

FACULDADE DE ENGENHARIA DA UNIVERSIDADE DO PORTO

Proposal for the Implementation of a Laboratory System of Tests for Qualification of Electrical Insulation of Motors

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Resumo

Esta tese centra-se no desenvolvimento de um sistema de teste de descargas parciais (DP) para motores de indução de baixa tensão, abordando especificamente os desafios associados à qualificação do sistema de isolamento no contexto de motores alimentados por inversores de frequência. Os objetivos deste trabalho são divididos em três partes. Em primeiro lugar, através de um estudo aprofundado dos fenômenos de DP, dos sistemas de isolamento e do impacto dos inversores de frequência no isolamento dos motores de indução, este trabalho visa compreender os fatores que contribuem para as falhas do sistema de isolamento e os riscos associados à fiabilidade e desempenho dos motores. Em segundo lugar, é proposto e implementado um sistema de teste alinhado com normas internacionais, nomeadamente a IEC 60034-18-41, para atribuição da *Impulse Voltage Insulation Class (IVIC)*. Por último, são realizados testes práticos e análises dos valores de DP obtidos utilizando a metodologia proposta, demonstrando os resultados na qualificação dos sistemas de isolamento. Embora seja necessária uma validação adicional através de testes interlaboratoriais, a tese estabelece as bases para a continuação do desenvolvimento de um sistema de teste e aprofundamento da pesquisa sobre teste de DP para a atribuição da IVIC em motores de indução de baixa tensão alimentados por inversores de frequência.

Abstract

This thesis focuses on the development of a comprehensive partial discharge (PD) testing system for low voltage induction motors, specifically addressing the challenges associated with insulation system qualification in the context of frequency inverter-fed motors. The objectives of this work are threefold. Firstly, through a thorough study of PD phenomena, insulation systems, and the impact of frequency inverters on the insulation of induction motors, the thesis aims to understand the factors contributing to insulation system failures and the associated risks to motor reliability and performance. Secondly, a testing system aligned with international standards, specially IEC 60034-18-41, is proposed and implemented, for the assignment of the *Impulse Voltage Insulation Class (IVIC)*. Lastly, practical testing and analysis of PD values are conducted using the proposed methodology, demonstrating the results in the qualification of insulation systems. While further validation through interlaboratory or round-robin tests is required, the thesis lays the foundation for the company to continue the development of a testing system and deepen their research on PD testing for IVIC assignment to frequency inverter-fed low voltage induction motors.

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A todos o meu sincero e profundo obrigado.

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“Don’t stop for nothing, it’s full speed or nothing.”

James Hetfield

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Abbreviations

GVPI	Global Vacuum and Pressure Impregnation
HFCT	High Frequency Current Transformer
IEC	International Electrotechnical Commission
IVIC	Impulse Voltage Insulation Class
NEMA	National Electrical Manufacturers Association
PD	Partial Discharge
PG	Phase-Ground
PDEV	Partial Discharge Extinction Voltage
PDIV	Partial Discharge Inception Voltage
PP	Phase-Phase
PWM	Pulse Width Modulation
RPDEV	Repetitive Partial Discharge Extinction Voltage
RPDIV	Repetitive Partial Discharge Inception Voltage
SBS	Step By Step
UHF	Ultra-High Frequency
UWB	Ultra-Wide Band

Chapter 1

Introduction

Electrical motors play a vital role in various industries, powering a wide range of machinery and equipment. Ensuring their reliable operation is important to prevent unexpected failures, downtime, and associated costs.

Insulation systems form a critical component of induction motors, serving as a safeguard against potential faults and ensuring their reliable operation. It is important to address the specific challenges posed by the use of frequency inverters for feeding induction motors, as these inverters and their *Pulse Width Modulation (PWM)* waveshapes have been identified as potential sources of damage to the insulation system. The repetitive switching actions associated with PWM waveforms can induce partial discharges within the insulation, gradually deteriorating its integrity over time. The qualification of these insulation systems is important as it directly impacts the longevity and performance of the machines.

Partial discharge (PD) testing provides valuable insights into the insulation condition and potential electrical faults within the motor's system. These faults, if left undetected, can lead to machine failures and premature end of life, resulting in significant costs. This thesis aims to address the challenges associated with PD testing on low voltage induction motors and proposes solutions to enhance the accuracy and efficiency of the testing process, in line with the requirements outlined in international standards, specially IEC 60034-18-41.

This work has been conducted within a industrial environment at WEGEuro, a WEG Group company, where the *Research & Development* team played an fundamental role in its development. The opportunity to work closely within WEGEuro's Laboratory in the final stage of this dissertation work provided me with valuable insights and practical perspectives about PD testing on induction motors. Moreover, through the realization of this dissertation in the WEGEuro context, this study permitted a close collaboration between the academic and the industrial universes.

1.1 Overview of the Research Process

This thesis encompasses four main stages, each contributing to the development and implementation of a testing system for assessing the insulation systems of low voltage induction motors in the context of partial discharge (PD) and frequency inverter-fed operations. The stages essentially consisted of:

1. Study of the problem
2. Assessment of the necessary resources to implement a testing system
3. Proposal of a testing system
4. Testing for proposal validation

In the first stage, a study was conducted to understand the theoretical foundations behind the insulation systems of induction motors, frequency inverters, and the PD phenomena that can occur due to the use of these drivers. This involved exploring the impact of PWM waveforms generated by inverters on insulation integrity and the principles of PD testing,.

The second stage involved an assessment of the resources required to implement an effective testing system. This included a comprehensive analysis of relevant International Electrotechnical Commission (IEC) standards, such as IEC 60034-18-41 and IEC 60034-27-5, to ensure compliance with industry guidelines and best practices. The standards were carefully examined to determine the necessary equipment, methodologies, and criteria for accurate and reliable insulation system assessment.

Building upon the knowledge gained in the previous stages, the third stage focused on proposing a testing system that utilized available equipment at WEGEuro and adhered to the IEC standards. This involved the development of an approach that integrated the PD testing methodology with the specific requirements of frequency inverter-fed low voltage induction motors. The proposed system aimed to provide WEG with a practical and effective solution for qualifying the insulation systems of their motors.

The final stage of the thesis involved testing and validating the proposed system. This consisted of conducting experimental tests on low voltage induction motors, applying the developed testing methodology, and analyzing the obtained results. The goal was to evaluate the performance and accuracy of the proposed system, ensuring its effectiveness in assessing insulation quality and IVIC assignment.

By addressing these four stages, this thesis lays the groundwork for a comprehensive approach to PD testing on low voltage induction motors. The proposed testing system, developed in alignment with IEC standards, serves as a starting point for the company to evaluate the integrity of insulation systems. While further testing is necessary to fully validate the system, it provides a solid foundation for future development.

1.2 Main Objectives and Contributions

The dissertation's main objective is to contribute to the field of PD testing on low voltage induction motors by proposing a comprehensive testing system and addressing the challenges associated with IVIC assignment. Through the subsequent chapters, the research aims to enhance the accuracy, efficiency, and reliability of PD testing, ultimately improving the understanding of insulation system qualification and providing valuable insights for maintenance and operation strategies, with a particular focus on the significance of IVIC in the assessment of insulation systems.

The main contributions of the dissertation can be summarized as follows:

1. Development of a proposal for a partial discharge testing system with repetitive impulse voltage.
2. Proposal of an Excel Spreadsheet to assist in the testing procedure proposed, more specifically in the calculation of the test voltages corresponding to each stress category, registration of the results obtained in the partial discharges test, assignment of the IVIC and an analysis of compliance with the IEC and NEMA standards applied.
3. Proposal of a Test Report to be filled in by the operator with the test parameters required by the IEC standards.
4. Proposal of a step-by-step guide for the application of the proposed test procedure in the laboratory.

1.3 Dissertation Structure

This dissertation is structured in five chapters. After an introduction to the problem, the structure and objectives of the dissertation are described as follows.

Chapter 1: Introduction

This chapter introduces the research topic of this work. It highlights the importance of PD testing in assessing the quality of insulation systems in low voltage induction motors and its impact on preventing motor failures. The chapter then presents the research objectives and the dissertation structure, which include investigating the challenges associated with PD testing, proposing a comprehensive testing system aligned with international standards, and focusing on IVIC assignment as a crucial aspect of insulation system qualification.

Chapter 2: State-of-the-art

This chapter provides a comprehensive overview of the state of the art in, induction motors insulation, frequency inverter-fed low voltage motors and PD testing. Additionally, this chapter analyzes relevant international standards to establish a solid foundation for the subsequent chapters, particularly in the context of IVIC assignment and PD testing under repetitive impulse voltage.

Chapter 3: Methodology

This chapter focuses on the methodology employed in the research. It describes the testing procedures established in international standards, such as IEC 60034-18-41 and IEC 60034-27-5, for PD testing on low voltage induction motors, with a specific focus on IVIC assignment. Furthermore, it presents the development of an Excel spreadsheet tool designed to simplify the testing process, including the calculation of test voltages, registration of measured quantities, and compliance checks, all contributing to accurate IVIC assignment.

Chapter 4: Partial Discharge Test Results

This chapter presents the results of PD testing conducted on two prototype motors using the proposed methodology outlined in Chapter 3. The primary focus of this chapter is to analyze and evaluate the RPDIV measurements obtained through the application of the developed testing system.

Chapter 5: Conclusions and Future Work

This last chapter provides a comprehensive overview of the conclusions drawn from the research conducted in this dissertation. It discusses the effectiveness of the proposed testing system in assessing insulation system quality and detecting potential faults related to partial discharges. Additionally, it emphasizes the importance of further testing and validation, including interlaboratory experiments, to enhance the credibility and reliability of the proposed system. The chapter also highlights the future works and areas of improvement.

Lastly, the appendices section of this dissertation includes essential supplementary materials. It encompasses the developed Excel spreadsheet layout, which serves as a user-friendly tool for simplifying the PD testing process. Additionally, a proposed template for the test report is included to ensure standardized documentation of parameters and results. A step-by-step guide was created and proposed to WEGEuro's laboratory colleagues, empowering them to autonomously perform the proposed PD tests. These appendices collectively provide valuable resources to support the implementation and understanding of the research, enhancing the usability and repeatability of the proposed testing system.

Chapter 2

State of the Art

2.1 The Three-Phase Induction Motor

The three-phase induction motor is an alternated current electrical machine that converts electrical energy into mechanical energy. It is made of two main components: the stator and the rotor. The induced circuit is typically found in the rotor of the machine, while the inductor electric circuit is typically found in the stator. These machines are referred to as induction motors since the rotor voltage, which generates the rotor current and magnetic field, is induced in the rotor windings, as opposed to being directly connected by wires [1].

The wide use of these electrical machines comes with the machine's main qualities: cost, robustness and ease of maintenance, making it the most popular AC electrical machine for driving mechanical loads [2].

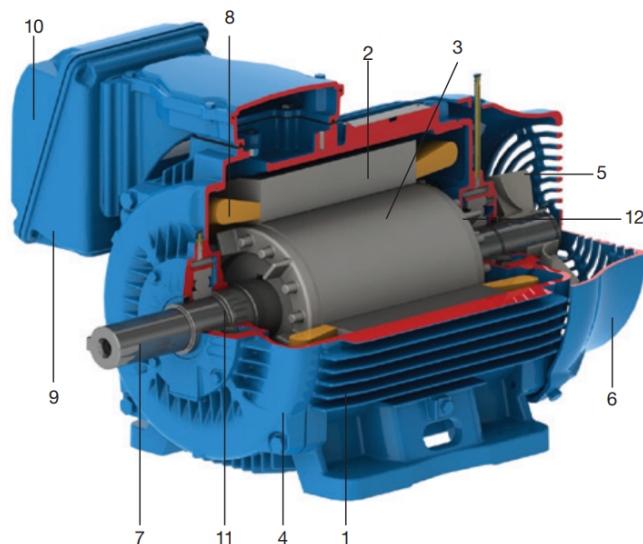


Figure 2.1: WEG Three-Phase Induction Motor [3]

The induction motor shown in Figure 2.1 is composed of:

- | | |
|----------------------------------|--|
| 1. Stator Frame | 7. Rotor Shaft |
| 2. Stator Lamination Core | 8. Three-Phase Winding |
| 3. Rotor Laminated Magnetic Core | 9. Terminal Box |
| 4. End Shields | 10. Terminals |
| 5. Fan | 11. Bearings |
| 6. Fan Cover | 12. Rotor Bars and Short-Circuit Rings |

The stator is composed of the frame, the lamination core and the three-phase winding [3]. The frame, which is made of iron, steel, and die-cast aluminum, serves as the assembly's supporting framework. It has cooling blades and is corrosion-resistant. The lamination core consists of magnetic steel plates, with low magnetic loss density, that are packed to form the magnetic stator circuit. The plates have a circular crown slot on the inner periphery, and are covered with an insulating varnish. As the three-phase winding is attached to a three-phase power source, a balanced three-phase system is created by three equal sets of coils, one for each phase. The windings are contained in the lamination core's slots [2].

There are three basic types of stator winding structures [4]:

- Random-wound Stators
- Form-wound Stators using multi-turn coils
- Form-wound Stators using Roebel bars

Figure 2.2 shows the differences between random wound and form wound stator windings.

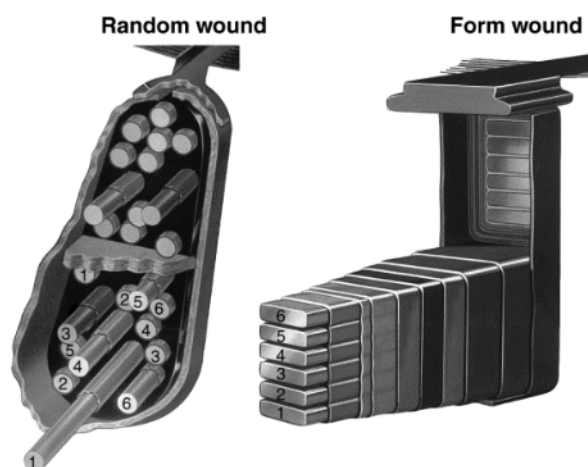


Figure 2.2: Random Wound and Form Wound Stator Windings [5]

Random-wound stators are usually used in low voltage induction motors (less than 1000 V) [4], which are the subject of this dissertation.

Random-wound stators are constructed by winding round, insulated copper conductors (also known as magnet or winding wire) through slots in the stator core to create a coil. This can be done by hand or by a winding machine. The term "random" is used because each turn (or loop) of magnet wire can be placed randomly against any other turn in the coil, without regard to the voltage level. As stated previously, random-wound stators are typically used in machines with operating voltages below 1000 V, since a turn that is connected to a phase terminal could be adjacent to a turn operating at a low voltage (i.e. at the neutral point). This voltage limitation effectively restricts the use of random-wound stators to machines that are smaller than a few hundred kilowatts or horsepower [4].

Induction motor rotors come in two varieties: cage rotors and wound rotors, both of which can be installed inside the stator. A cage induction motor rotor is made up of the shaft, which transmits the mechanical output produced by the motor, the laminated magnetic core, which is made of magnetic steel plates, and the bars and short-circuit rings, which are aluminium die castings that are formed as a single unit [3].

A wound rotor has a full set of three-phase windings that are symmetrical of the windings on the stator. The ends of the three rotor wires are linked to slip rings on the rotor shaft, and the three phases of the rotor circuit are typically Y-connected. The rotor windings are shorted by brushes that are mounted on the slip rings. Induction motors with wound-rotors are more expensive than those with cages, and because their brushes and slide rings wear out more quickly, they require a lot more maintenance. Wound-rotor induction motors are hence not frequently employed [1].

2.1.1 Working Principle

The induction motor's basic operation principles described in [1] are now presented:

When a three-phase set of voltages is applied to the stator, it generates a three-phase set of stator currents that produce a magnetic field B_s . The magnetic field B_s rotates in a counterclockwise direction, and its speed of rotation is given by the following equation:

$$n_{sync} = \frac{120 \times f_e}{P} \quad (2.1)$$

Where:

- f_e is the system frequency, in Hertz
- P is the number of poles in the machine

Figure 2.3 shows three single-phase windings displaced 120° from each other, composing a three-phase winding.

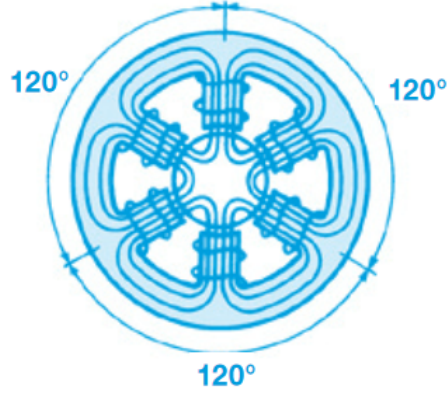


Figure 2.3: Three-Phase winding consisting of three single-phase windings displaced 120° from each other [3]

There is a voltage induced in the rotor bars by the rotating magnetic field B_S , and is given by the following equation:

$$e_{ind} = (v \times B) \times l \quad (2.2)$$

Where:

- v is the velocity of the bar, in relation to the magnetic field
- B is the magnetic flux density vector
- l is the length of the conductor in the magnetic field

The induced voltage in a rotor bar is produced by the relative motion of the rotor compared to the stator magnetic field. Current flows from the upper bars into the lower bars as a result of the induced voltage in the rotor bars, creating a rotor magnetic field B_R . The peak rotor current has a delay to the peak rotor voltage because the rotor assembly is inductive.

