FACULDADE DE ENGENHARIA DA UNIVERSIDADE DO PORTO

Development of a Supporting Tool for Medium-Voltage Variable Speed Drives Testing

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Resumo

Os Variadores de Velocidade de Média-Tensão desempenham um papel crucial na indústria pesada, aumentando a eficiência energética e a segurança operacional em aplicações críticas. Ao contrário dos de Baixa-Tensão, os Variadores de Velocidade de Média-Tensão são soluções de engenharia altamente complexas e específicas para cada projeto, exigindo procedimentos de ensaios de rotina rigorosos e extensos para cumprir as normas internacionais e garantir a qualidade antes do comissionamento. No entanto, o fluxo de trabalho de ensaios atual na WEG assenta fortemente na interação manual. Por exemplo, no fluxo de trabalho tradicional, modificar e ler parâmetros exige uma navegação contínua, morosa e propensa a erros pela Interface Homem-Máquina do equipamento.

Para colmatar estas limitações e otimizar o processo de ensaio, esta dissertação foca-se na conceptualização, desenvolvimento e integração de uma ferramenta de *software*, batizada com o nome MVW3000 Test Wizard. Desenvolvida em Python, a aplicação faz a interface direta com o Variador de Velocidade—concretamente, o MVW3000—utilizando o protocolo de comunicação industrial Modbus TCP/IP. Ao analisar automaticamente o ficheiro de parâmetros do projeto e ao descodificar o código de identificação do MVW3000, a ferramenta calcula dinamicamente as parametrizações necessárias. Tanto quanto é do nosso conhecimento, não existe atualmente nenhuma ferramenta em código aberto ou solução dos maiores fabricantes desenvolvida para este propósito específico.

O *software* automatiza a parametrização do MVW3000 ao longo de todo o procedimento. Também lê parâmetros de *status* e de medição essenciais para a validação do equipamento. Este novo fluxo de trabalho reduz significativamente o esforço associado a tarefas altamente repetitivas, que anteriormente exigiam uma interação constante com a Interface Homem-Máquina e o registo manual dos dados de ensaio. Consequentemente, o tempo total de ensaio do MVW3000 foi reduzido em aproximadamente 20% e a capacidade efetiva de testes do laboratório aumentou aproximadamente 20%. O sistema incorpora um mecanismo robusto de persistência de dados através de ficheiros de dados estruturados para gerir o processo ao longo de vários turnos de trabalho. Adicionalmente, no final dos ensaios, a ferramenta exporta automaticamente um relatório de ensaio em formato PDF. Esta exportação automática torna o processo mais expedito e elimina as discrepâncias causadas pela transcrição manual. Para facilitar a implementação e integração da ferramenta, foi também desenvolvido um manual de utilizador.

Palavras-chave: Média-Tensão, Variadores de Velocidade, Ensaios de Rotina, Automação de Ensaios, Python, Modbus TCP/IP.

Abstract

Medium-Voltage Variable Speed Drives play a crucial role in heavy industry, enhancing energy efficiency and operational safety across critical applications. Unlike Low-Voltage ones, Medium-Voltage Variable Speed Drives are highly engineered, project-specific solutions that demand strict, extensive routine testing procedures to comply with international standards and ensure quality before commissioning. However, the current testing workflow at WEG relies heavily on manual interaction. For instance, in the traditional workflow, modifying and reading parameters requires continuous, time-consuming, and error-prone navigation through the equipment's Human-Machine Interface.

To address these limitations and streamline the verification process, this dissertation focuses on the conceptualization, development, and integration of an automated desktop software tool, named MVW3000 Test Wizard. Developed in Python, the application interfaces with the Variable Speed Drive—concretely, the MVW3000—using the industrial communication protocol Modbus TCP/IP. By automatically parsing the project parameters' file and decoding the MVW3000's identification code, the tool dynamically computes the required parametrization. To the best of our knowledge, there is no available open-source tool or solution from other major manufacturers that serves this specific purpose.

The software automates the parameterization throughout the procedure. It also reads key status and measurement parameters essential for equipment validation. This new workflow significantly reduces the effort associated with repetitive tasks, which previously demanded constant interaction with the Human-Machine Interface and the manual logging of test data. Consequently, the total MVW3000 testing time was decreased by approximately 20% and the laboratory's effective testing capacity per shift increased by approximately 20%. The system incorporates a robust data persistence mechanism using structured data files to manage multi-shift operations. Additionally, at the end of the testing routine, it automatically exports a test report in PDF format. This automatic exportation creates a more expeditious process and eliminates discrepancies caused by manual transcription. To facilitate the deployment and integration of the tool, a user manual was also developed.

Keywords: Medium-Voltage, Variable Speed Drives, Routine Tests, Automation of Testing, Python, Modbus TCP/IP.

UN Sustainable Development Goals

The United Nations (UN) Sustainable Development Goals (SDGs) [1] provide a global framework for achieving a better and more sustainable future for all. This dissertation, which focuses on the analysis and automation of Medium-Voltage (MV) Variable Speed Drives (VSDs) routine testing procedure, contributes directly to targets related to energy efficiency, industrial innovation, and technological modernization.

SDG 7 Ensure access to affordable, reliable, sustainable and modern energy for all.

SDG 8 Promote sustained, inclusive and sustainable economic growth, full and productive employment and decent work for all.

SDG 9 Build resilient infrastructure, promote inclusive and sustainable industrialization and foster innovation.

SDG	Target	Contribution	Performance Indicators and Metrics
7	7.3	By improving the reliability of MVW3000 testing through automation, the procedure reduces testing errors and inefficiencies, contributing indirectly to better performance and energy-efficient commissioning of MV VSDs.	Reduction of test-stage rework; increased reliability and consistency of test outcomes.
8	8.2	Automating elements of the test procedure increases productivity in industrial testing workflows by reducing manual steps.	Successful integration of automated logic in selected parts of the procedure; measurable reduction in manual operations.
9	9.4	Digitalizing parts of the test routine supports innovation, reduces complexity, and modernizes industrial testing infrastructure, which contributes to more resilient and scalable industrial processes.	Improvement in test reliability; enables future full automation.

[1] https://sdgs.un.org/goals

Acknowledgements

Life has taught me that the journey loses its meaning if the path only becomes easier. With every passing academic year, I was warned that the challenges would grow—and they did. As I conclude this academic chapter with a sense of fulfillment, I do not expect the road ahead to be any less demanding, nor do I wish for the challenges to end. It is through them that we grow.

I would like to begin by thanking those who made this work possible. First, to WEG and my colleagues at SAQE. A very special thank you to Eng. Sérgio da Costa Mendes and Eng. Carlos Sousa Anjos, whose availability, rigor, and genuine interest were fundamental in transforming what was once a mere idea into a reality.

