate different real world operating scenarios a car might endure and their effects on insulation materials.

- Prolonged or accelerated ageing tests-
  Implementing ageing tests with longer cycles or accelerated ageing can provide a more detailed investigation into the lifespan of insulation materials, helping to predict failure modes over extended periods and under varying cycles.

- Evaluation of materials alongside recent innovations-
  This encompasses an expansion of the scope of the project to include a wider range of insulation materials for example cutting edge polymer and composites technologies which would offer valuable data for optimizing material selection in automotive electric machines.

- Advanced diagnostic techniques-
  Incorporating non destructive testing methods such as infrared thermography, partial discharge analysis, or dielectric spectroscopy could possibly improve early detection of insulation material failures and ageing progression.

- Diverse environments and operation conditions-
  Subsequent research could explore the effects of different ambient and operational conditions, including humidity cycles, load fluctuations, and vibration to reflect real world scenarios more accurately.

By addressing these areas, subsequent investigations can build on this project's findings to contribute to more efficient, reliable, and longer lasting electric motors in automotive and industrial applications.
Lastly, the test needs to be repeated, avoiding the technical errors encountered previously, in order to study the effects of humidity and temperature cycling

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