The induced torque in the machine is given by the following equation:

$$\tau_{ind} = k B_R \times B_S \quad (2.3)$$

Where:

- B_S is the magnetic field produced by the stator current flow
- B_R is the magnetic field produced by the rotor current flow
- k is a constant.

The maximum speed of the motor has a finite upper limit. The rotor bars would be stationary in relation to the magnetic field and therefore, there wouldn't be any induced voltage if the induction motor's rotor were rotating at synchronous speed. Without any induced voltage on the rotor bars,

the rotor current and magnetic field would be null. The induced torque would be zero in the absence of a rotor magnetic field, and the rotor would slow down as a result of friction losses. Thus, although an induction motor can accelerate to speeds that are close to synchronous, it will never actually reach synchronous speed. While the rotor itself rotates at a slower speed during normal operation, the magnetic fields of the stator B_S and rotor B_R both rotate at synchronous speeds.

The speed of the rotor in relation to the magnetic fields affects the voltage induced in the rotor bar of an induction motor. It is more common to refer to this relative speed because the voltage and current of the rotor determine how an induction motor behaves. The relative motion of the rotor and magnetic fields is typically described by two terms:

- Slip speed, which is determined by the gap between synchronous and rotor speeds, by the following equation:

$$n_{slip} = n_{sync} - n_m \quad (2.4)$$

- Slip, which is relative speed expressed in terms of percentages or per-units, is another term for the relative motion, and is given by the following equation:

$$s = \frac{n_{slip}}{n_{sync}} \quad (2.5)$$

Or:

$$s = \frac{n_{sync} - n_m}{n_{sync}} \quad (2.6)$$

Slip can also be given in terms of angular velocity, w , by the following equation:

$$s = \frac{w_{sync} - w_m}{w_{sync}} \quad (2.7)$$

Therefore, for a given slip s , the rotor shaft speed n_m , can be expressed by the following equation, according to [3]:

$$n_m = n_{sync} \times (1 - s) \quad (2.8)$$

2.1.2 Insulation System

An insulation system is defined by [3] as a combination of two or more insulation materials applied to an electric equipment.

Insulation materials are used to block the current flux from a cable to the ground or to the lowest potential, although it also provides mechanical, environmental and thermal protection to the cable [3].

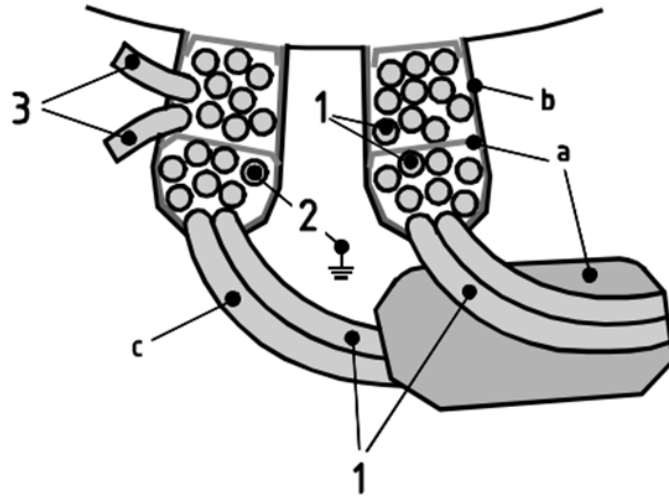


Figure 2.4: Random-Wound Winding Insulation System [6]

The basic stator insulation system shown in Figure 2.4 is composed of:

- | | |
|------------------------|-----------------|
| a. Phase Insulation | 1. Phase-Phase |
| b. Mainwall Insulation | 2. Phase-Ground |
| c. Turn Insulation | 3. Turn to Turn |

One of the most crucial parts of the motor is the round enameled wire because it conducts the electric current that generates the magnetic field necessary for motor functioning. [3] By using smaller conductors, the losses are reduced because of the skin effect (AC current tends to flow on the conductor's edge, if a copper conductor has a large enough cross-sectional area). Small conductors also help to reduce eddy current losses, since the magnetic flux that can be encircled by a path on the conductor's periphery will increase with increasing cross-sectional area, and the induced current will also increase. With the use of small conductors, comes the necessity to insulate the strands from one another. The voltage across them is low, hence the insulation used can be thin [4].

The wire insulating material is affected throughout the production process when the wires are subjected to mechanical traction efforts, flexing, and abrasion electrical effects. The wire insulation material is affected by the operation's thermal and electrical impacts. This requires that

the wire have exceptional mechanical, thermal, and electrical insulation resistance. These features are guaranteed by the enamel that is currently applied to the wire, with the mechanical property being guaranteed by the outside enamel layer that resists abrasion while placing the wire into the stator slots [3]. Figure 2.5 shows the layout of the wire and the insulation inside of the stator slot.

All of the motor winding components are meant to be thermally and electrically isolated using films and laminated insulating materials. These films, which are made of polyester and aramid, are also applied to the following areas:

- To insulate the lamination core (ground) from the enameled wire coil between the coils and the slot (slot bottom film)
- Between phases: to isolate electrically one phase from another
- Closing of the stator slot to insulate electrically that coil placed on the top of the stator and for mechanical purposes so as to keep the wires inside the stator slot

Impregnation varnishes and resins are a key component of the induction motor's insulation system. They are usually polyester varnishes, although silicon resin may be used in special motor designs. These varnishes are applied during the Global Vacuum and Pressure Impregnation (GVPI) process. The GVPI procedure involves vacuuming out the insulation and any remaining moisture, then filling the empty spaces with a particular resin. With this process, the product can be significantly more homogeneous, repeatable, reliable, and robust [7].

The main purposes of the impregnation varnishes and resins are to fill all gaps within the slot and to maintain the enameled wire coils as a block with all stator components through the agglutination of such materials. By agglutinating the wires, vibration and friction are reduced. A short-circuit could result from this friction if the wire enamel fails. When motors are fed by frequency inverters, the agglutination (filling of voids) primarily prevents the formation of partial discharges inside the motor. It also aids in the dissipation of heat produced by the wire.

Figure 2.5 shows the cross section of a random winding in stator slot, where its main components are pointed out.

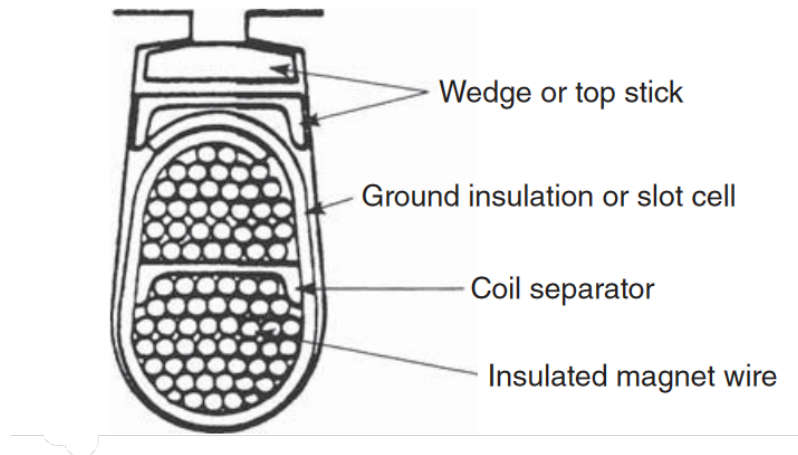


Figure 2.5: Cross section of a random winding in a stator slot [4]

2.1.3 Variable-Frequency Driven Motors

A Variable-Frequency Drive (VFD) is a type of AC motor drive that allows to control the motor's speed and torque by varying the frequency of the input electricity. It regulates the associated voltage or current variation, depending on its topology.

Currently, the use of Pulse Width Modulation (PWM) voltage source frequency inverters is the most efficient method to control the speed of induction motors [8].

The converter's function is to take electrical energy from the utility supply and transfer it to the motor at the voltage and frequency required to produce the desired mechanical output. This energy is taken from the utility supply at a constant voltage and frequency [9].

Figure 2.6 shows an example of a Variable-Frequency Drive produced by WEG.



Figure 2.6: WEG Frequency Inverter CFW900

As shown in Figure 2.7, and according to [8], the input signal must pass through three stages in a frequency inverter in order to produce an output signal with the desired voltage and frequency:

- Rectification of the AC input voltage coming from the power grid, through a Diode Bridge
- Regulation of the rectified signal with energy storage through a capacitor bank, consisting of a DC Link
- Inversion of the DC voltage into an AC voltage of variable frequency and amplitude, through IGBT power transistors

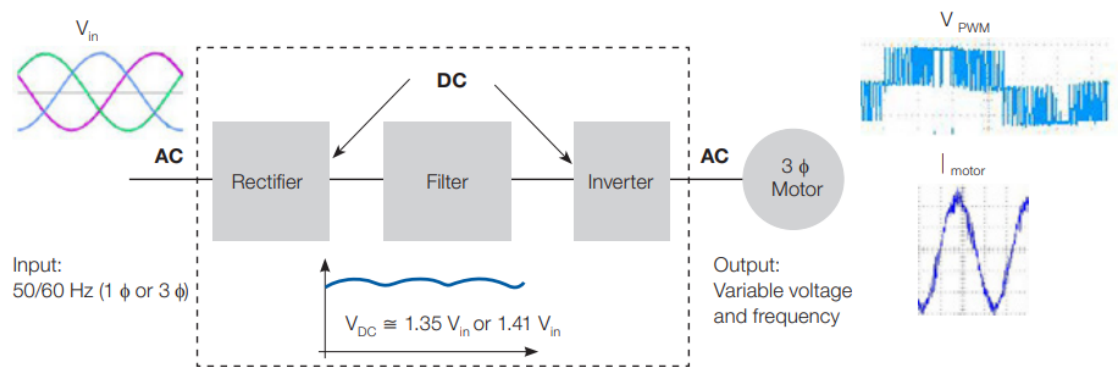


Figure 2.7: VFD Motor with PWM, from [8]

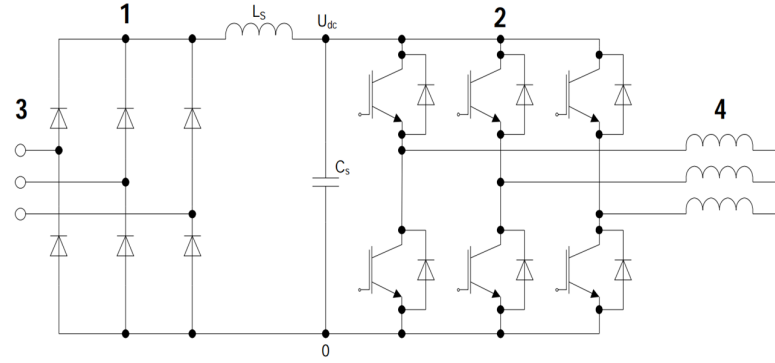


Figure 2.8: Equivalent Circuit of VFD Motor [6]

Figure 2.8 shows the equivalent circuit of the system, where:

- | | |
|-----------------|--------------------|
| 1. Rectifier | 3. AC input |
| 2. PWM Inverter | 4. Machine Winding |

- L_S and C_S represent the system's inductance and capacitance, respectively.

From the equivalent circuit shown in 2.8, it can be concluded that the impulse voltage that is being output by the converter is equal (or less) to the voltage at the DC bus, U_{DC} [6].

IEC Standard 60034-18-41 [6] sets the mathematical expression to define the voltage magnitude of a multiphase AC voltage following rectification:

$$U_{DC} = a \times \left(\frac{\varphi}{\pi}\right) \times \sin\left(\frac{\pi}{\varphi}\right) \times U_{Max} \quad (2.9)$$

Where:

- a is the rectifying type ($a = 1$ for half wave rectification or $a = 2$ for full wave rectification);
- φ is the number of phases (commonly $\varphi=3$);
- U_{Max} is the maximum value of the phase to neutral voltage.

U_{Max} can be given by the following expression:

$$U_{Max} = \sqrt{2} \times U_{Phase} \quad (2.10)$$

Where U_{Phase} is the phase to neutral voltage.

The phase to neutral voltage, U_{Phase} , can be given in terms of the phase to phase voltage (rated voltage), U_{Line} by the following expression:

$$U_{Phase} = \frac{U_{Line}}{\sqrt{3}} \quad (2.11)$$

Therefore, the equation 2.9 can be rewritten in terms of U_{Line} (or rated voltage, U_N) as:

$$U_{DC} = a \times \frac{\varphi}{\pi} \times \sin\left(\frac{\pi}{\varphi}\right) \times \frac{\sqrt{2}U_{Line}}{\sqrt{3}} \quad (2.12)$$

2.1.4 Inverter Control

When it comes to inverter controlling techniques, there are two main types of inverter control:

- **Scalar** (open loop)
- **Vector** (open or closed loop)

The scalar control is based on the original idea of a frequency inverter: a signal with a specific voltage-to-frequency ratio is applied to the motor terminals, and this ratio is maintained constant over a frequency range to maintain the motor's magnetising flux. It is typically used when quick responses to torque and speed commands are not required, and it is especially interesting when there are several motors connected to a single drive [8].

Since the frequency is imposed on the stator windings, the control is open loop, and the speed precision is a function of the motor slip, which is dependent on the load. Some drives use special features like slip compensation (attenuation of the speed variation as function of load) and torque boost (increasing the Voltage-to-frequency ratio to compensate for the voltage drop due to the stator resistance) to enhance the performance of the motor at low speeds while maintaining the torque capacity of the motor. Due to its simplicity and the fact that the majority of applications do not need for high precision or quick speed control responses, this control type is the most common.

Fast responses and a high degree of precision in the motor speed and torque control are made possible by vector control. The motor current is split into two vectors, each of which is controlled separately and produces either magnetising flux or torque. Open loop (sensorless) or closed loop (feedback) are both possible.

The feedback vector control (closed loop) requires a speed sensor on the motor, and provides great accuracy on torque and speed control, even at low and null speeds, while the sensorless vector control (open loop) is simpler, but limited at very low speeds. At higher rotation speeds, the open loop control is nearly as good as the closed loop control [8].

The primary distinction between the two control types is that scalar control, also known as steady state equations, uses equations based on the equivalent electrical circuit of the motor and only takes into account the magnitudes of the instantaneous electrical quantities (magnetic flux, current, and voltage) referred to the stator. However, the vector control treats the instantaneous electrical quantities associated with the rotor linkage flux as vectors, and its equations are based on the spatial dynamic model of the motor. With torque and flux being independently controlled, the vector control sees the induction motor as a DC motor [8].

2.1.5 Consequences of VFD on the Motor's Insulation System

The use of VFDs to control induction motors has proven to be an efficient and reliable way of varying the motor's speed and torque. However, the fast rise time voltage surges that arise in the machine's terminals subject the machine to high dielectric stress that can cause the electrical breakdown of the insulation in motor stator windings [10].

Power electronic components have quickly developed, creating a new cause of voltage surges. Using Insulated Gate Bipolar Junction Transistors (IGBTs), PWM-type inverter fed drives (IFDs) may produce up to 20,000 fast rise time voltage spikes per second [11].

The use of IGBT in modern frequency inverters can have some unfavorable effects like increased electromagnetic emission, the potential for voltage peaks, and the occurrence of high dV/dt ratios (which is the time derivative of the voltage, or rate of electrical potential rise), at the inverter fed motor terminals [8].

In order to reduce switching losses in the output semiconductors, impulse voltage rise times are kept as short as possible, between 0.05 and 2 microseconds [6].

Figure 2.9 shows the regular voltage surges measured at a converter output and at the motor terminals. The pulses cause voltage overshoots at the electrical machine terminals depending on the rise time of the voltage pulse at the converter output, the cable length, and the electrical machine impedance.

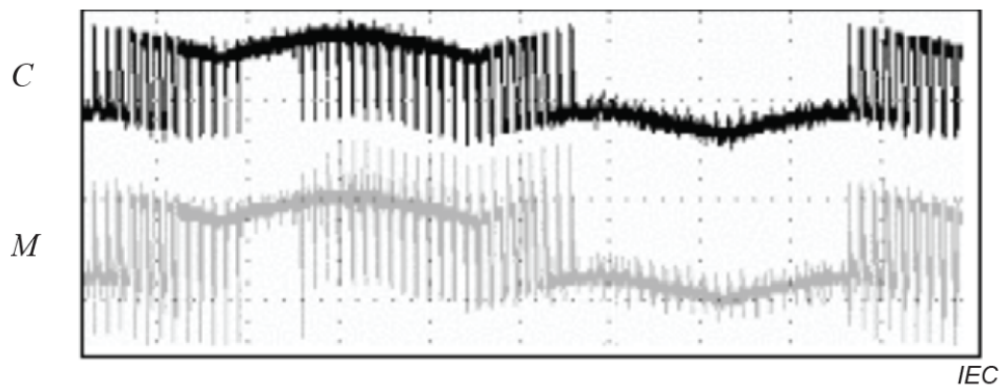


Figure 2.9: Usual voltage surges on one phase at the converter and at the motor terminals (2 ms per division) [12]

Where:

- **C** is the phase voltage at the converter
- **M** is the phase voltage at the motor.