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To my parents, Jorge and Célia: my most sincere thank you. You have been the fundamental structure of my education, shaping not only the person I am today but also the person I aspire to become. Everything I achieve is a reflection of the foundation you built.

To my closest friends, who need no names to know who they are: thank you for every moment, every shared laugh, and for all the times we helped each other heal and stay motivated. Thank you for reminding me that there is a world outside of my laptop screen and for keeping me (relatively) sane throughout this process.

Finally, a very special word to my girlfriend, Carla. You deserve an honorary degree just for the amount of patience you have shown. Thank you for standing by me every single day and for your incredible ability to bring a smile to my face in any situation. I know I can be a difficult person... sometimes... okay, a lot of times... but I am incredibly lucky to have you by my side through it all. I promise to be a much more fun person to be around now that this is over.

To everyone mentioned above: this work is as much yours as it is mine.

Pedro M.

"Eu procuro dizer como tudo é outra coisa.
Falo, penso."

Herberto Helder

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List of Acronyms

AC	Alternating Current
BOM	Bill of Materials
BLDC	Brushless DC Motor
CHB	Cascaded H-Bridge
CMI	Cascaded Multilevel Inverter
DC	Direct Current
DOL	Direct-on-line
EMI	Electromagnetic Interference
ERP	Enterprise Resource Planning
FACTS	Flexible AC Transmission Systems
FAT	Factory Acceptance Test
FOC	Field Oriented Control
GUI	Graphical User Interface
HiL	Hardware-in-Loop
HMI	Human-Machine Interface
HP	High-Power
HV	High-Voltage
IDE	Integrated Development Environment
IEC	International Electrotechnical Commission
IGBT	Insulated Gate Bipolar Transistor
I/O	Input/Output
IP	Ingress Protection
LV	Low-Voltage
MCU	Microprocessor Control Unit
MLI	Multilevel Inverter
MV	Medium-Voltage
PWM	Pulse Width Modulation
SCADA	Supervisory Control and Data Acquisition
SDG	Sustainable Development Goal
SOTA	State-of-the-Art

THD Total Harmonic Distortion

UL Underwriters Laboratory

UN United Nations

VFD Variable Frequency Drive

VSD Variable Speed Drive

WPS WEG Programming Suite

Chapter 1

Introduction

Medium-Voltage (MV) Variable Speed Drives (VSDs) play an important role in enhancing efficiency, safety, and connectivity across heavy industrial applications, such as large-scale compressors, pumps, fans, conveyors, and mills [50]. In this chapter, we present the background and motivation for this dissertation under the topic of testing these products, establishing the primary goals and expected outcomes. It also provides an overview of the host company and concludes by outlining the overall structure of the document.

1.1 Background and Motivation

VSDs are available for a wide range of voltage levels. Based on the IEC 60038 standard, we can group them as follows:

- **Low-Voltage (LV)**: Rated supply voltages up to 1 kV AC;
- **Medium-Voltage (MV)**: From 1 kV to 35 kV AC;
- **High-Voltage (HV)**: Above 35 kV AC.

However, a significant distinction exists between LV and MV VSDs. While LV VSDs—commonly used in industries such as printing, textiles, material handling, and agriculture—are typically standardized and manufactured in high volumes, MV VSDs operate at higher voltages and are highly engineered, project-specific solutions. Their applications in heavy industries, such as mining and oil & gas, are considered highly critical because any equipment failure or unforeseen downtime can result in massive financial losses, severe safety hazards, or even widespread operational disruptions. Consequently, these VSDs must undergo extensive testing procedures to comply with both stringent regulatory standards and specific customer technical requirements.

Beyond acting as a regulatory obstacle, these tests serve as an important quality assurance milestone for both the manufacturer and the end-user. For the customer, the successful execution of these tests provides the necessary guarantees that the equipment will operate reliably within its specific industrial context.

This procedure is characterized by a high volume of manual and repetitive tasks. Furthermore, it demands a highly skilled and specialized workforce, which is difficult to train and retain. Relying on manual intervention also introduces the potential for human error; when mistakes occur, entire testing phases may need to be repeated, further prolonging lead times.

Although multiple VSDs can be assembled concurrently, testing capacity within the host company is restricted to a single unit at a time mainly due to limitations in available space and specialized personnel. This limitation generates a queue of VSDs awaiting testing, creating a bottleneck that is increasingly incompatible with current market trends of rising demand and pressing delivery schedules.

In this context, a significant opportunity for process optimization arises. The internal parameters of WEG's MV VSDs—which must be frequently adjusted during the testing phase—can be easily accessed and modified through standardized industrial communication protocols. By leveraging these native communication features, it becomes possible to automate many of the manual and repetitive tasks currently required during the testing workflow, thereby reducing execution time and mitigating the risk of human error.

1.2 Goals and Expected Outcomes

The primary goal of this dissertation is to conceptualize and develop an automated tool to structurally support and optimize the testing procedures for MV VSDs. By establishing direct communication with the VSD to manipulate parameters and automate test execution, this work aims to reduce testing duration. This approach minimizes the margin for human error and ensures faster delivery cycles.

To achieve this, the specific goals and expected outcomes of this research are defined as follows:

- **Conduct a comprehensive analysis of the current testing procedures**, identifying specific manual and repetitive tasks, as well as procedural ambiguities, that can be improved through digitalization;
- **Define a robust software and communication architecture** capable of interfacing directly with the VSD, enabling secure and real-time data exchange;
- **Develop and deploy the automated platform**, integrating an intuitive Graphical User Interface (GUI) to guide technicians through standardized test sequences and parameter adjustments;
- **Produce complete technical documentation**, including a comprehensive user manual to facilitate personnel training and ensure the correct utilization of the developed tool on the factory floor.

Based on these expected outcomes, this dissertation is guided by three main research questions. The first addresses whether the testing procedure can be partially automated by converting

manual operations and configuration rules into software logic, thereby reducing reliance on technicians' interpretations. The second examines if direct communication with the VSD can minimize the manual effort, Human-Machine Interface (HMI) interaction, and transcription errors associated with parameterization and data collection. Finally, the third assesses whether the developed tool delivers measurable improvements to the overall workflow, specifically regarding testing time reduction and documentation consistency.

1.3 About WEG

WEG[1] is a global Brazilian electromechanical company founded in 1961 in Jaraguá do Sul. It has become one of the world's largest manufacturers of electric motors and industrial automation solutions, operating production plants and commercial units in numerous countries and serving customers in over 135 countries. WEG supplies equipment to sectors such as oil & gas, mining, paper, steel, infrastructure, and energy.