This can lead to the slow deterioration and final breakdown of the turn insulation, due to the repeated overvoltages that may appear on the motor terminals. A sufficiently high interturn voltage can also cause partial discharge (PD) between the turns [11]. For the motor insulation system to withstand the high voltage gradients present in a PWM environment, it must have superior dielectric properties [8].

According to [6], the short rise time voltage impulses of substantial magnitude will generate high voltage stresses in the following areas:

- Between conductors in different phases
- Between conductors and ground
- Between consecutive turns in the line-end coil

Figure 2.10 shows the voltage waveform at the different insulation system components, for a 2-level converter. It is noticeable that the voltage has a different waveform between conductors in different phases, conductors and ground, and between consecutive turns in the line-end coil.

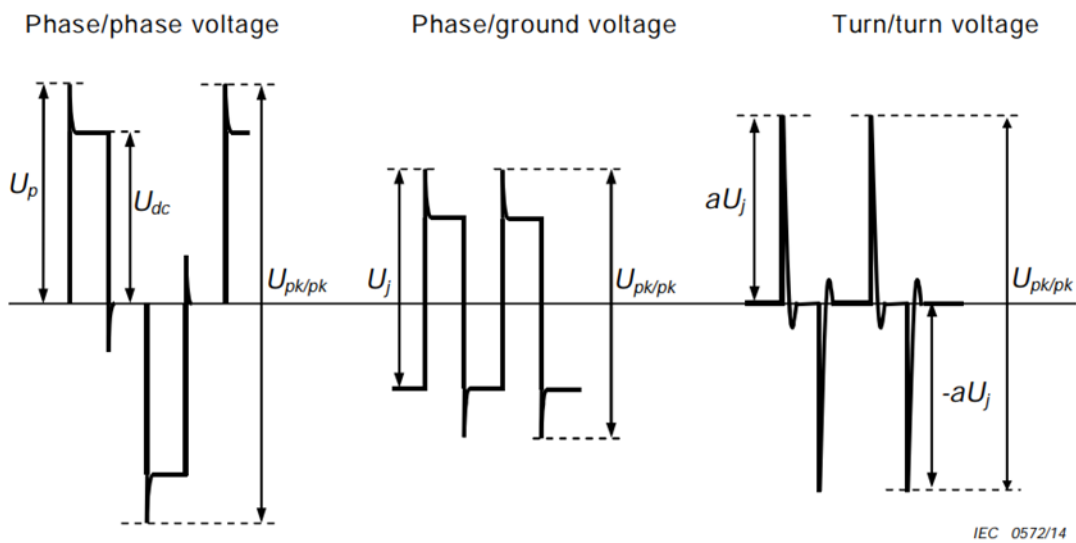


Figure 2.10: Voltage waveform at the different insulation system components, for a 2-level converter [6]

Figure 2.11 shows a single pulse at the converter and at the motor terminals. There is a noticeable oscillation in the electrical machine, that will put the insulation under electrical stress.

Figure 2.12 shows the voltage impulse waveform and its fundamental parameters.

Where:

- U_p is the impulse voltage peak value
- U_b is the impulse voltage overshoot
- U_a is the steady state impulse voltage magnitude
- t_r is the impulse rise time

These parameters are defined in [6]. The rise time of an impulse is the time for the voltage to rise from 10% to 90% of its final value. The impulse voltage peak value is the maximum numerical value of voltage reached during a unipolar voltage impulse (Note that for bi-polar voltage

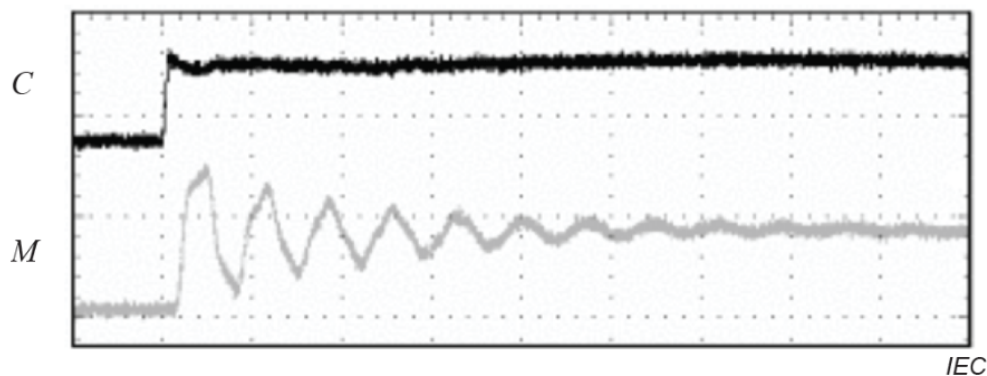


Figure 2.11: Usual voltage surges on one phase at the converter and at the motor terminals ($1 \mu\text{s}$ per division) [12]

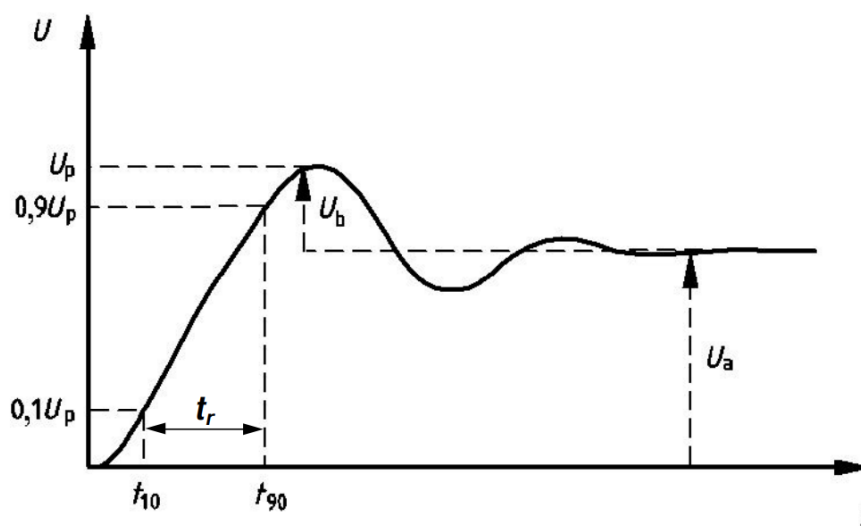


Figure 2.12: Voltage Impulse Waveform [6]

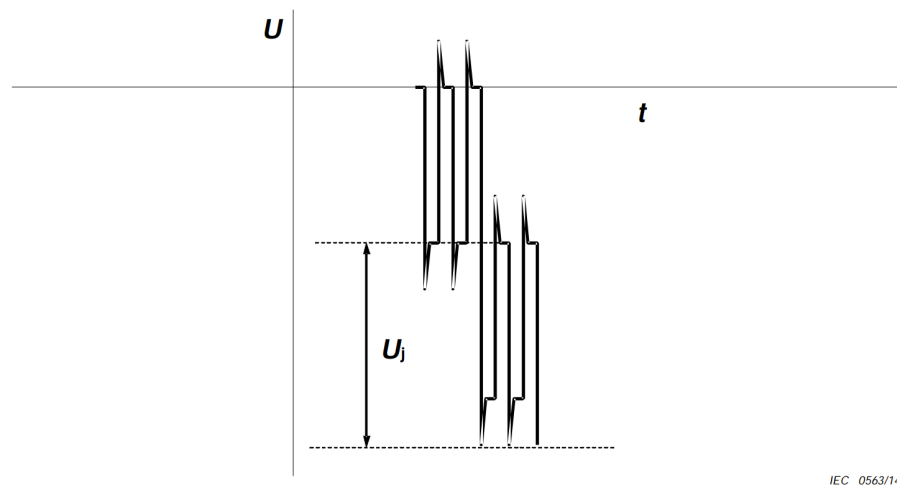
impulses, the impulse voltage peak value is half of the peak-peak value). The impulse voltage overshoot is the peak voltage above the steady state impulse voltage's magnitude.

The cable and the motor can be seen as a resonant circuit. This circuit is excited by the inverter rectangular pulses. When the peak voltage exceeds the supply voltage due to the values of R , L , and C , the circuit response to this excitation is referred to as "overshoot". Specifically, overshoots have an impact on random-wound windings' interturn insulation [8].

As it is shown in Figure 2.12, the steady state impulse voltage magnitude is the final magnitude of the voltage impulse.

Another important parameter defined in [6] is the jump voltage, U_J . It is the change in voltage at the terminals of the motor occurring at the start of each impulse when fed from a converter, as shown in Figure 2.13.

The peak to peak voltage, the rise-time and the frequency of the impulses generated by the

Figure 2.13: Jump voltage (U_j) at the motor terminals [6]

converter are all factors that affect the dielectric stress of the winding insulation. High levels of stress are present between turns at the line end coil of the individual phase winding due to the uneven voltage distribution caused by short rise-time impulses [12].

Figure 2.14 shows the voltage distribution across the first turn of the coil as a function of the impulse rise time. As displayed, the shorter the rise times, the higher the voltage across the first turn of the coil.

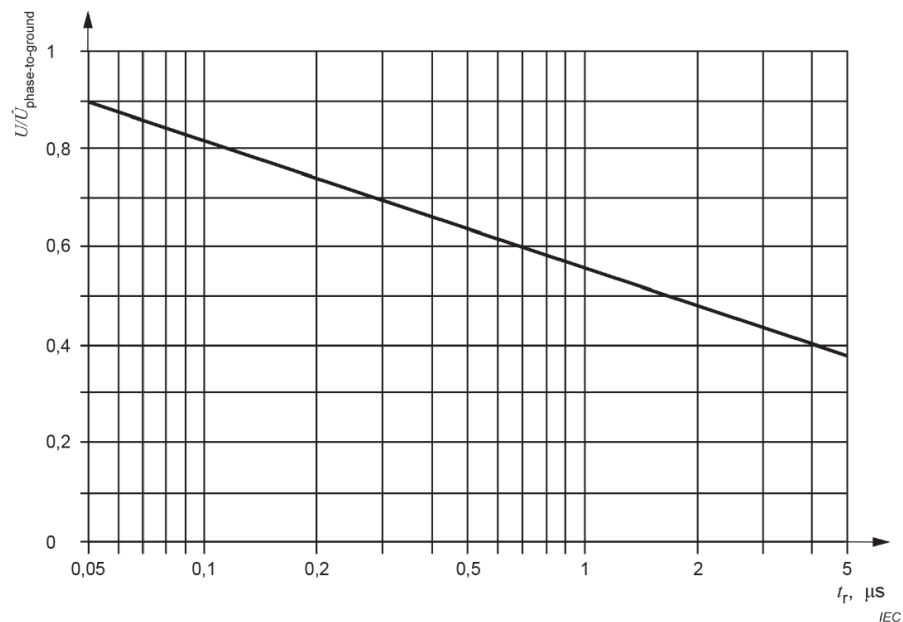


Figure 2.14: First turn voltage as a function of the rise-time [12]

Figure 2.1 shows the influence of the features of the machine terminal voltage on the different components of Type I insulation systems.

Insulation component	Fundamental frequency	Impulse voltage repetition rate	Peak/peak impulse voltage (Fundamental frequency)	Peak/peak impulse voltage (Impulse voltage repetition rate)	Jump voltage	Impulse rise time
Turn to turn insulation	○	○	○	○	●	●
Main wall insulation	○	○	●	●	○	○
Phase/phase insulation	○	○	●	●	○	○
NOTE ○ Less significant ● More significant						

Table 2.1: The effect of machine terminal voltage features on components of Type I insulation systems [6]

As shown in table 2.1, the jump voltage and the short impulse rise times will be more significant in the damage caused to turn to turn insulation, while the peak/peak value of the impulse voltage at the fundamental frequency, and at the impulse voltage repetition rate will be more damaging to the main wall insulation, and the Phase-Phase insulation.

2.2 Partial Discharges

Partial Discharges (PD) are defined in IEC 60270 [13] as "localized electrical discharges that only partially bridge the insulation between conductors and which can or can not occur adjacent to a conductor." Partial discharges frequently have no impact on the electric field's short-term strength. However, erosion caused by partial discharges results in a frequently significantly shorter service life, particularly in the case of frequent and repetitive discharge impulses at AC voltage and repetitive impulse voltages. As a result, the occurrence of partial discharges is a crucial factor in determining how good an insulation system is [14].

In figure 2.15 a model is shown, of partial discharges occurring inside the insulation system, and on the insulation surface,

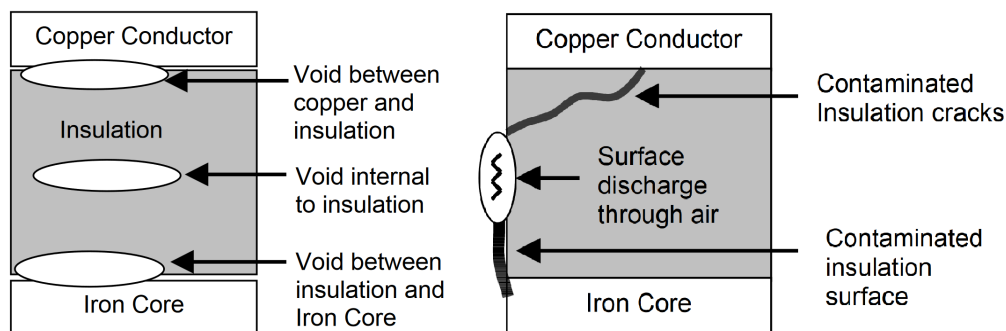


Figure 2.15: Partial discharges occurring inside the Insulation System (left) and on the Insulation Surface (right) [15]

Dielectric defects like airborne sharp edges and gaseous inclusions in liquid and solid dielectrics can lead to partial discharges [16]. Any space between the copper conductor and the grounded motor frame reference is susceptible to these discharges. The voids may be found inside the insulation itself, between the outer insulation wall and the grounded frame, between the copper conductor and the insulation wall, or along the surface of the insulation. Since the pulses have high frequencies, they rapidly attenuate as they reach the ground. The discharges constitute small arcs that happen within the insulation system, causing the insulation to deteriorate and eventually fail entirely [15].

Figure 2.16 is a schematic illustrating a possible location for partial discharges between turns in inverter-fed driven motors.

The air in any void between two turns will breakdown due to the high voltage across those turns. The turn-to-turn fault caused by the PD will quickly transform into a ground fault as it slowly erodes the insulation on the magnet wire. Therefore, inverter-fed motors are required to be free of partial discharges at the operating voltage of the inverter. In essence, random-wound inverter duty windings require more effective resin impregnation than conventional stators do. Because of this, these stators are frequently produced using the GVPI or trickle impregnation processes [4].

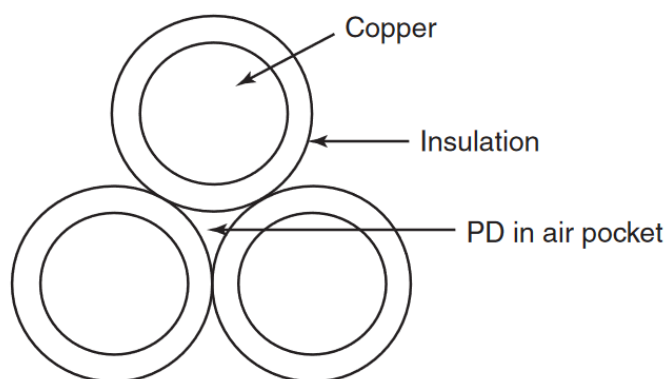


Figure 2.16: Partial Discharge between turns in inverter-fed driven motors [4]

There is a rapid flow of electrons from one side of the gas-filled void to the other when a partial discharge pulse happens. The pulse typically lasts just a few nanoseconds because the electrons are traveling over a very short distance at speeds that are nearly equal to the speed of light. The pulse duration decreases with increasing gas pressure in the voids. Each discharge generates a pulse of current since each electron carries a charge q . The current pulse can be expressed by the following equation:

$$i = \frac{dq}{dt} \quad (2.13)$$

Since each discharge pulse lasts a few nanoseconds, the Fourier transform shows that each discharge produces frequencies ranging from 0 Hz to several hundred MHz. As a result, PD can be detected over a very broad frequency range, which will affect the results of the measurement [17].

2.2.1 Partial Discharge Testing on Induction Motors

Since more than 60 years ago, stator winding insulation in motors and generators has generally been evaluated using partial discharge (PD) testing [17]. Partial discharge tests on rotating machines can be performed by two methods [18]:

- On-line tests, which are carried out at operating voltage;
- Off-line tests, in which the motor is de-energized from its operating voltage, being powered by an external voltage source.

While on-line tests allow the assessment of PD characteristics with various load conditions and without causing a power outage, off-line tests allow the determination of PDIV, PDEV, RPDIV and RPDEV, since the applied test voltage can be set by the operator. When it comes to a lab setting, off-line tests are more practical to perform [18].

Both methods allow machine owners and manufacturers to judge the condition of the stator winding insulation, identifying whether maintenance is required. Some faults can be detected,

such as loose coils in the stator slots, contamination leading to electrical breakdown and thermal ageing of the insulation [17].