Figure 1.1: WEG Logo.

In recent years, the company has intensified investments in innovation, focusing on energy efficiency, electric mobility, digitalization, and integrated automation systems. Its offer now includes electric motors, frequency inverters, soft-starters, controllers, Supervisory Control and Data Acquisition (SCADA) systems and others. WEG's operations in Portugal are based in an industrial park in Santo Tirso (Figure 1.2), which was expanded with the inauguration of a new factory on October 17, 2024.



Figure 1.2: WEG's industrial park in Santo Tirso, Portugal.

[1] All information of WEG was retrieved from https://weg.net

This dissertation will be carried out at WEG's facilities in Santo Tirso, specifically at the Automation Solutions and Electric Panels Department. It offers Europe's most advanced testing laboratory, allowing for a real industrial environment for the development and validation of the work presented in this document.

1.4 Document Structure

This document is organized into six main chapters, as follows:

- **Chapter 1:** Presents the background and motivation for the study, establishing the primary goals and expected outcomes. It also provides an overview of WEG, the industrial partner where this research is conducted.
- **Chapter 2:** Explores the operating principles of VSDs and their role in motor control compared to traditional starters. It provides a detailed technical characterization of the MVW3000 MV VSD, which serves as the target equipment for this work.
- **Chapter 3:** Explains the testing procedure's structure and the MVW3000 testing environment. It contains an overview of the procedure's structure, a detailed description of the laboratory where the tests are conducted, and important findings from the analysis of the testing procedure. Finding opportunities to automate certain aspects of the testing workflow is the chapter's conclusion.
- **Chapter 4:** Explains the development of the automated test logic, the communication architecture between the VSD and the dedicated PC application. The validation of the implemented solution and the modifications made following the validation phase are also covered in this chapter.
- **Chapter 5:** Evaluates the practical impact of the developed automated tool on the testing workflow, followed by a discussion of challenges faced and limitations of the tool.
- **Chapter 6:** Includes the conclusions of the work, summarizing the main results achieved and discussing development perspectives.

Chapter 2

Variable Speed Drives: From Fundamental Concepts to the Target Equipment

Understanding how VSDs work and why they outperform traditional motor starters is fundamental. Furthermore, when dealing with MV applications, these systems face unique electrical and structural challenges. These details are crucial, as they directly shape the architecture of the equipment. While WEG manufactures two MV VSD models—the MVW01 and the MVW3000—this work focuses on the MVW3000, as it is a more demanded product in the market, making its testing optimization a priority.

While the terms VSD and Variable Frequency Drive (VFD) are often used interchangeably in industrial contexts, they represent distinct technical concepts. A VFD is a specific type of electronic controller designed to regulate the speed of an Alternating Current (AC) motor—typically an induction motor—by exclusively varying the frequency and voltage of the electrical power supplied to it. In contrast, VSD is a broader term that encompasses any system capable of controlling the operating speed of a mechanical load, which includes VFDs, Direct Current (DC) motor drives, and other advanced control topologies [13].

Throughout this dissertation, the term VSD is adopted. This choice is technically justified because the target equipment, the MVW3000, extends its capabilities beyond standard AC induction motors. Furthermore, VSD is the common terminology used by personnel within WEG's everyday operations.

2.1 What is a Variable Speed Drive?

A VSD is an electronic device that controls the speed and torque of an electric motor by varying the frequency and voltage of its power supply. Its main purpose is to optimize process performance and improve energy efficiency by adapting the motor's behaviour to varying load requirements [42]. Beyond simple speed adjustment, VSDs allow for the smooth start and stop of the

motor through programmed acceleration and deceleration ramps [27].

LV VSDs, like the WEG's CFW500 (Figure 2.1) with an output power ranging from 0.18 and 132 kW, are typically used in general-purpose industrial applications such as conveyor belts, extruders, roller tables, palletizers, welding machines, and fans [48].



Figure 2.1: WEG's CFW500 VSD for general purposes [48].

MV VSDs such as the WEG's MVW3000 (illustrated in Figure 2.2) are intended for high-power applications—for instance, mills in the mining industry, as well as fans, pumps, and compressors across power generation (such as hydroelectric dams), petrochemical, paper, and cement industries [50]. As mentioned above, this VSD model is the target equipment of this dissertation.



Figure 2.2: WEG's MVW3000 MV VSD [50].

Despite differences in scale and topology, all these VSDs share the same fundamental working principle, as shown in Figure 2.3.

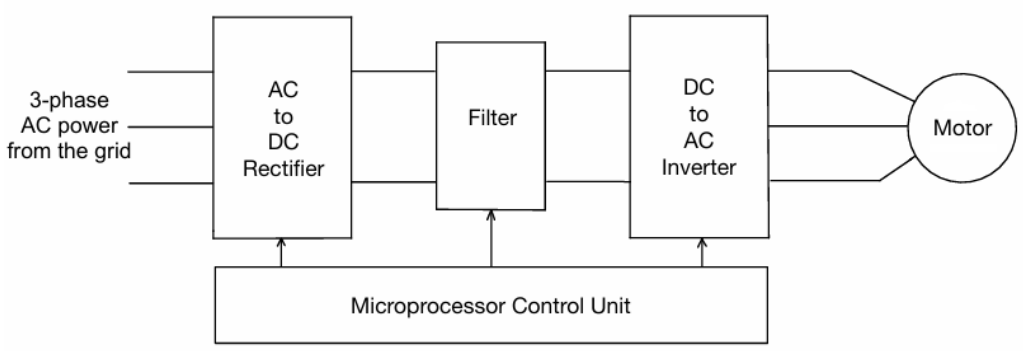


Figure 2.3: General working principle of a three-phase VSD. Adapted from [30].

A VSD is managed by a Microprocessor Control Unit (MCU), which acts as the system's "brain" by monitoring user inputs and precisely timing the internal switching process. In addition, feedback information such as motor current, torque, or speed can be included to allow closed-loop control. VSDs first convert the fixed-frequency AC power from the grid into DC through a rectifier, which takes the standard AC voltage from the grid and uses rectifier circuits based on power diodes to allow current to flow in a single direction. This operation creates a DC output that flows into the DC bus, where it is instantly conditioned by a capacitor bank, which serves as a filter to maintain a smooth, consistent voltage. Finally, an inverter converts the smoothed signal back into a variable-frequency AC signal. This conversion is achieved through Pulse Width Modulation (PWM) [42].