Partial discharge measurement circuits are essentially composed of [19]:

- a PD measuring instrument;
- an adequate PD coupling unit;
- a high-voltage power supply;
- a voltage measuring device;
- high-voltage connections;
- a connection cable from the measuring impedance to the PD device that has enough low damping qualities and appropriate shielding.

When the test object is exposed to supply voltage impulses, the standard narrow-band and wide-band frequency methods described in IEC 60270 [13] cannot be used to measure PD pulses [20].

2.2.2 Partial Discharge Testing under Repetitive Impulse Voltage

IEC TS 61934 [20] and IEC TS 60034-27-5 [21] describe the allowed methods for the measurement of partial discharges under repetitive impulse voltage on stator windings.

One of the techniques proposed in [20] consist of measuring the current or the electromagnetic wave of the PD pulse at ultra-high frequency (UHF), with a higher frequency than the one from the voltage impulse. This is achieved by using an appropriate filter to suppress the frequency components of the impulse voltage. IEC TS 61934 [20] proposes the use of a high-pass filter to remove the undesired low-frequency components of the impulse voltage. The alternative technique involves integrating PD current at a frequency that is extremely low in comparison to the impulse voltage.

Figure 2.17 shows the impulse voltage and the PD pulse before and after filtering, for a given example in [20]. As stated previously, it is mandatory that the measurement system is able to suppress the impulse voltage to a magnitude below than the expected from the PD pulse, without suppressing the PD pulse.

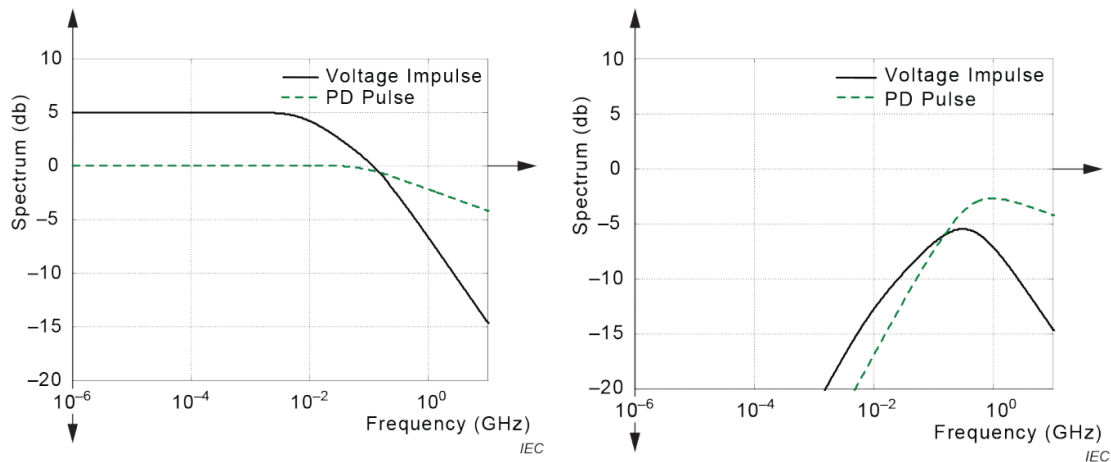


Figure 2.17: Voltage impulse and Partial Discharge pulse frequency spectra before and after filtering [20]

The following electrical PD pulse detection devices are presented in IEC TS 60034-27-5 [21] and IEC TS 61934 [20]:

- Coupling Capacitor with higher order analogue filter
- High Frequency Current Transformer (HFCT) with higher order analogue filter
- Electromagnetic Couplers

2.2.2.1 Coupling Capacitor with higher order analogue filter

Figure 2.18 shows the circuit defined in IEC TS 61934 [20] for the measurement of PD pulses through a coupling capacitor. The coupling capacitor shall have a voltage rating that exceeds the expected impulse voltage. The filter, that can be designed using passive or active filtering technology, is expected to attenuate the test voltage impulses that are feeding the test sample. is expected to attenuate the test voltage impulses that are feeding the test sample.

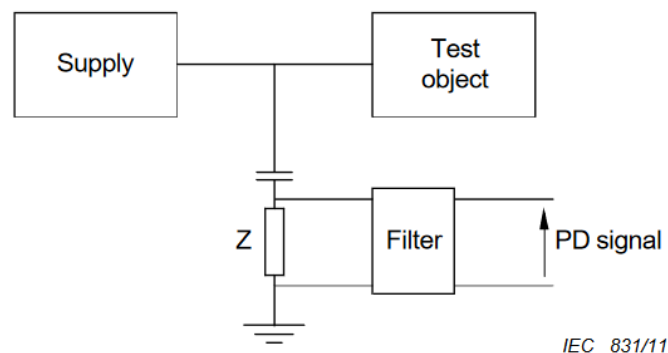


Figure 2.18: Coupling capacitor with high order filter PD measurement method [20]

2.2.2.2 High Frequency Current Transformer (HFCT) with higher order analogue filter

Figure 2.19 shows the circuit established in IEC TS 61934 [20] for the measurement of PD pulses through an HFCT placed over the high-voltage cable between the test object and the impulse voltage supply. It should be noted that HFCTs may have a very broad range of upper cut-off frequencies that could impact how well this method works. The cut-off frequency of the HFCT must be greater than the voltage impulse frequency, and both passive and active filtering techniques can be used to implement the filter. The HFCT can be placed over the high-voltage cable between the impulse supply and the test object, or connected between the test object and earth.

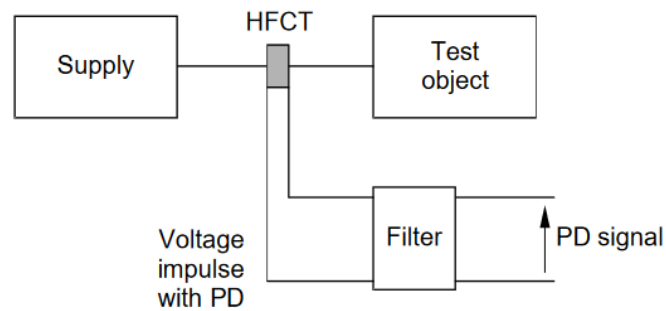


Figure 2.19: HFCT with high order filter PD measurement method [20]

2.2.2.3 Electromagnetic Couplers

Electromagnetic couplers, or antenna-type couplers can be used to detect an electromagnetic signal from the location in the test sample where the PD is occurring. Figure 2.20 shows a PD measurement circuit with an electromagnetic coupler, used to attenuate the impulse voltage. In order for the suppression of the impulse voltage to be effective, the electromagnetic coupler must have a fixed coupling impedance.

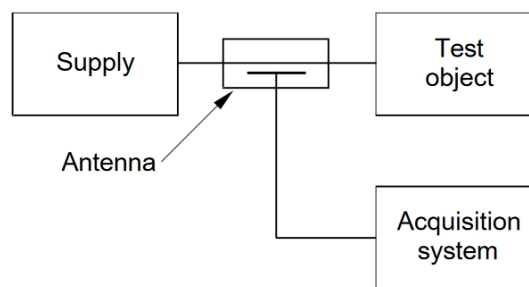


Figure 2.20: Electromagnetic coupler PD measurement method [20]

According to [22], a directional electromagnetic coupler method offers a good sensitivity to the measurement of PD pulses, being able to sufficiently suppress the impulse voltage. Figure 2.21 shows a PD measurement circuit with electromagnetic UHF antenna described in [20].

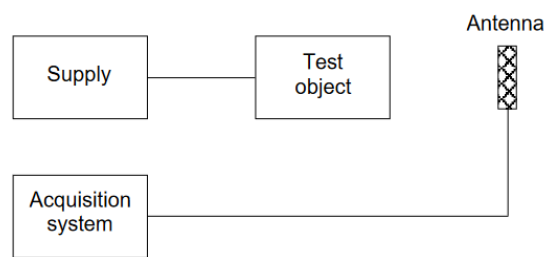


Figure 2.21: Electromagnetic UHF antenna PD measurement method [20]

Electromagnetic UHF antennas can detect the radiated electromagnetic signals that propagate through free space from the location in the windings where the PD is occurring. In case the antenna has UWB characteristics, in which the lower frequencies of the impulse voltage is included, a filter is necessary to attenuate the impulse voltage signal. There are some antennas with a cut-off frequency above 0,5GHz that dismiss the use of filters, like horn antennas and UHF antennas with narrow-band characteristics [20]. It is important to notice that the distance between the antenna and the test sample will affect the measurement quality.

The proposed method for the measurement of PD pulses must be in compliance with the IEC Standards, more specifically IEC TS 61934 [20] and IEC TS 60034-27-5 [21].

Chapter 3

Methodology

The Methodology chapter serves as the backbone of this research, providing a comprehensive understanding of the experimental setup, procedures, calculations, and equipment selection employed in the investigation of Partial Discharge (PD) Testing for Insulation Evaluation on Low Voltage Induction Motors, based on the IEC Standard 60034-18-41. This chapter delves into the specific methodologies used to address the research objectives, ensuring the reliability and validity of the results obtained.

3.1 Overview of the IEC Standards

The **International Electrotechnical Commission** (IEC) Standards consulted in the scope of this work establish the requirements, rules, and procedures for developing partial discharge tests to qualify the insulation of induction motors. The qualification is made through the assignment of the Impulse Voltage Insulation Class (IVIC), whose assignment process is also defined in the IEC standards.

IEC 60034-18-41[6] was the main standard analyzed, as it generally contains the necessary information for assigning an IVIC in induction motors with Type I insulation systems, which are insulation systems used in machines with a rated voltage of 700 V or less.

IEC 60270 [13] defines the terms and requirements for the measurement of partial discharges that occur in systems tested with alternating voltages up to 400 Hz or with direct voltage. This standard also defines the quantities to be measured during partial discharge testing, and describes the different methods and test circuits for the measurement of partial discharges. The calibration procedures, and the instruments to be used for such, are also defined in this standard.

In general, IEC/TS 61934 [20] offers a technical explanation and several PD measurement techniques, which are cited in [6]. IEC/TS 60034-27-5 [21] was developed as practical test guidance, for off-line measurement of PD inception and extinction voltages during repetitive impulse condition.

IEC/TS 60034-25 [12] and NEMA MG-1 [23] specify the recommended IVIC that assures a reliable operation of the electrical machines, for general purpose applications.

3.2 PDIV, RPDIV, PDEV and RPDEV

The tests described in IEC 60034-18-41 [6] are aimed at measuring four main quantities:

- **PDIV**, Partial Discharge Inception Voltage, defined in [6] as the lowest voltage at which partial discharges are initiated from a lower value at which no such discharges are observed.
- **RPDIV**, Repetitive Partial Discharge Inception Voltage, defined in [21] as the minimum peak-to-peak impulse voltage at which more than five PD pulses occur on ten voltage impulses of the same peak-to-peak values when the impulse voltage applied to the test object is increased with step-by-step method. In the Annex D of [21] it is redefined as the voltage in which there is a 50% probability of occurring PD events against the number of applied impulses, in case the number of applied impulses is higher than 10.
- **RPDEV**, Repetitive Partial Discharge Extinction Voltage, defined in [21] as the maximum peak-to-peak impulse voltage at which fewer than five PD pulses occur on ten voltage impulses of the same peak-to-peak values when the voltage applied to the test object is decreased with step-by-step method from a higher value at which such discharges are observed.
- **PDEV**, Partial Discharge Extinction Voltage, defined in [6] as the voltage at which partial discharges are extinguished in the test arrangement when the voltage applied to the test object is gradually decreased from a higher value at which such discharges are observed.

3.3 Impulse Voltage Insulation Class

The IVIC is defined in IEC 60034-18-41 [6] as the "peak to peak voltage classes A, B, C, D, or S for reliable operation, assigned by the manufacturer in relation to the rated voltage for a specified converter-driven machine and indicated in its documentation and, if applicable, on its rating plate."

Overshoot stress is divided into four categories, as shown in table 3.1. These categories allow the qualifying of insulation systems for converter operation in various Impulse Voltage Insulation Classes.

Stress category	Overshoot factor (OF) U_p/U_a
A – Benign	$OF \leq 1,1$
B – Moderate	$1,1 < OF \leq 1,5$
C – Severe	$1,5 < OF \leq 2,0$
D – Extreme	$2,0 < OF \leq 2,5$

Table 3.1: Overshoot Stress Categories for Type I insulation systems according to [6]

The assignment of the IVIC is made through a Partial Discharge Type Test, described in [21], in which the measured RPDIV will have a corresponding stress category, and therefore, a corresponding IVIC. The test procedures for the measurement of the RPDIV will be described later in this dissertation.

3.4 Tests Described in IEC 60034-18-41

IEC 60034-18-41 [6] distinguishes between two essential categories of tests:

- Design qualification tests
- Type tests

3.4.1 Design qualification tests

Design qualification tests are conducted during the development phase of a machine to ensure it meets the required performance criteria and safety standards. These tests assess factors such as electrical and mechanical design and thermal performance. These tests consist of:

- Pre-Diagnostic tests
- Diagnostic tests
- Thermal ageing cycles
- Partial discharge tests

The test samples go through thermal and mechanical cycling and various electrical withstand tests. After each sub-cycle, a partial discharge diagnostic test takes place. The test ends when the PDIV drops below the required test voltage for the selected stress category.

Since these tests are only carried out during the development phase of a machine, they do not integrate the system proposed in this project.

3.4.2 Type tests

On the other hand, Type tests are performed on a representative machine from a specific design series to verify its compliance with the established requirements. These tests consist of partial discharge tests:

- Partial Discharge test at Power Frequency (Sinusoidal Voltage with 50/60 Hz);
- Partial Discharge test under Repetitive Impulse Voltage.

The main difference between these two Type tests is the test voltage that is applied to the test samples. According to [6], the repetitive impulse voltage is a more realistic representation of the expected stress under converter operation. Therefore, the repetitive impulse voltage test was chosen for the proposed testing system.

3.4.3 Test Samples

The test samples that shall be used in the Design Qualification Tests and in the Type Tests are described in [6] and consist of:

- Twisted Pairs
- Motorette
- Complete Winding

Figure 3.1 shows a twisted pair. These test samples can be used to evaluate the behaviour of the turn to turn insulation, either with sine or impulse voltages.



Figure 3.1: Twisted Pair

Figure 3.2 shows a fully assembled and varnished motorette. It essentially consists of two coils mounted in the same pair of slots, with four insulators fixed on the base. The construction and assembly instructions are given in [24]. Phase to phase insulation and phase to ground insulation can be represented using these models.

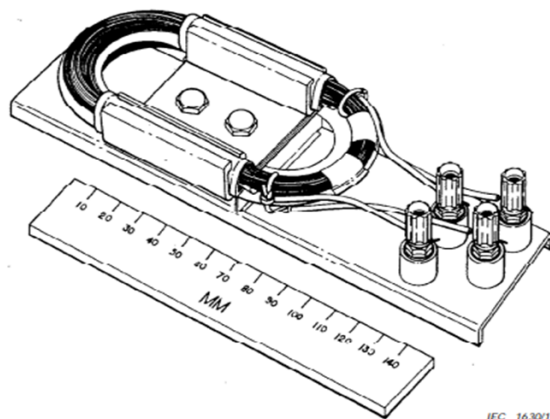


Figure 3.2: Fully assembled Motorette with ruler for scale [24]

Figure 3.3 shows the complete windings used in the tests performed during the development of this dissertation. Complete windings allow the phase to phase and phase to ground insulation to be tested. The turn to turn insulation can also be tested using these test samples, when fed by an impulse voltage.



Figure 3.3: Complete winding of a WEG Induction Motor

Table 3.2 specifies whether sinewave or impulse voltage shall be used during the tests, depending on which test sample is being used.

Component to be tested	Design qualification tests				Type test	
	Twisted pair or equivalent		Motorette or formette or complete winding		Complete winding	
	Sine	Impulse	Sine	Impulse	Sine	Impulse
Turn/turn	✓	✓	*	✓	*	✓
Phase/phase	No	No	✓	✓	✓	✓
Phase/ground	No	No	✓	✓	✓	✓
* A special test winding is required in which the turn/turn insulation is simulated by at least two electrically isolated conductors wound in parallel, one of which is grounded and the other is energised.						

Table 3.2: Voltage waveforms that are acceptable when testing system components [6]

Twisted pairs and motorettes can only be used during the Design Qualification Tests, while complete windings may be used in the Design Qualification Tests and Type Tests. An impulse wave shape for testing has the benefit of allowing for representative stressing of all winding areas. Therefore, using a complete winding under impulse voltage allows the testing of all the insulation components, during the Design Qualification Tests and the Type Tests, making it the more practical solution.

A complete winding was chosen as the test sample for the proposed testing system.

3.4.4 Test Voltages

According to [6], partial discharge testing is performed at the maximum peak/peak operating voltage multiplied by an enhancement factor. The voltages that shall be used to test the Phase to Phase and the Phase to Ground insulation during the PD tests can be estimated by the following expressions:

- Phase to Phase:

$$2 \times (U_{DC} + U_b) \quad (3.1)$$

- Phase to Ground:

$$0,7 \times 2 \times (U_{DC} + U_b) \quad (3.2)$$

Where:

- U_{DC} is the voltage at the DC bus, from equation 2.12.
- U_b is the voltage overshoot corresponding to each stress category, as shown in Figure ??.