To switch the DC voltage thousands of times per second, the inverter relies on high-speed transistors, usually Insulated Gate Bipolar Transistors (IGBTs). By applying PWM to vary the pulse width, the system approximates a sine wave at the required frequency and voltage, enabling precise control over the motor's performance [55].

While VSDs offer significant control benefits, they are nonlinear loads, as their rectifier and switching electronics draw non-sinusoidal current pulses from an otherwise sinusoidal supply, which, in turn, generates harmonic distortion in the network. These high-frequency distortions can cause overheating in transformers and interference with sensitive electronics nearby. To mitigate this, modern installations often include line reactors or harmonic filters to ensure that the "cleanliness" of the power grid remains within regulatory limits while also limiting the high-frequency components of current and voltages to the motor side [4].

2.2 Variable Speed Drives in Motor Control

VSDs can be positioned as the most versatile and process-oriented motor control solution when compared with traditional starters. Direct-on-line (DOL) or star-delta starters are simpler and cheaper than VSDs. However, they simply apply full line voltage and leave the motor running at essentially fixed speed, while VSDs actively adjust both voltage and frequency to control motor torque and speed over a wide operating range. Electronic soft starters already reduce inrush

current and mechanical stress by ramping the voltage during start-up, but they do not regulate speed in steady state and, therefore, remain suited mainly to fixed-speed applications where only a smoother start is required. In contrast, a VSD enables continuous closed-loop speed control, integration with fieldbuses and higher-level automation systems, and precise adjustment of motor behaviour to match process demands. This is particularly valuable in applications where operating away from nominal speed can deliver substantial energy savings and reduced mechanical wear [11, 42, 44].

From energy-efficiency and lifecycle perspectives, VSDs' efficiency is generally high (92 to 99%) [32], but the true energy savings come from the ability to adapt motor speed and torque to the actual load curves. Considering *Affinity Laws*, since power consumption in centrifugal loads is proportional to the cube of the speed, even modest reductions yield substantial results. For instance, decreasing a fan's speed by 20% can cut its energy requirements by nearly 50% [42]. Apart from the savings on the electricity bill, VSDs can improve operational efficiency and promote savings in maintenance and spare part costs [3].

2.3 Medium-Voltage Variable Speed Drives: A Specific Domain

The global demand for clean energy and energy efficiency has triggered a rapid expansion of sustainable power generation and the use of VSDs [41]. In heavy industries, VSDs operating at MV have become indispensable. This shift is not only driven by industrial needs but also by the integration of renewable sources (wind and solar) and the implementation of Flexible AC Transmission Systems (FACTS) to improve grid stability and capacity [10, 14, 17, 39].

Historically, reaching MV levels with traditional two-level inverters required the use of bulky, lossy, and expensive transformers. These components often introduce nonlinearities and saturation problems, challenging system control. The emergence of Multilevel Inverters (MLIs) provided a transformative solution, allowing for HV operation and reduced harmonic distortion without the need for transformers. Among these, the Cascaded Multilevel Inverter (CMI) stands out due to its modularity and low component count, making it the preferred choice for FACTS and modern MV VSDs [17].

Understanding the advantages of MLIs requires a comparison between traditional two-level inverters and multilevel topologies.

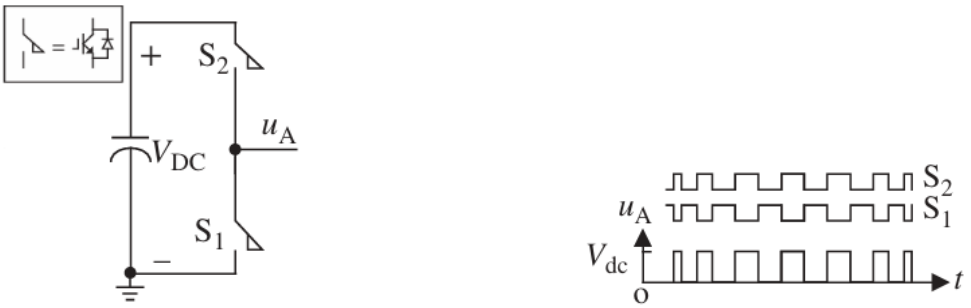
2.3.1 Two-level Inverters

The two-level inverter[1] is the most basic topology, where each phase output is connected to either the positive or negative terminal of the DC bus. The switching states of the single-phase two-level inverter, illustrated in Figure 2.4a, are controlled to regulate the output voltage u_A. To prevent a destructive short circuit, switches S_1 and S_2 must operate complementarily:

[1] The review on two-level and multilevel inverters is primarily based on the work presented in [17].

- When S_2 is conducting and S_1 is blocked, the output voltage u_A equals the DC bus voltage (V_{DC}).
- Conversely, when S_1 is conducting and S_2 is blocked, the output terminal is pulled to the reference voltage, resulting in $u_A = 0$.

As a result of this alternating sequence, the output alternates between these two discrete levels, producing the waveform illustrated in Figure 2.4b.



(a) Single-phase two-level inverter.

(b) Two-level voltage.

Figure 2.4: Single-phase two-level inverter [17].

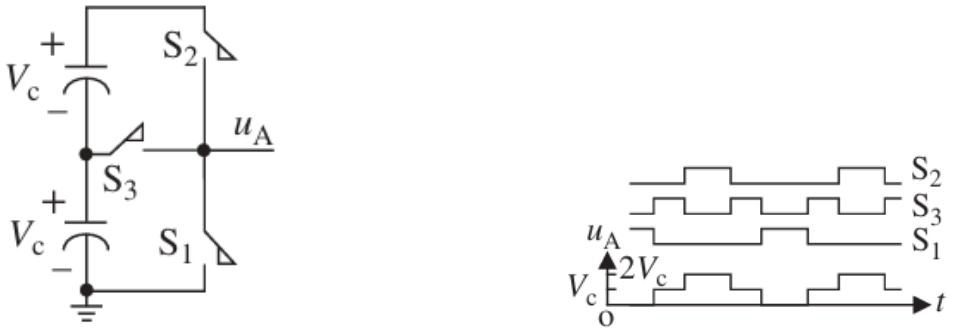
While effective for LV applications, its implementation in MV faces significant obstacles [43]:

- **Voltage Limitation:** Standard semiconductors cannot handle the full MV line voltage, necessitating the bulky and lossy transformers mentioned previously.
- **High** $\mathrm{d}u/\mathrm{d}t$ **Stress:** The large voltage steps during switching cause high Electromagnetic Interference (EMI) and premature insulation stress on motor windings.
- **Harmonic Distortion:** The output waveform is a rough approximation of a sine wave, requiring large and expensive filters to ensure power quality.