These voltages shall be multiplied by an enhancement factor and by an additional factor to represent the line voltage variation in service, which may vary by $\pm 10\%$.

3.4.4.1 Enhancement Factor

There are three main factors that should be taken into account for the enhancement of the maximum peak/peak operating voltages specified in [6].

The first factor is required by [25], which establishes a PD safety factor of 1,25, by which the PD test voltages shall be increased.

There is a second factor that should be considered, that is described in [12], which states that an increase in winding temperature from 25°C to 155°C typically results in fall in the PDIV by 30%. Due to the cooling effect of the slot on the neighbouring turns, this factor is reduced to 10% on the Phase-Ground test.

The third factor is related to the effect of thermal ageing. When the machine is operating near to the class temperature of the insulation, the PDIV is expected to fall, due to the thermal ageing. According to [6], a value between 1,0 and 1,2 can be used to consider this phenomenon.

Table 3.3 summarises this information, for Design qualification and Type tests. From that figure we can observe that the enhancement factor used must be contained between 1,25 and 1,95 for the Phase-Phase test, and between 1,25 and 1,65 for the Phase-Ground test.

Under the regulation from [6], specifically the 2019 ammendment, the relative humidity and altitude can affect the PDIV during testing, and although it indicates that a new factor should be considered because of this two factors, the Standard does not establish any values to assign no these factors.

		Enhancement factors (EF)			
		PD Safety factor	Temperature	Ageing	Total EF
Qualification test	Phase/phase	1,25	1,0 – 1,3	1,0	1,25 – 1,63
	Phase/ground		1,0 – 1,1		1,25 – 1,38
	Turn/turn		1,0 – 1,3		1,25 – 1,63
Type test	Phase/phase	1,25	1,0 – 1,3	1,0 – 1,2	1,25 – 1,95
	Phase/ground		1,0 – 1,1		1,25 – 1,65
	Turn/turn		1,0 – 1,3		1,25 – 1,95
NOTE The total enhancement factor (Column 6) is the product of the individual factors in columns 3-5.					

Table 3.3: Summary of enhancement factor to be applied to the test voltages [6]

3.5 Proposed Excel Spreadsheet

A Microsoft Excel spreadsheet was developed and proposed in order to simplify the testing process to the test operator. The full layout of the Excel Spreadsheet is shown in Appendix A. It was divided into 4 sections:

- Test Voltage Calculation
- Register of the RPDIV results from the PD test
- IVIC Assignment
- Compliance check

3.5.1 Test Voltage Calculation

In order to simplify the calculation process for the test voltages to apply during each test, this section of the Excel Spreadsheet was developed.

The test operator is expected to introduce the following inputs:

- U_N , Motor Rated Voltage
- a , type of rectification of the converter that will feed the motor (1 for half wave, 2 for full wave)
- EF , the enhancement factor to be used

By inputting the Motor Rated Voltage and the type of rectification of the converter, the software outputs the DC bus voltage, U_{DC} , calculated according to equation 2.12, as it is shown in the example in Table 3.4.

Ensaio de Descargas Parciais Medição da RPDIV para determinação da IVC, segundo a IEC 60034-18-41					
U_N (V)	400	Incluir Fator de melhoramento?	Sim	Definir Fator de melhoramento (1,25 $\geq$ EF $\geq$ 1,95)	1,25
Tipo de Retificação (1 para meia onda, 2 para onda completa)	2	Incluir aumento de 10% devido à variação da tensão de fase em serviço?	Sim		
U_{DC} (V)	540,19				

Table 3.4: Software section for the operator to introduce motor specifications

The software will then output the test voltage that corresponds to each stress category, for the Phase-Phase test and for the Phase-Ground test, according to equations 3.1 and 3.2, respectively, and multiplying them by the chosen enhancement factor, and the additional factor to represent the line voltage variation in service, which may vary by $\pm 10\%$. Table 3.5 shows the Test Voltages for the Phase-Phase and Phase-Ground tests, for each stress category, that are output by the software.

Cálculo das Tensões de Teste de cada Categoria de Severidade		
Categoria de Severidade	Tensões de Teste (Vpp)	
	Fase-Fase	Fase-Terra
A - Benigno	1634,07	1143,85
B - Moderado	2228,28	1559,80
C - Severo	2971,04	2079,73
D - Extremo	3713,80	2599,66

Table 3.5: Test voltages calculation for the Phase-Phase and Phase-Ground tests

The measured RPDIV will be compared to these values, in order to assess to which category does the measured RPDIV correspond, and the software will automatically assign an IVC to the Phase-Phase and Phase-Ground insulations.

3.5.2 Register of the RPDIV results from the PD test

After the PD tests for the measurement of the RPDIV, the test operator should introduce the RPDIV results of each phase, for the Phase-Phase and Phase-Ground tests, on the appropriate section of the Excel spreadsheet. The software will select the minimum RPDIV measured for each test, as shown in table 3.6.

Registo dos resultados obtidos na Medição da RPDIV		
	RPDIV Fase-Fase (Vpp)	RPDIV Fase-Terra (Vpp)
Fase U	3000,00	2300,00
Fase V	3100,00	2200,00
Fase W	3200,00	2100,00
Menor RPDIV Medida (Vpp)	3000,00	2100,00

Table 3.6: Excel spreadsheet section for the register of the measured RPDIV

The values shown in table 3.6 are an example, as a demonstration of how the software selects the minimum RPDIV measured and assigns an IVIC to the machine. They do not represent real measured values during the tests.

3.5.3 IVIC Assignment

Following the introduction of the measured RPDIV during the PD tests, the software will compare this value to the test voltages that correspond to each stress category. Table 3.7 shows an example of the IVIC that would be assigned for the example presented in table 3.6.

Atribuição da IVIC		
IVIC	Isolamento Fase-Fase	Isolamento Fase-Terra
	C - Severo	C - Severo

Table 3.7: Excel spreadsheet IVIC assignment section

For the given example in table 3.6, the assigned IVIC would be C - Severe for both insulation components tested, since the minimum measured RPDIV corresponds to this range of voltages.

The same machine might have different IVICs, one for the Phase-Phase insulation, and one for the Phase-Ground Insulation, since these tests are independent.

3.5.4 Compliance check

Although IEC 60034-18-41 [6] sets the procedures to assign an IVIC to a low voltage induction motor, IEC TS 60034-25 [12] and NEMA MG-1 [23] outline the recommended IVIC, or the voltage limits for the machine to operate partial discharge free, for low voltage induction motors.

According to IEC TS 60034-25 [12], the recommended IVIC is the following:

- Class C for Phase-Phase insulation, able to withstand $5,9 \times U_N$
- Class B for Phase-Ground insulation, able to withstand $3,1 \times U_N$

According to [23], the recommended limits for the PD free operating voltage are the following:

- For the Phase-Phase insulation, the machine should be able to withstand $5,6 \times U_N$
- For the Phase-Ground insulation, the machine should be able to withstand $3,9 \times U_N$

Therefore, the measured RPDIV shall be above this limits, for the machine to be in compliance with these standards. This should be taken into account, specially when the customer is in a market that is covered by NEMA Standards instead of IEC Standards. The software will compare the measured RPDIV to the values outlined by these standards, and will perform a compliance check, as shown in table 3.8.

Análise de Conformidade			
IEC 60034-25	FASE-FASE	FASE-TERRA	
IVIC Recomendada	C - Severo	B - Moderado	
Tensão em ordem a U_N	5,90	3,10	
Tensão (Vpp)	2360,00	1240,00	
Cumpre os requisitos?	✓	✓	

NEMA MG1 Part 30 & 31	FASE-FASE	FASE-TERRA	
Tensão em ordem a U_N	5,60	3,90	
Tensão (Vpp)	2240,00	1560,00	
Cumpre os requisitos?	✓	✓	

Table 3.8: Compliance check performed by this section of the software

3.6 Proposed PD Tests under Repetitive Impulse Voltage

As described previously in this work, the PD tests under repetitive impulse voltage, with a complete winding as test sample, allows the testing of all the insulation components, and therefore, the proposed test consists of a PD Type Test with Repetitive Impulse Voltage, for the measurement of the RPDIV, which will correspond to an IVIC.

These tests were first defined in [20] and redefined in [21]. Essentially, the repetitive impulse voltage would be generated by an impulse generator into the test sample, and a PD measuring circuit would measure the PD pulses on the test sample. The test is carried out using the Step-by-Step method.

3.6.1 Step-by-Step Method

The Step-By-Step (SBS) method is defined in [21] as the method of impulse voltage application of trains of repetitive impulse with step-by-step increase and decrease of peak values. As shown in Figure 3.4, the step-by-step method allows the measurement of the PDIV, RPDIV, PDEV and RPDEV, by increasing the impulse voltage from a start voltage U_S until a maximum voltage U_m , with a step voltage increase of ΔU .

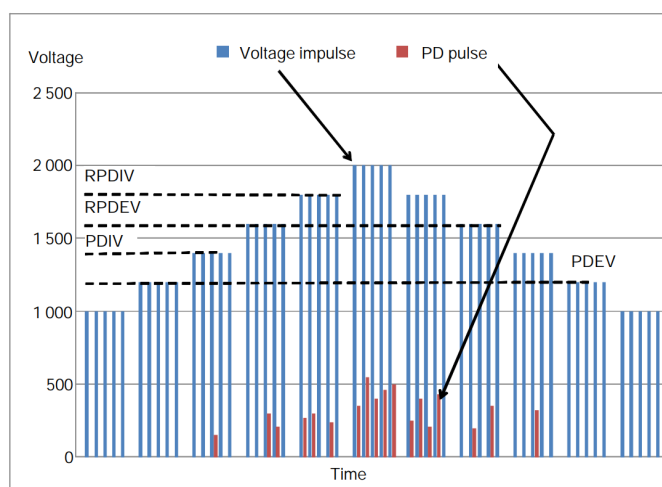


Figure 3.4: Application example of the SBS method [20]

This was the proposed method for the PD tests under repetitive impulse voltage. The test operator, while operating the Impulse Voltage Generator, shall increase the voltage by steps, after a defined number of impulses N_P in each voltage step (which should be no less than 10). The voltage should then be decreased when it reaches U_m , until the starting voltage U_S .

The PDIV will be registered once the first PD pulse occurs inside the stator windings. The RPDIV will be registered when for a N_P number of impulses, there are at least $0,5 \times N_P$ PD pulses. During the decrease of the test voltage, the RPDEV will be registered when there are less than $0,5 \times N_P$ PD pulses for a total of N_P number of impulses, and the PDEV will be registered when there are no PD pulses occurring inside the stator windings.

The test ends when the starting voltage U_S is reached.

3.6.2 Equipment

For the development of PD tests under repetitive impulse voltage, the necessary equipment consists of an impulse generator and a partial discharge measurement system, that is able to measure the PD pulses from the test sample, when the test sample is being submitted to an impulse voltage. Therefore, the equipment to be used on the proposed testing system would need to be in compliance with [6], [21] and [20].

3.6.2.1 Research

The first phase of the research consisted of a survey of the equipment available at WEGEuro, in order to understand the resources needed to implement the proposed method. A market study was also conducted so that, in the event that WEGEuro lacked the equipment required to conduct the tests, it would be possible to offer a variety of options for a potential equipment purchase.

After evaluating the existing equipment in WEGEuro's Laboratory, one of the proposed setups for PD testing consisted of:

- Megger Baker DX6 - Impulse Voltage Generator
- Omicron MPD800 - PD filter
- Omicron MCC 124 - Coupling Capacitor (1nF)
- PC with Omicron MPD Suite - Software to analyze test reports

The schematics in figures 3.5 and 3.6 show the proposed setup for the Phase-Ground and insulation PD test, and for the Phase-Phase insulation PD test, respectively. The difference between the two setups is the connection of the stator frame to the ground, according to IEC TS 60034-27-5 [21]. Also according to IEC TS 60034-27-5 [21], the turn/turn insulation can be tested with the same setup as the one proposed in figure 3.5. In this case, we would be testing the insulation for phase U, since it is the one being energized by the Impulse Voltage Generator, while phases V and W are grounded. In order to test the other phases' insulation, we would need to energize the phase we would like to test, and ground the remaining phases. These tests would allow the measurement

of the RPDIV, and the proposed equipment is in compliance with the IEC Standards, specifically the measurement system described in 2.2.2.1.

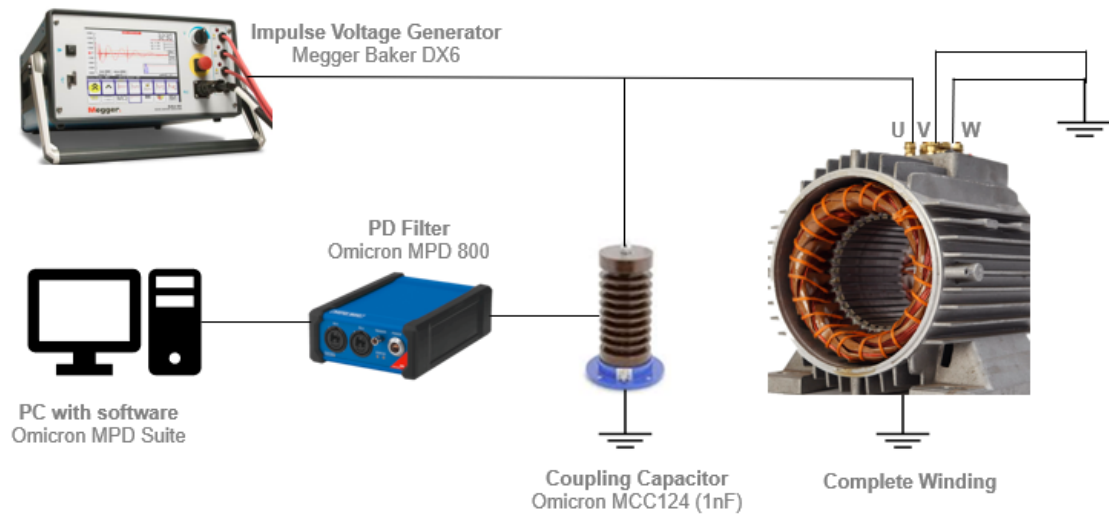


Figure 3.5: Test Setup proposed for the Phase-Ground insulation PD test

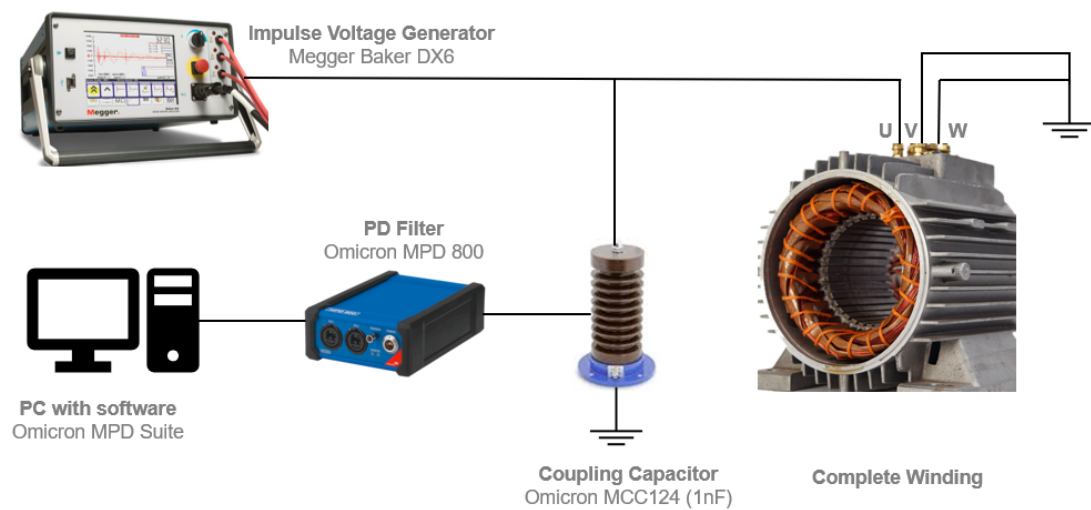


Figure 3.6: Test Setup proposed for the Phase-Phase insulation PD test

The other proposed setup consisted of using the Megger Baker DX6 with PD extension directly connected to the test sample, as the schematic in figure 3.7 shows. The Megger Baker DX6 with Surge PD extension available at WEGEuro's Laboratory allowed us to simplify the test setup, since it was a mobile equipment, and therefore could be used in various locations of the factory (or even other factories), and it didn't require for the use of the Laboratory Bench, leaving it available for other tests. This setup also dismisses the use of a PD filter, since the equipment (which is in compliance with IEC TS 61934 [20]) works as a impulse voltage generator and PD filter. This setup allowed for the automatic measurement of the RPDIV, and outputs the measured RPDIV and other measured quantities in the test report generated by the equipment.