2.3.2 Multilevel Inverters

MLIs emerged as a solution to overcome the limitations of the two-level topology in High-Power (HP) applications. The fundamental concept of an MLI is to synthesize a staircase-like output voltage waveform from several levels of DC voltages.

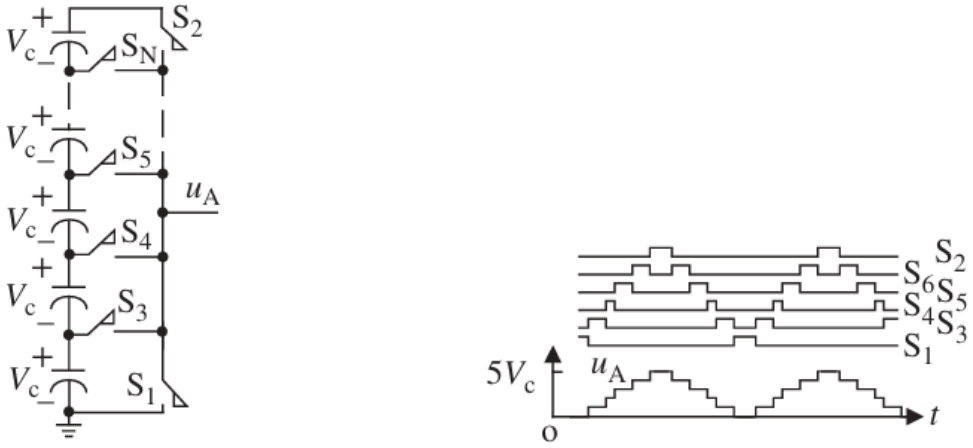
Figure 2.5a illustrates a single-phase three-level topology and Figure 2.5b shows the resulting three-level voltage, which is closer to a pure sine wave than the two-level one.



(a) Single-phase three-level topology. (b) Three-level voltage.

Figure 2.5: Single-phase three-level inverter [17].

As the number of levels increases, the output waveform becomes smoother and closer to a pure sine wave, as it is possible to see in Figure 2.6.



(a) Single-phase N-level topology. (b) Six-level voltage.

Figure 2.6: Single-phase MLI [17].

When extending these concepts to a three-phase configuration, individual single-phase multilevel legs are typically replicated for each phase. MLIs offer other benefits beyond a smoother waveform, like a lower $\mathrm{d}u/\mathrm{d}t$, less EMI, higher power quality, and fault-tolerant operation. Adding more levels makes the system harder to control, requires more parts, and creates challenges with voltage balancing [43].

While the fundamental operating principles are consistent across voltage levels, MV VSDs operate in a distinct environment defined by higher power ratings, complex multilevel topologies (like the CMI), and critical applications. The strategic importance of these drives extends beyond simple motor control; they are essential for energy savings and process optimization in environments where control challenges are far more pronounced than in LV scenarios [31].

Using advanced multilevel structures and offering high programmability, the MVW3000 serves as an ideal platform to explore the implementation of sophisticated drive-centric control algorithms in this demanding domain [50].

2.4 The MVW3000

The operational capabilities of the MVW3000 are defined by its internal topology, core design principles, and the specific motor types it is engineered to control.

2.4.1 Supported Motors

The MVW3000 is engineered for the precise speed and torque control of three-phase induction motors [51]. An example of these motors, shown in Figure 2.7, is WEG's W60 series, with an output power from 185 kW to 16 MW.

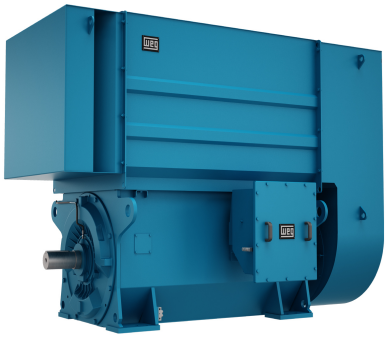


Figure 2.7: WEG's W60 series three-phase induction motor [54].

These motors are supported via two primary control strategies:

- **Scalar (V/f) Control:** Maintains a constant magnetic flux at the desired steady-state value in the motor's air gap by regulating the magnitude of stator voltages and frequency [5]. It is ideal for steady-state applications, such as pumps and fans, where high dynamic performance is not a primary requirement [8].
- **Vector Control:** Also known as Field Oriented Control (FOC), this method provides torque control by decoupling the stator current into two components, one that produces torque and the other that produces flux [57]. By aligning the reference frame with the rotor flux vector, it is possible to achieve independent control of flux and torque under both steady-state and dynamic conditions [38]. This control strategy enables the induction motor-inverter system to outperform conventional DC drives [18].

To extend its capabilities to synchronous motors, which include Brushless DC Motors (BLDCs), the MVW3000 incorporates specialized software functions and dedicated hardware modules. In

this case, the VSD integrates an independent excitation control system. This system is powered by an auxiliary grid through an AC-DC converter to regulate the rotor's field winding currents. Controlling synchronous machines requires the use of an absolute encoder to determine the precise spatial position of the rotor relative to the stator [51]. An example of these motors, shown in Figure 2.7, is WEG's S series, with an output power up to 100 MW.

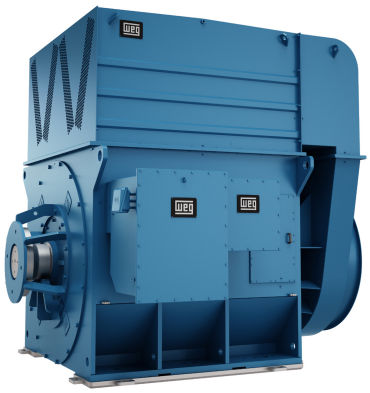


Figure 2.8: WEG's S series synchronous motor [53].

2.4.2 Core Design

This drive implements a multilevel Cascaded H-Bridge (CHB) inverter topology, which is one of the predominant architectures for modern MV VSDs [50, 55]. A key characteristic of the CHB topology, as seen in the MVW3000, is its use of series-connected LV IGBT-based power cells to achieve MV operation (Figure 2.9), rather than relying on a single converter. To understand how the inverter builds its voltage waveform, we can look at the combination of the power cells. Each individual H-bridge power cell can produce three distinct voltage levels ($+V_{DC}$, 0, and $-V_{DC}$), depending on how its internal IGBTs are switched. In the example of Figure 2.9, there are nine power cells equally split across three electrical phases, meaning there are three series-connected cells per phase.

Because these three cells are series-connected, their individual voltage levels simply add up. By controlling the switching of the IGBT, their outputs combine chronologically to create a phase-to-neutral voltage that ranges anywhere from $+3V_{DC}$ (when all three cells are at $+V_{DC}$) down to $-3V_{DC}$ (when all three cells are at $-V_{DC}$). This gives exactly seven voltage levels per phase: $-3V_{DC}$, $-2V_{DC}$, $-V_{DC}$, 0, $+V_{DC}$, $+2V_{DC}$, and $+3V_{DC}$. Thus the number of voltage levels in this topology can be given by $2N+1$, where N is the number of series-connected power cells.

The phase-shifting transformer[2] is an indispensable device in this topology. It isolates power supplies from the power cells, reduces line current Total Harmonic Distortion (THD), and isolates the utility from the converter for common-mode voltage mitigation. This design offers significant advantages, including modular construction for cost reduction and easy repair, nearly sinusoidal

[2] A phase-shifting transformer serves as a specialized device designed to regulate and direct AC power distribution. By adjusting the voltage phase angle between the transmission and distribution nodes, this equipment balances power lines and mitigates overload conditions [55].

output waveforms, and a bypass function of the faulty power cells for improved system availability [55].

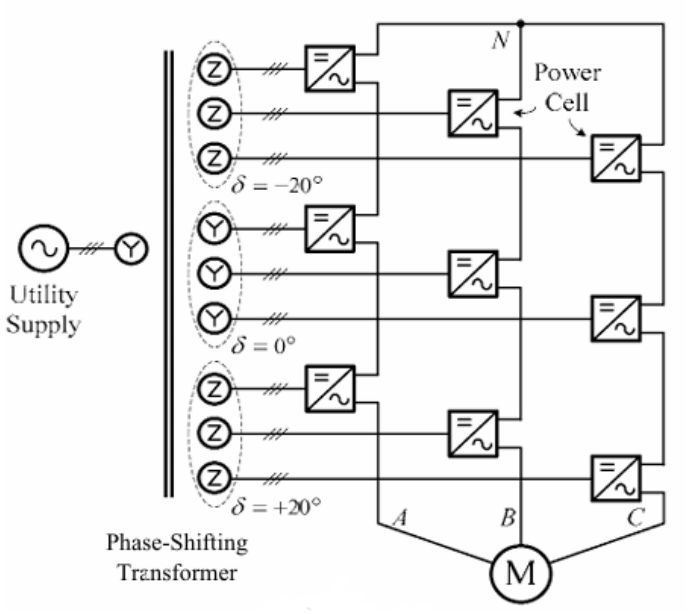


Figure 2.9: CHB inverter featuring nine power cells in total, with $N = 3$ series-connected cells per phase yielding an output phase voltage of $2N + 1 = 7$ levels [55].

As shown in Figure 2.10, each power cell is composed of a diode rectifier, a DC bus capacitor (C_d) and a single phase H-Bridge inverter. The output graph across the two terminals on the right side depends on the switching states of the four IGBTs. By utilizing different switching combinations, this H-bridge can commute the DC bus voltage to generate the three distinct voltage levels ($+V_{DC}$, 0, and $-V_{DC}$) previously mentioned at the output of each individual power cell.

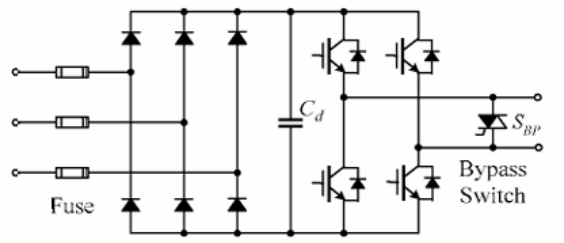


Figure 2.10: 18-pulse IGBT-based power cell [55]. The three inputs on the left side (protected by fuses) represent the three-phase AC power supply.

Figure 2.11 shows the phase voltage waveform of an MVW3000 with three power cells per phase.

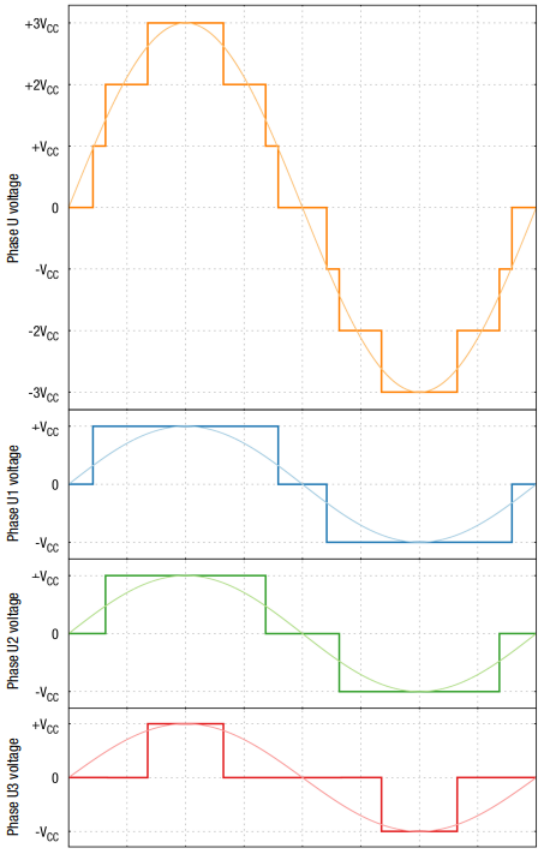


Figure 2.11: Phase voltage waveform of an MVW3000 with three power cells per phase [51].

To provide a clearer understanding of the VSD's internal architecture, we provide a brief description. The cabinet is generally divided into four main columns: the input column, the transformer column, the inverter column, and the control column. Figure 2.12 illustrates this physical arrangement of the MVW3000 cabinet and its primary components [50]:

1. **Input Column:** Contains the incoming protection, featuring a three-phase switch disconnector with fuses and a vacuum contactor. It includes a mechanical interlock system to prevent access to the MV compartment while the switch is in the ON position. Cable entry can be configured through either the bottom or the top of the cabinet.

2. **Cooling System:** An air-cooling system that can optionally be equipped with redundant fans to ensure thermal stability under heavy loads.

3. **Phase-Shifting Transformer:** Equipped with a lightning arrester on the high-voltage side[3] and impedance matching on the secondary winding to optimize harmonics and reduce losses on the line side.

[3] In transformer terminology, "high-voltage side" refers to the winding with the higher rated voltage compared to the other windings and does not correspond to the HV system classification defined in Section 1.1.

4. **Power Cells:** Withdrawable power cells designed with clamp connections to make installation and maintenance fast and easy. As previously mentioned, these cells can optionally include an automatic bypass function; in the event of a failure, the VSD automatically removes the faulty cell from the circuit, enabling continuous operation.