MEGGER BAKER DX6 with SURGE PD

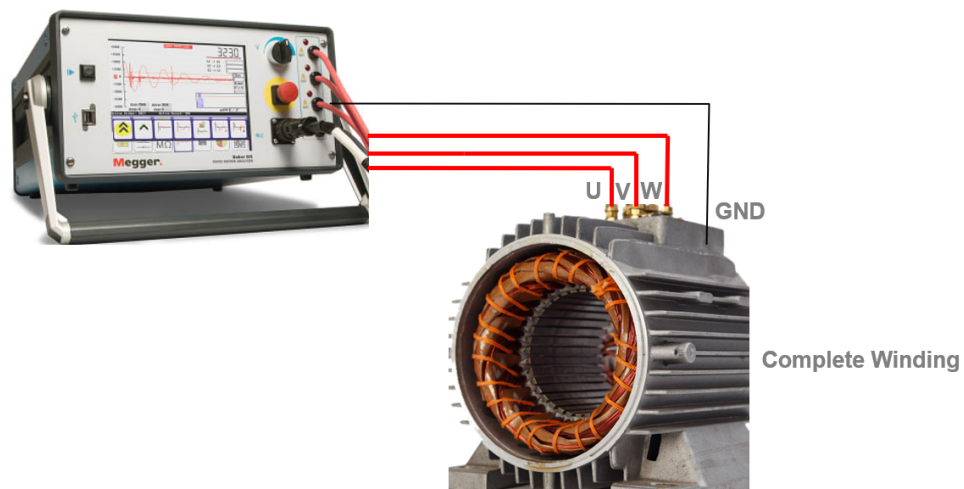


Figure 3.7: Proposed Test Setup with the Megger Baker DX6

One of the main characteristics that was taken into account when researching for the adequate equipment was the feature that some Impulse Voltage Generators (or Surge Testers, as they are also called) have, which is the automatic measurement of the RPDIV. Equipment like the Schleich MTC2 with the appropriate PD module (which uses an microwave antenna to detect PD pulses) has the ability to count how many impulses of voltage are being fed into the test sample, and how many PD pulses are occurring inside the test object's winding, and automatically output the values of the quantities we aim to measure: PDIV, RPDIV, PDEV and RPDEV. This feature reduces the variability of the results, and helps to simplify the test setup, since it does not require the use of a PD filter and an oscilloscope.

3.6.3 Experimental Setup

The proposed experimental setup is the one shown in figure 3.8, that was used in WEGEuro's Laboratory, with one of the two motors that were tested. Figure 3.9 shows the motor's terminal box, and how the leads from the Megger Baker DX6 were connected to each motor phase, and to the motor frame. This proposed setup allowed the testing of the Phase-Ground insulation.



Figure 3.8: Laboratory Setup of the proposed testing system: Test Sample (left) and Megger Baker DX6 (right)

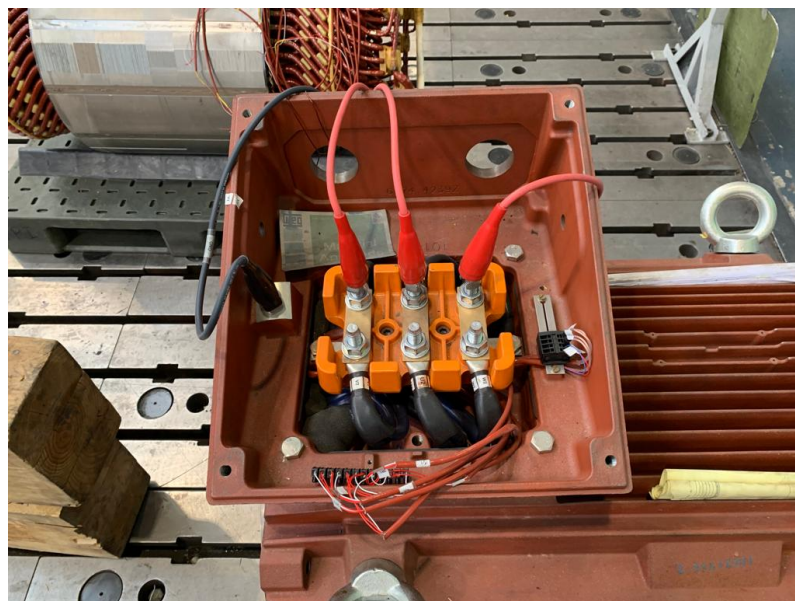


Figure 3.9: Connection of the Megger Baker DX6 test leads to the motor windings



Figure 3.10: Impulse voltage generator Megger Baker DX6

Figure 3.10 shows the impulse voltage generator Megger Baker DX6 that was used in the Laboratory during the conducted tests.

This proposal of a final setup allowed the testing of the Phase-Ground insulation of two low voltage induction motors with this specific characteristics:

- Motor #1: 315 kW, 4 Pole, $U_N = 400\text{V}$ (Delta Configuration), 315L
- Motor #2: 160 kW, 4 Pole, $U_N = 400\text{V}$ (Delta Configuration), 315S/M

These motors are prototypes in development, used for Research Tests, and were made available for these tests by WEGEuro's Research and Development Team.

3.7 Proposed Test Report

The Test Report template developed for partial discharge (PD) testing on low voltage induction motors, aligned with the requirements outlined in IEC TS 60034-27-5 [21], offers a comprehensive and structured framework for test operators to record essential parameters and observations during the testing process. This template serves as a standardized tool to ensure consistency and completeness in test reporting, facilitating accurate data documentation and analysis.

The Test Report Template consists of the following sections:

- Motor Specifications
- Parameters of Impulse Voltage
- Parameters of Train of Repetitive Impulses

- Parameters of Step-By-Step method
- Sensitivity, noise level and threshold for PD detection
- Type of Test Object and connections
- Relative humidity, temperature and air pressure during test
- Measured RPDIV during the PD test

These parameters are required by IEC 60034-27-5 [21] as data that shall be attached as a test report. The proposed report template is shown in Appendix B.

This report template was proposed in order to be possible to make a complete analysis on the test results and how the variation of a specific parameter can influence the measured RPDIV.

3.8 Proposed Laboratory Guide for the development of the tests

A step-by-step guide was written for the proposed method to enable the laboratory colleagues to perform the tests autonomously. For this, a training session was also carried out with the laboratory colleagues, where the procedures for applying this test were demonstrated, from assembling and connecting the test equipment, configuring the Megger Baker DX6 for RPDIV measurement, to recording the final results. The step-by-step guide is presented in Appendix C.

Chapter 4

Partial Discharge Test Results

This chapter presents an analysis of the results obtained from the PD testing conducted on low voltage induction motors. The tests were conducted with the setup proposed in Chapter 3, in WEGEuro's laboratory, with the assistance of the laboratory colleagues.

The tests were performed in order to validate the proposed testing system, and to evaluate the viability of performing these tests in WEGEuro's Laboratory with the available equipment.

The Impulse Voltage Generator used during these tests was the Megger Baker DX6 (as shown in Figure 3.8). The manufacturer Megger has an available PC software called Surveyor DX, which allowed us to export the results of the tests from the equipment to a PC, for a later analysis of this data. The configuration of the Megger BakerDX6 used during the tests was obtained after several illustrative tests. The "PD Sensitivity" (in mV) was one of the main parameters that had to be adjusted in the equipment configurations. It was required to be >7 mV, since the tests with a value of "PD Sensitivity" below that limit would read the existing noise in the system as PD pulses, making the tests inconclusive. This information was included in the Proposed Step-By-Step Guide shown in Appendix C.

The Step-By-Step method established in IEC TS 60034-27-5 [21], and described in chapter 3.6.1 was applied. For the various tests developed, the starting voltage U_S was 1000V and the step voltage increase ΔV was 200V.

The 2 test samples used were the motors described in chapter 3.6.3. The conducted tests allowed to test the Phase-Ground insulation of the 2 motors tested, and the chosen enhancement factor to apply to the testing voltages was 1,25.

4.1 Motor #1 Test Results

Figure 4.2 shows the test report generated by the Surveyor DX software, for the test developed on Motor #1. The PD Sensitivity was set to 10 mV in this test. The registered temperature in this test was 27°C and the relative humidity was 55%.

Figure 4.1 shows the applied Impulse Voltage waveform during the PD tests performed.

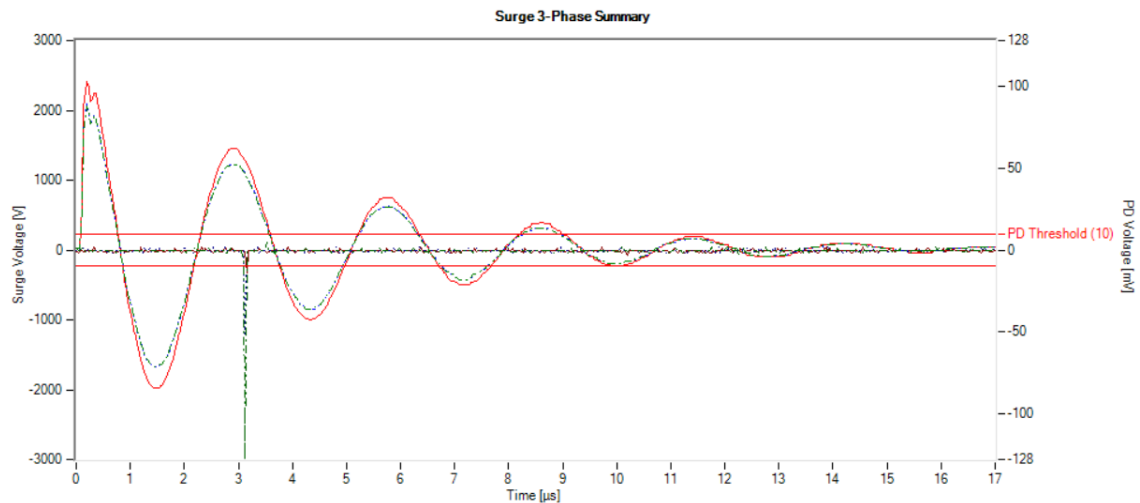


Figure 4.1: Waveform of the Impulse Voltage applied by the Megger BakerDX6 to the Motor#1

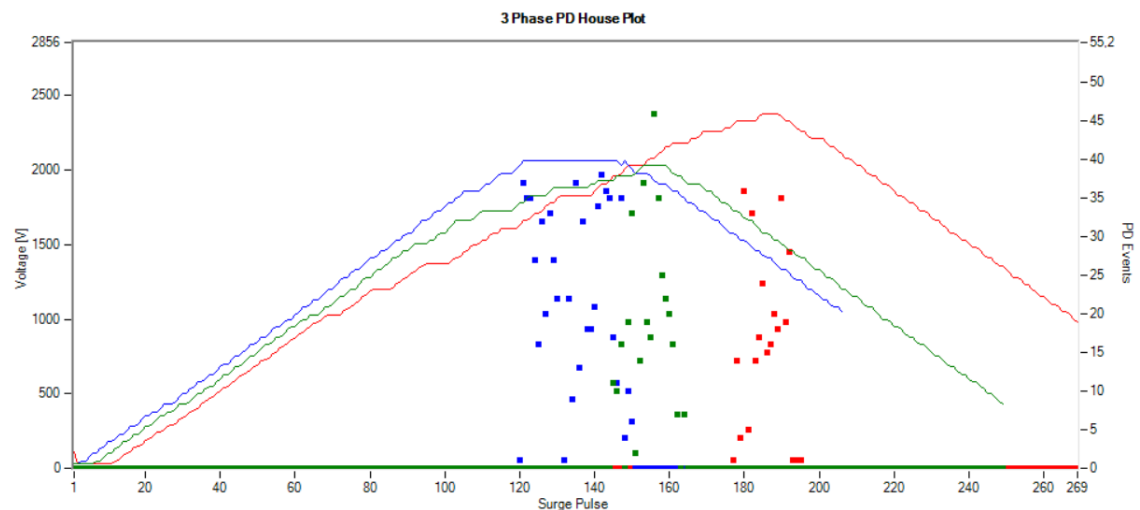


Figure 4.2: PD Test report on Motor #1, from the Surveyor DX software

The red, green and blue waveforms represent the test voltage for each phase. The red, green and blue points represent the PD pulses recorded by the equipment.

Phase	RPDIV Phase-Phase (Vpp)
Phase U	2330,00
Phase V	2060,00
Phase W	1960,00
Min RPDIV (Vpp)	1960,00

Table 4.1: Results for the measured RPDIV for Motor #1

By analysing the graphic shown in figure 4.2 and the values from table 4.1, there is evidence that the insulation in Phase W has the weakest Phase-Ground insulation, since the measured RPDIV has the lowest value in this phase. Phase U has the highest measured RPDIV, which would indicate that this phase's Phase-Ground insulation is more robust than the ones from the remaining phases.

Entering the test results on the proposed Excel Spreadsheet, we verify that the obtained IVIC for the Phase-Ground insulation is B - Moderate and that the Motor #1 Phase-Ground insulation was in compliance with the requirements set in IEC TS 60034-25 [12] and NEMA MG-1 [23].

4.2 Motor #2 Test Results

Figure 4.3 shows the applied Impulse Voltage waveform during the PD tests performed.

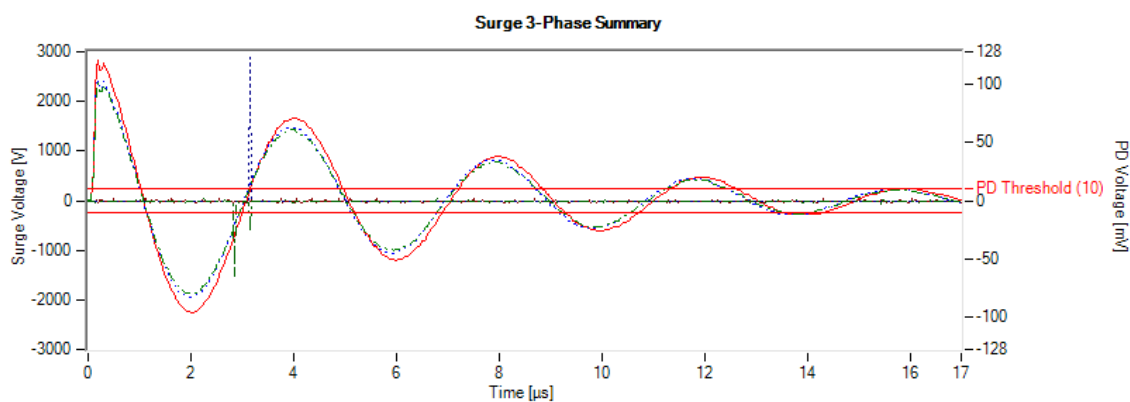


Figure 4.3: Waveform of the Impulse Voltage applied by the Megger BakerDX6 to the Motor#2

Figure 4.4 shows the test report generated by the Surveyor DX software, for the test developed on Motor #2. The PD Sensitivity was set to 10mV in this test. The registered temperature in this test was 25°C and the relative humidity was 58%.

Phase	RPDIV Phase-Phase (Vpp)
Phase U	2710,00
Phase V	2410,00
Phase W	2330,00
Min RPDIV (Vpp)	2330,00

Table 4.2: Results for the measured RPDIV for Motor #2

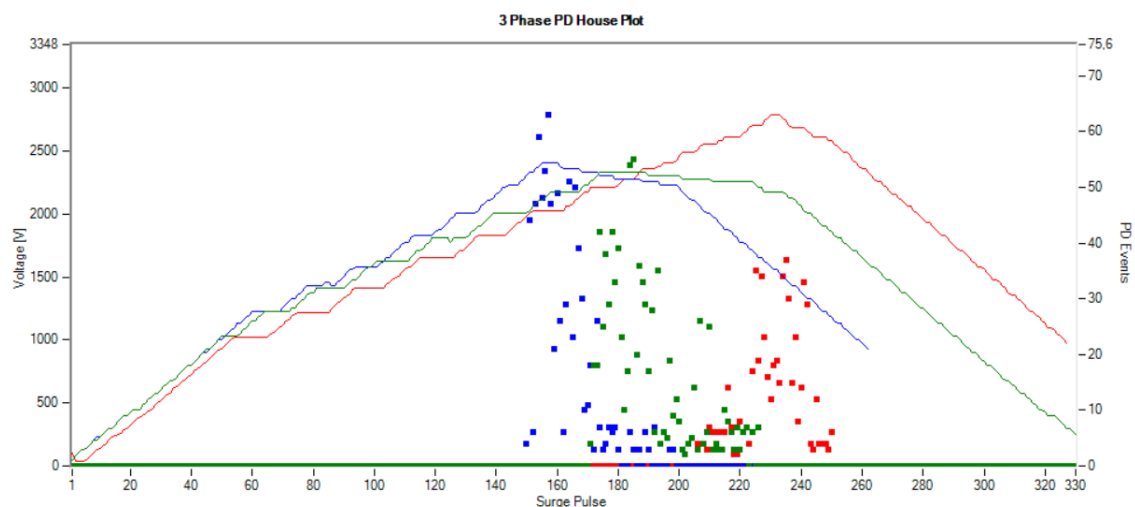


Figure 4.4: Results for the measured RPDIV for Motor #2

By analysing the graphic shown in figure 4.4 and the values from table 4.2, there is evidence that the insulation in Phase W has the weakest Phase-Ground insulation, since the measured RPDIV has the lowest value in this phase. Phase U has the highest measured RPDIV, which would indicate that this phase's Phase-Ground insulation is more robust than the ones from the remaining phases. These results are similar to the ones shown in the Motor #1 Test Results, although the RPDIV values are higher for this motor.