5. **Thermal Protection:** A Tecsystem NT538 AD electronic microcontroller-based unit dedicated to transformer and electric motor temperature monitoring, utilizing eight inputs for PT-100 sensors [46].

6. **Control and Monitoring:** A 10-inch touch screen HMI that serves as a graphical display for the drive. It enables full operation, navigation, programming, and real-time monitoring. Furthermore, it provides complete parameter instructions and detailed fault descriptions, allowing technicians to visualize data through numerical and/or bar graph displays.

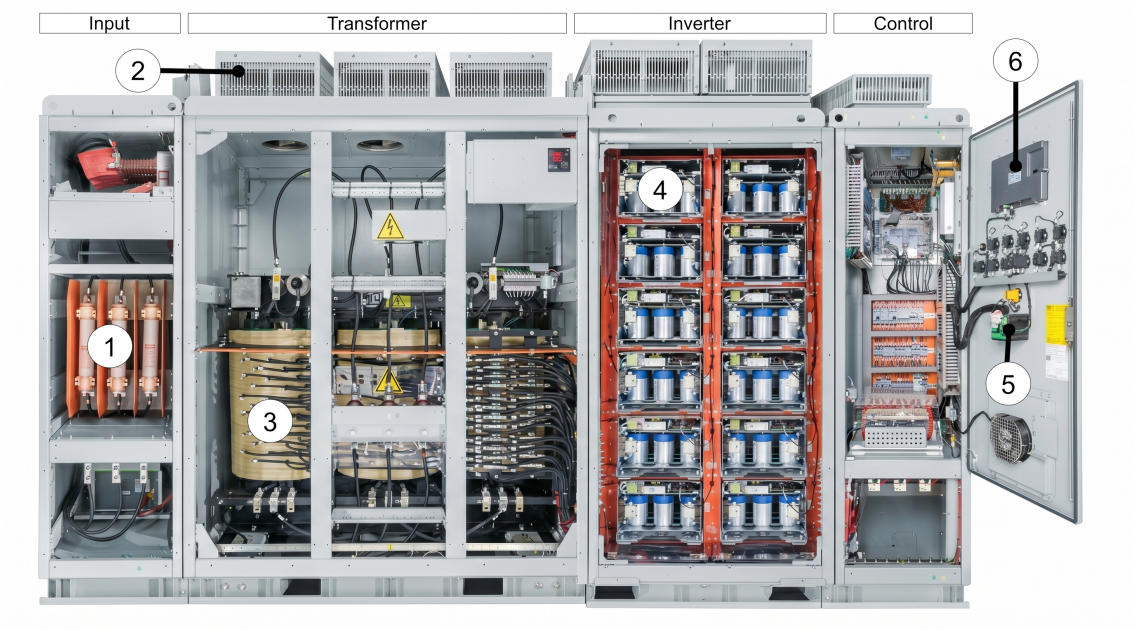


Figure 2.12: MVW3000's main components [50]. Although the illustrated configuration features 12 power cells, this number varies depending on the specific design.

The mentioned thermal protection unit is shown in Figure 2.13.



Figure 2.13: Tecsystem NT538 AD [46].

The VSD's touch screen HMI is illustrated in Figure 2.14.



Figure 2.14: MVW3000's HMI [52].

The physical location of the VSD's core processor within the control column is shown in Figure 2.15.

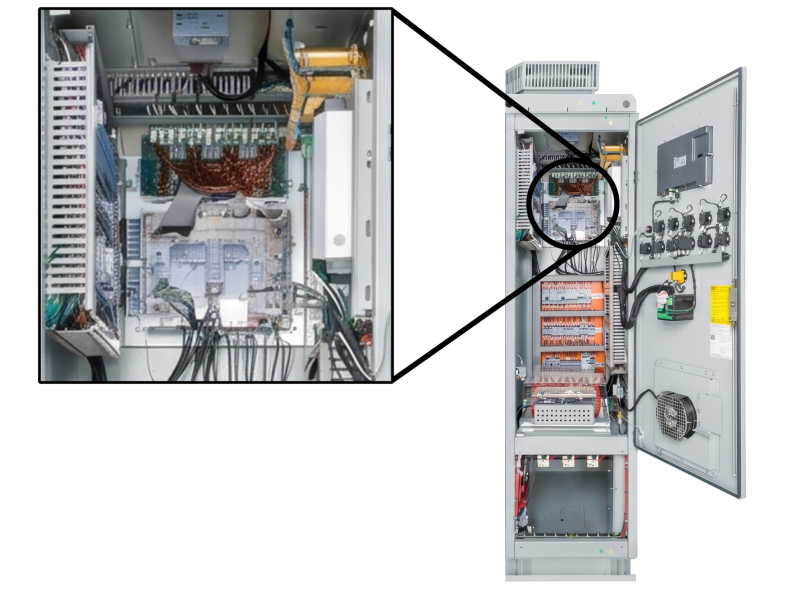


Figure 2.15: Location of the MVW3000's main processor.

The MVW3000 supports a wide range of communication protocols (Modbus RTU, Modbus TCP/IP, Ethernet/IP, MQTT, CANopen, DeviceNet, EtherCAT, Profibus-DP, PROFINET-IRT, and others under request) and comes with free dedicated software—the WEG Programming Suite (WPS) [50].

The configuration and monitoring of the MVW3000 are managed through a structured set of parameters, which are accessed via the HMI or dedicated software. These parameters are organized into logical groups to facilitate commissioning, maintenance, and real-time process adjustments [52]. To ensure an intuitive user experience, the MVW3000's set of parameters is divided into functional blocks:

S **Status**

D **Diagnostics**

C **Configurations**

A **Application**

Each of these primary blocks follows a multi-level structure. Beyond this high-level menu, the parameters branch into specialized subgroups and individual registers. A comprehensive and detailed mapping of this complete parameter tree, including every specific sub-level and its corresponding functionality, is provided in the MVW3000 Programming Manual (present in Appendix A) [52]. Figure 2.16 shows an example of a detailed parameter description that can be found in this manual. However, alongside this structure, there exists an alternative parameter mapping inherited from legacy MVW3000 generations. For instance, consider the parameter C2.1.1 that defines the motor type. In the 4th Generation (G4) of the equipment used in this work, its official designation in the P-format is P00205.

C2.1 Motor data

C2.1.1 Motor type

Range: 0 ... 4 **Default:** 0

Properties: Stopped

Description:
Sets the type of motor to be driven by the MVW3000 inverter.

Indication	Description
0 = Induction	It selects that it is an induction motor
1 = Synchronous - IPSM	Selects a permanent magnet motor.
2 = Synchronous - SPSM	It select synchronous motor with surface permanent magnet
3 ... 4 = Not used	Not used

Figure 2.16: Detailed parameter description example [52].