Entering the test results on the proposed Excel Spreadsheet, we verify that the obtained IVIC for the Phase-Ground insulation is C - Severe and that the Motor #1 Phase-Ground insulation was in compliance with the requirements set in IEC TS 60034-25 [12] and NEMA MG-1 [23].

Comparing the obtained IVICs for the two tested motors, it is noticeable that Motor #2 withstands higher repetitive impulse voltages without the occurrence of repetitive PDs. At first sight, the proposed testing system allows the measurement of the RPDIV for the Phase-Ground insulation, and the proposed Excel Spreadsheet reveals to be helpful in aiding with the Test Voltage calculation, assignment of the IVIC and IEC and NEMA Standards compliance check.

Chapter 5

Conclusion and Future Work

In conclusion, this dissertation has addressed the critical issue of insulation system qualification in low voltage induction motors through the development of a proposed testing system. The research encompassed several key stages, including a thorough study of the problem, assessment of necessary resources, proposal of the testing system, and validation through practical testing.

The testing system presented in this work has shown promising results in the qualification of insulation systems. The conducted PD tests have provided valuable insights into the integrity of the insulation and potential faults within the motor's system. However, it is important to note that further testing is required to fully validate the proposed system. An interlaboratory test or a round-robin test involving multiple laboratories would be valuable to assess the system's performance across different settings and ensure its robustness.

Moreover, it is recommended that WEGEuro continues to deepen their research on PD testing for IVIC assignment to frequency inverter-fed low voltage induction motors. This could involve the development of a comprehensive database to register the results from various tests performed, allowing for better analysis and monitoring of insulation system conditions over time. Additionally, the future work should be focused on the development of a phase-phase test methodology, complementing the proposed phase-ground test. This would provide a more comprehensive assessment of insulation integrity under different stress conditions.

Furthermore, it would be interesting to compare the two methods proposed in this research, namely the coupling capacitor method and direct connection to the surge tester. Such a comparison would shed light on the main differences between the two methods in terms of the resulting RPDIV values. This comparative analysis would contribute to a deeper understanding of the strengths and limitations of each method, aiding in the selection of the most suitable approach for specific testing scenarios.

In summary, this dissertation has provided a starting point for the company to advance their research on PD testing for insulation system qualification in low voltage induction motors. The proposed testing system and the insights gained from the conducted tests lay the foundation for further developments and improvements in motor performance assessment. By continuing this research journey, the company can enhance their understanding of insulation system conditions,

strengthen their maintenance strategies, and ensure the long-term reliability and performance of their motor operations.

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Appendix A

Excel Spreadsheet Proposal

Ensaio de Descargas Parciais Medição da RPDIV para determinação da IVC, segundo a IEC 60034-18-41					
U _N (V)	400	Incluir Fator de melhoramento?	Sim	Definir Fator de melhoramento (1,25 ≥ EF ≥ 1,95)	1,25
Tipo de Retificação (1 para meia onda, 2 para onda completa)	2	Incluir aumento de 10% devido à variação da tensão de fase em serviço?	Sim		
U _{DC} (V)	540,19				

Cálculo das Tensões de Teste de cada Categoria de Severidade

Categoria de Severidade	Tensões de Teste (Vpp)	
	Fase-Fase	Fase-Terra
A - Benigno	1634,07	1143,85
B - Moderado	2228,28	1559,80
C - Severo	2971,04	2079,73
D - Extremo	3713,80	2599,66

Registo dos resultados obtidos na Medição da RPDIV

	RPDIV Fase-Fase (Vpp)	RPDIV Fase-Terra (Vpp)
Fase U	3000,00	2300,00
Fase V	3100,00	2200,00
Fase W	3200,00	2100,00
Menor RPDIV Medida (Vpp)	3000,00	2100,00

Atribuição da IVC

IVC	Isolamento Fase-Fase	Isolamento Fase-Terra
	C - Severo	C - Severo

Análise de Conformidade

IEC 60034-25	FASE-FASE	FASE-TERRA
IVC Recomendada	C - Severo	B - Moderado
Tensão em ordem a U _N	5,90	3,10
Tensão (Vpp)	2360,00	1240,00
Cumprir os requisitos?	✓	✓

NEMA MG1 Part 30 & 31	FASE-FASE	FASE-TERRA
Tensão em ordem a U _N	5,60	3,90
Tensão (Vpp)	2240,00	1560,00
Cumprir os requisitos?	✓	✓

Appendix B

Test Report Template Proposal

		Relatório de Ensaio Medição do <i>RPDIV</i> para determinação da <i>IVIC</i>		Nº de Série 000000000	
Motor					
Tensão Nominal (V)		Tipo de Retificação			
Número de Fases		Número de Níveis do Conversor			
Tensão de Impulso					
Forma de Onda		Tempo de subida do impulso t_r (μs)			
Polaridade		Tempo de descida do impulso t_d (μs)			
Tipo de Distorção		Duração do Impulso t_w (μs)			
		Tempo de descida do impulso retangular t_f (μs)			
Conjunto de Impulsos					
Número de Impulsos N_p		Tempo entre impulsos t_{pp} (μs)		Padrão de Polaridade	
Método Step-By-Step					
Tensão de Início U_s (V)		Intervalo de Tensão entre conjuntos de impulsos ΔU			
Tensão máxima U_M (V)		Tempo entre conjuntos de impulsos t_{ss} (ms)			
Parâmetros Opcionais					
Presença de Rotor		Acondicionamento de Tensão			
Tipo de Rotor		Tensão (V)		Duração da Aplicação (s)	
Descargas Parciais					
Sensibilidade		Nível de Ruído		Limiar de Detecção DP	
Objeto de Teste					
Tipo de Objeto de Teste:					
Ligações de Teste para o Estator Bobinado	FASE-FASE		FASE-TERRA		
	Eletrodo AT	Eletrodo Terra	Eletrodo AT	Eletrodo Terra	
	Fase U				
	Fase V				
	Fase W				
Condições de Teste					
Humidade Relativa (%)		Temperatura (°C)		Pressão do Ar	
Medição <i>RPDIV</i>					
Fase U		Fase V		Fase W	
RPDIV Fase-Fase (Vpp)	RPDIV Fase-Terra (Vpp)	RPDIV Fase-Fase (Vpp)	RPDIV Fase-Terra (Vpp)	RPDIV Fase-Fase (Vpp)	RPDIV Fase-Terra (Vpp)
Nota: Incluir em anexo imagens da forma de onda da Tensão de Impulso e do Impulso de Descargas Parciais					

Appendix C

Laboratory Test Guide Proposal

Guia de Procedimentos de Teste Proposto para medição da *RPDIV*

REV.0 23/06/2023

1. Objetivo

Este guia tem como objetivo apresentar os passos necessários para a realização do ensaio de **Descargas Parciais** para medição da **Repetitive Partial Discharge Inception Voltage** (RPDIV), em motores de indução com sistema de isolamento do Tipo I, utilizados em máquinas com U_N até 700V, conforme a norma **IEC 60034-18-41**.

Este ensaio deve ser aplicado somente em máquinas que possuem fios circulares e enrolamentos randômicos. A **RPDIV** é definida como a tensão de início de descargas parciais repetitivas, que é o valor pico-a-pico da tensão de impulso a partir do qual ocorrem $0,5 \cdot N$ impulsos de DP a cada N impulsos de tensão aplicados. A partir da medição da RPDIV, é atribuída uma classe IVIC - **Impulse Voltage Insulation Class** à máquina.

Este ensaio permite a medição da *RPDIV* para o isolamento Fase-Terra.

2. Documentos complementares

- IEC 60034-18-41:2014+AMD1:2019;
- IEC TS 61934:2011;
- IEC TS 60034-27-5:2021;
- IEC TS 60034-25:2022;
- WPR – 25375 Rev. 01;
- Guia de Utilização do Baker DX6 – abril/2020.

3. Procedimento

3.1 Configuração Experimental

O equipamento principal necessário para aplicação dos ensaios de DP para medição da RPDIV é:

- Gerador de Impulsos de Tensão – **Megger Baker DX6** com extensão *Surge PD*;
- Objeto de Teste – Estator (sem rotor inserido);

O esquemático do sistema de teste é apresentado na Figura 1.

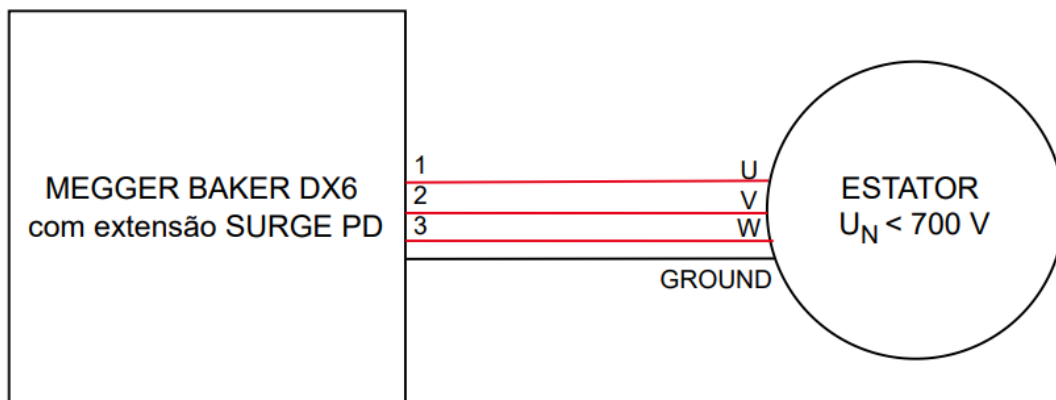


Figura 1 – Esquema do sistema de teste.

As fotografias da Figura 2, no Laboratório da WEG na Maia, mostram o sistema de teste utilizado (à esquerda), e a ligação das pontas de prova do Megger Baker DX6 na caixa de terminais do estator (à direita):



Figura 2 - Fotografias do Sistema de teste no Laboratório.

É importante observar que cada uma das pontas de prova de cor vermelha deve ser conectada a cada uma das fases dos enrolamentos do estator, enquanto a ponta de prova de cor preta deve ser conectada à carcaça do motor.

As pontas de prova vermelhas estão numeradas (1,2,3) e a ponta de prova preta etiquetada com “GND”. Deve ser registada em que fase dos enrolamentos é que foi ligada cada ponta de prova.

3.2 Configuração do Megger Baker DX6 no modo *Surge PD*

Passo 3.2.1 – Ligar Megger Baker DX6

Após ligação das pontas de prova, o gerador Megger Baker DX6 deve ser ligado e deverá aparecer o menu da Figura 3.

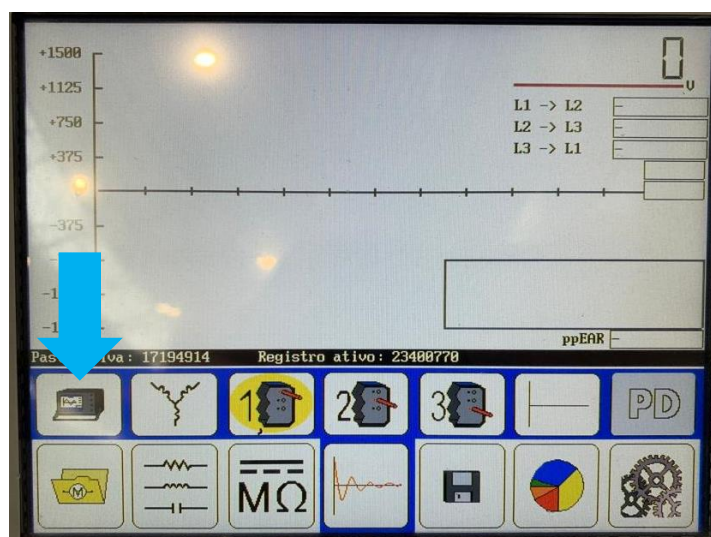


Figura 3 – Ecrã inicial.

Passo 3.2.2 – Aceder ao menu opções de Configuração

Para aceder ao menu de opções de Configuração, clique no botão indicado com a seta azul na Figura 3. O menu aparecerá, como mostrado na Figura 4. Em seguida, selecione o primeiro ícone, indicado com a seta vermelha.

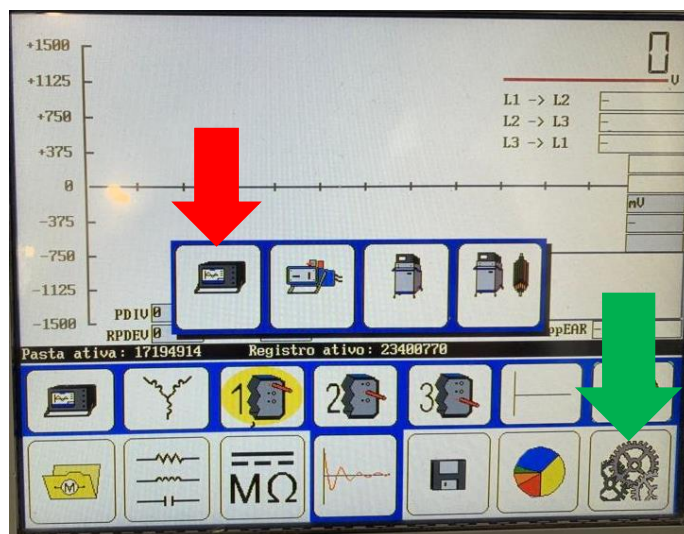


Figura 4 - Opções de Configuração.

Passo 3.2.3 – Configuração para a medição PD

Para configurar a medição PD, clique no ícone indicado na Figura 4 com a seta verde e, em seguida, aparecerá o menu de configurações, como mostrado na Figura 5.

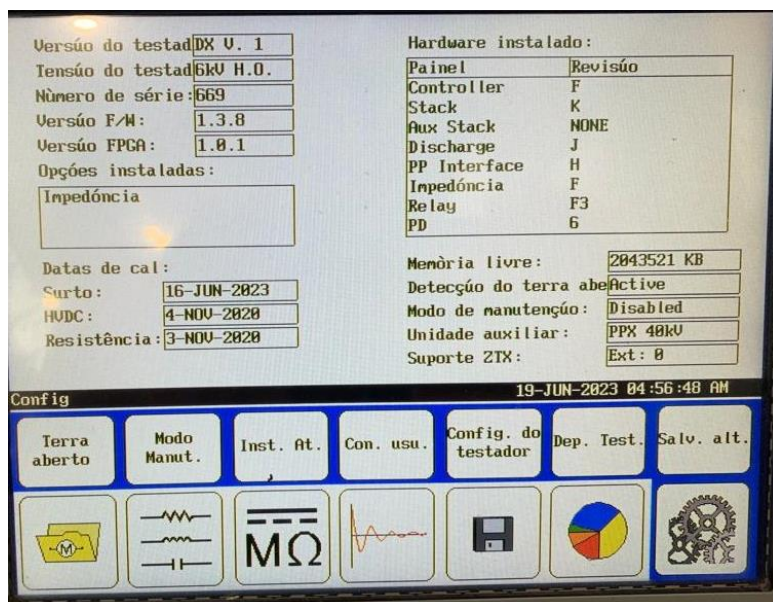


Figura 5 – Configuração para a medição PD – Ecrã 1.

É necessário ativar o Modo de Manutenção, de forma a ser possível alterar as configurações da medição PD (clicando no ícone “Modo Manut.”), e de seguida em “Ativar” como mostrado na Figura 6.

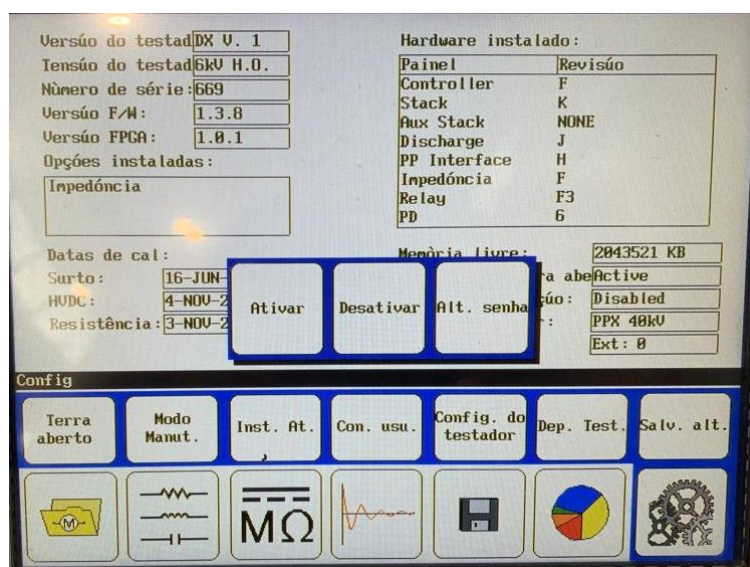


Figura 6- Configuração para a medição PD – Ecrã 2.

Para ativar o Modo de Manutenção é necessário introduzir a palavra-passe, que por definição é “BAKER”, como mostra a Figura 7.

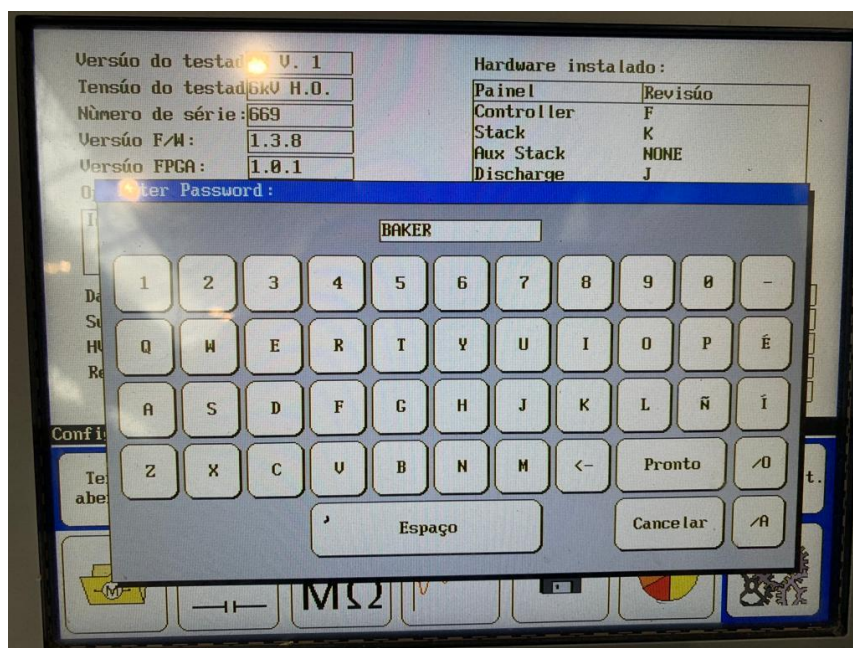


Figura 7- Ecrã para aceder ao Modo de Manutenção.

Depois de ativado o Modo de Manutenção, o equipamento deverá voltar a mostrar o menu da Figura 5, e deverá ser selecionado o ícone “Con. usu.” para abrir o menu que é mostrado na Figura 8.

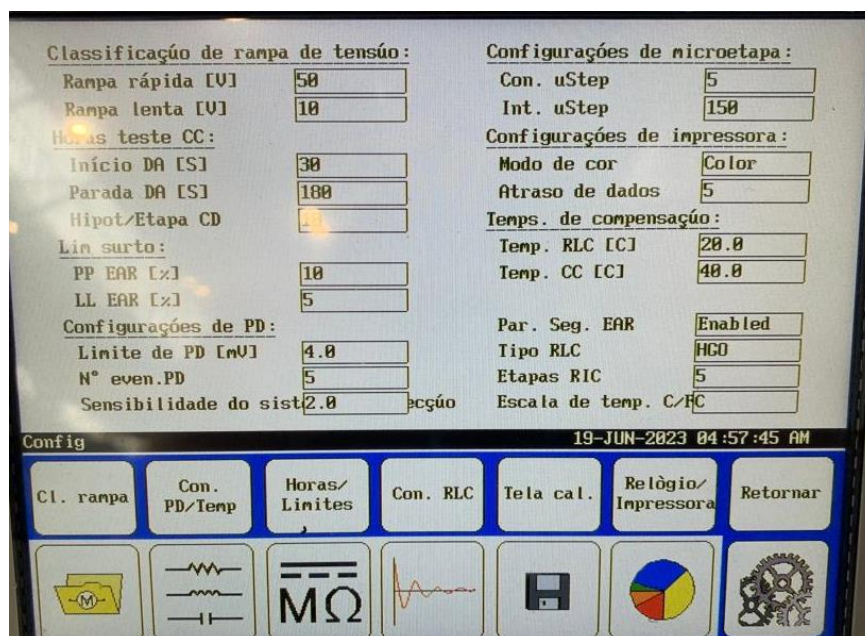


Figura 8- Configuração da Rampa de Tensão e PD - Ecrã 1

Aqui deverão ser ajustados os parâmetros de

- Classificação de rampa de tensão;
- Configurações de PD.

Classificação de rampa de tensão

A Rampa Rápida deverá ter 50 V e a Rampa Lenta 10 V, para que o aumento de tensão durante o teste seja suave e não seja ultrapassado o ponto exato onde se verifica o aparecimento das grandezas a medir (*PDIV*, *RPDIV*, *PDEV* e *RPDEV*). Isto pode ser regulado selecionando o ícone “Cl. rampa”.

Configurações de PD

Quanto às Configurações de PD, o limite de PD em mV deverá ser escolhido de forma que só os impulsos de descargas parciais ultrapassem este limite, e não o ruído das medições. A experiência com o equipamento e com as medições mostra que um limite de PD abaixo dos 7 mV capta ruído como impulsos de DP, e que por isso o limite de PD deverá ser superior ou igual aos 7 mV. O N° de eventos PD não deve ser inferior a 5, pela mesma razão. A Sensibilidade do Sistema de Detecção não pode ser inferior a 2.0, e não deverá ser superior ao N° de eventos PD. O Guia de Utilização do Baker DX contém mais informações sobre estas configurações. A Tabela 1 contém os valores aconselhados das Configurações PD para desenvolvimento do ensaio.

Limite PD (mV)	≥ 7
Nº Eventos PD	≥ 5
Sensibilidade do Sist. Detecção	≥ 2

Tabela 1 - Configurações PD

Estas configurações podem ser alteradas ao clicar no ícone “Con. PD/Temp” da Figura 8. De seguida, e como mostra a Figura 9, podem ser alterados o limite de PD (“Lim. PD”), o número de eventos PD (“Nº even. PD”) e a sensibilidade (“Sensibilidade do sistema de deteção”).

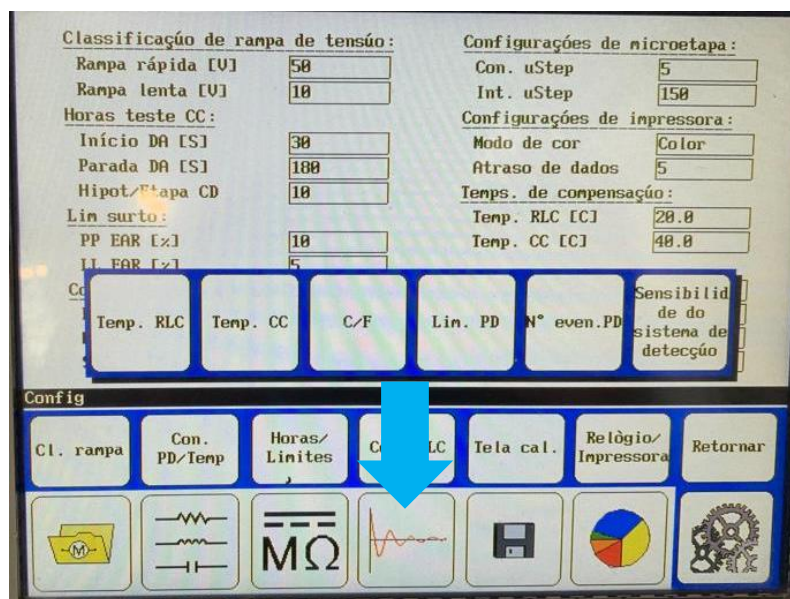


Figura 9 - Configuração da Rampa de Tensão e PD - Ecrã 2

Clicando no ícone indicado com a seta azul na Figura 9, o equipamento volta ao menu do teste de impulso mostrado na Figura 3. Aqui deverá ser ativado o modo PD, ao seleccionar o ícone “PD” de forma a que este fique com a cor verde, como mostra a Figura 10.

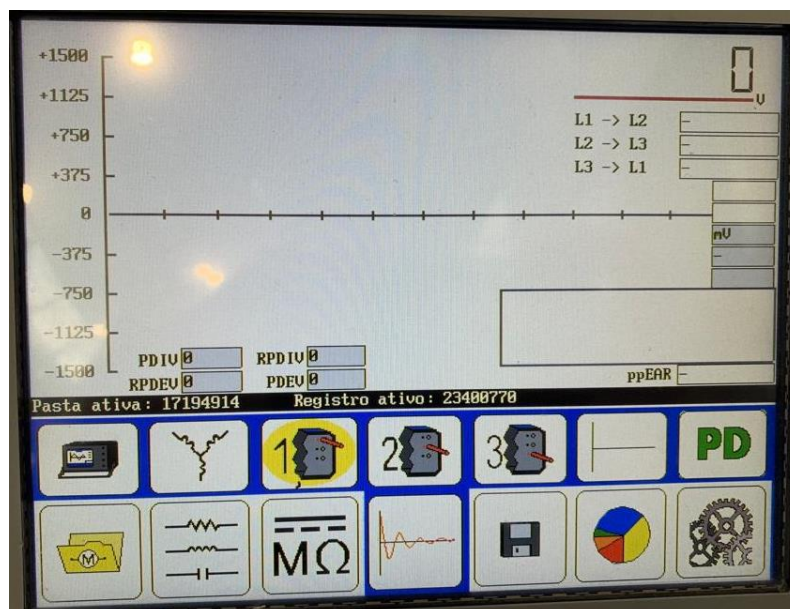


Figura 10 – Ativação do modo PD

Depois de completados os passos até este ponto, o operador estará pronto para iniciar o teste.

De notar que na Figura 10, o equipamento está pronto para iniciar o teste na Fase 1 (assinalada com a cor amarela). Para iniciar o teste nas outras fases, elas deverão ser seleccionadas antes de iniciar o aumento da tensão de teste.

3.3 Procedimento do Ensaio

Passo 3.3.1 – Início do Teste

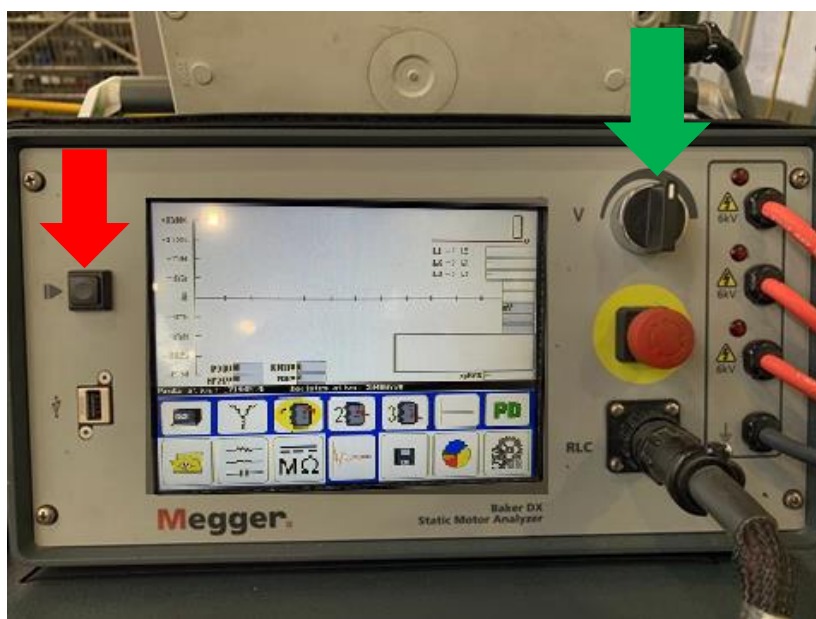


Figura 11 – Equipamento - botão e manípulo para início do teste (esquerda) e pedal (direita)

Para iniciar o teste, o operador terá de clicar no botão indicado com a seta vermelha na Figura 11, e no pedal (à direita) **ao mesmo tempo**, e fazer aumentar a tensão no manípulo indicado com a seta verde. Dessa forma o ecrã do equipamento deverá mostrar a mensagem “CONDUTORES ENERGI” (Condutores energizados) que se pode ver na Figura 12. É também no ecrã da Figura 12 que deverá ser seleccionada a opção de Rampa Lenta (assinalada a amarelo) e o ícone indicado com a seta azul deverá ser seleccionado de forma a que o cadeado esteja fechado. Isto garante que as formas de onda do Impulso de tensão e dos impulsos de PD estão sincronizadas.

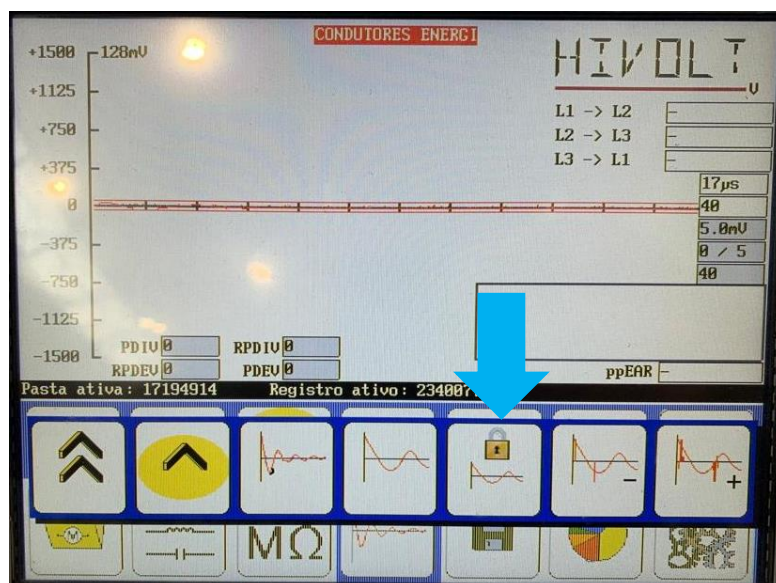


Figura 12 – Sincronização das formas de onda de Impulso e PD

A partir daqui, o teste poderá ser iniciado. O teste consistirá em aumentar a tensão de teste de forma suave e com uma rampa de subida lenta até que seja registado um valor de RPDIV. De seguida a tensão de teste deverá ser reduzida até aos 0V, terminando assim o teste.

A tensão de teste deve ser aumentada em degraus, com um ΔV igual para todos os degraus. Nos testes desenvolvidos na elaboração deste guia, o ΔV escolhido foi de 200V, em que se prosseguia para o degrau seguinte de tensão ao fim de aproximadamente 10 impulsos. Isto é, 10 impulsos a 800V, 10 impulsos a 1000V, 10 impulsos a 1200V e assim sucessivamente até atingir o RPDIV. O facto do aumento de tensão ser feito com rampa de subida lenta permite detetar rapidamente o ponto em que ocorre a PDIV e a RPDIV.

Verificou-se que o equipamento tem uma limitação de 4520 V na tensão de impulso gerada, o que pode não ser suficiente para gerar descargas parciais em máquinas com tensão nominal de 690V e categoria IV/C C - Severo ou D - Extremo.

3.4 Registo e Processamento dos Resultados

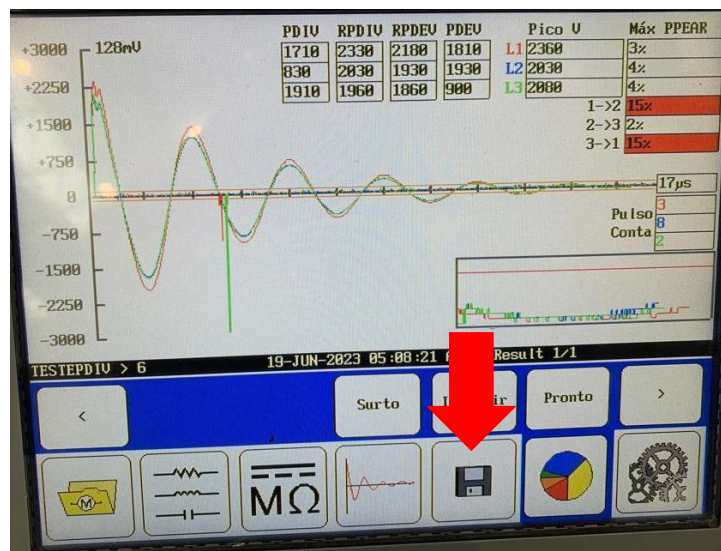


Figura 13 – Processamento dos resultados – função “Salvar Resultados”

A Figura 13 mostra o ecrã do equipamento no fim do teste das 3 fases. Para guardar os resultados deverá ser selecionado o ícone assinalado com a seta vermelha. A partir deste ecrã deverão ser registados os valores de PDIV, RPDIV, RPDEV e PDEV para as 3 fases. Os valores de RPDIV medidos em cada fase devem ser introduzidos no Dashboard do Excel, na secção “Resultados Obtidos” para processamento dos resultados pelo software, e posterior atribuição da IVIC à máquina.

O equipamento tem ainda a possibilidade de exportar os resultados para uma drive USB, para que possam posteriormente ser analisados no software Surveyor DX, que é o software próprio da Megger.

Deve ainda ser registada a temperatura e a humidade durante o ensaio, disponíveis no equipamento, como mostra a Figura 14.



Figura 14 – Termo higrómetro disponível no equipamento

Registo dos dados do Ensaio de DP para medição da RPDIV

Ponta de Prova	Fase do Enrolamento
1	
2	
3	

Temperatura (°C)	Humidade (%)

Resultados

Fase	PDIV	RPDIV	RPDEV	PDEV
1				
2				
3				