This equipment uses acceleration and deceleration ramps to manage the motor's transition between speed states, ensuring smooth operation and mechanical protection. While the MVW3000 can apply an immediate voltage step if the ramp time is disabled, it primarily relies on these timed transitions to maintain stability and predictable torque. In order to achieve this smoothed operation,

users can program a second ramp, being both ramp profiles switched dynamically via digital inputs (Figure 2.17).

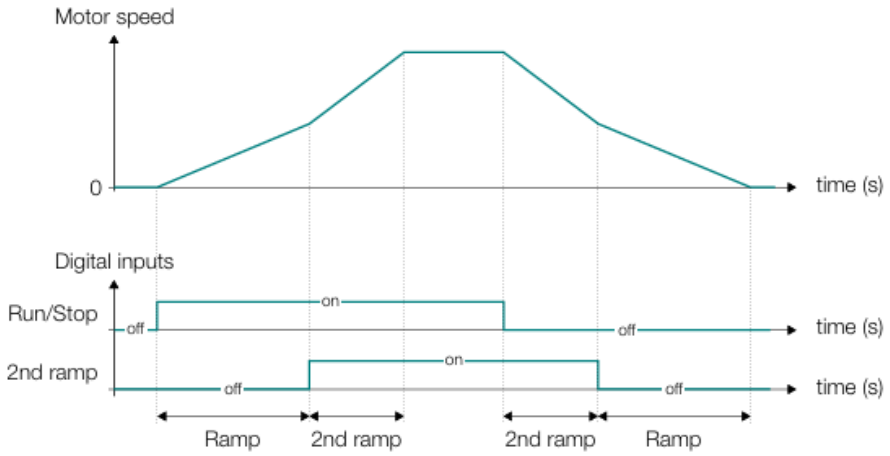


Figure 2.17: Second ramp [52].

In addition to the linear ramp, this VSD offers an "S" ramp profile to further refine motor dynamics. This feature allows for the rounding of the acceleration and deceleration curves, smoothing the sharp transitions at the start and end of speed changes (Figure 2.18).

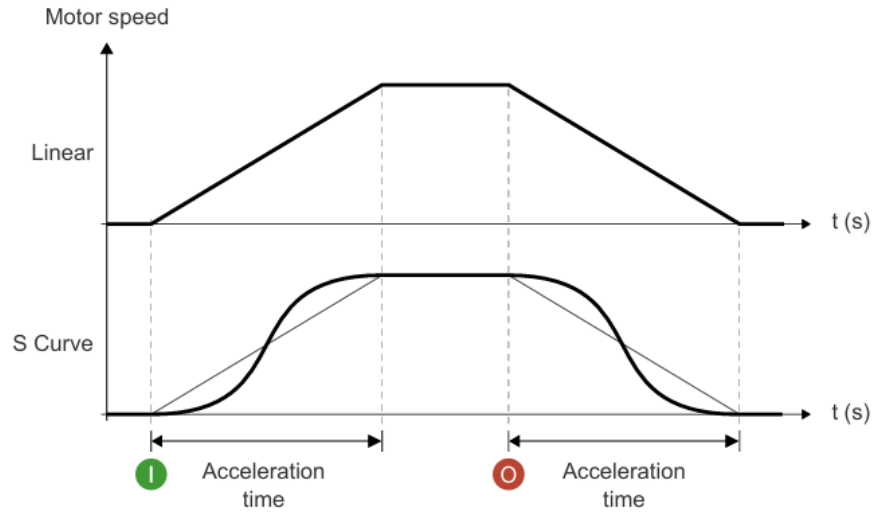


Figure 2.18: Comparison between linear and "S" ramp [52].

Beyond ramp management, the MVW3000 offers versatile reference handling through multispeed configurations, Scalar (V/f) Control capabilities (such as V/f curve configuration, optimization for specific motor type, and current stabilization), among others.

A multi-level access system is used to protect the integrity of settings and overall operating safety, especially for critical MV applications. This prevents unauthorized or accidental modification of sensitive parameters [52]. The access levels are characterized as follows:

- **Operation:** Access to commands via windows or settings menus, inverter operations, and commands.
- **Maintenance:** Reading access to the settings of the HMI operating system and writing access to general settings.
- **ASTEC:** Reserved for WEG technical assistance.
- **WEG:** Reserved for WEG technical assistance.

2.4.3 Market Positioning

Defining the absolute State-of-the-Art (SOTA) VSD technology is a complex task, as various manufacturers employ distinct topologies and engineering approaches, each presenting specific trade-offs when compared to the WEG's MVW3000. This comparative analysis focuses on ABB's ACS580MV, Rockwell Automation's PowerFlex 6000, and Siemens' Sinamics GH180, as WEG internally recognizes these specific models as the primary global competitors to the MVW3000.

Table 2.1 provides a comparative overview of these VSDs based on standard technical specifications.

Table 2.1: WEG's MVW3000 positioning among primary competitors [1, 7, 45, 50].

Product	Power Range	Voltage Range	Efficiency	Overload Capacity
WEG MVW3000	Up to 30 MW	1.15–13.8 kV	>96%[1]/ >96.5%[2]	115%[3]/ 150%[4]
ABB ACS580MV	Up to 5.6 MW	3.3–11 kV	>96%	110%
Rockwell PF6000	Up to 11 MW	2.3–11 kV	96 – 96.5%	110%[3]/ 150%[4]
Siemens GH180	Up to 24.6 MW	2.3–11 kV	96.5%[1]/ >97%[2]	110% (higher on request)

[1] With aluminium windings transformer.
[2] With copper windings transformer (higher efficiencies on request).
[3] Normal Duty overload capacity: maximum current/power with the specified percentage of overload for 1 minute every 10 minutes.
[4] Heavy Duty overload capacity: maximum current/power with the specified percentage of overload for 1 minute every 10 minutes.

As illustrated in Table 2.1, performance metrics such as efficiency, overload capacity, and standard voltage ranges show high convergence among the selected products. Consequently, the selection process often shifts from raw hardware specifications to specific customization capabilities. These include requirements for specialized IP ratings, physical optimization to fit existing electrical rooms or enhanced efficiency targets that exceed standard configurations.

2.4.4 VSD-motor Combination

The Automation Solutions and Electric Panels Department at WEG's Santo Tirso plant operates with a high degree of flexibility regarding VSD-motor combination. The department frequently handles two primary project scenarios:

- **Integrated WEG Solutions:** Providing a complete package where both the MV VSD and the electric motor are manufactured by WEG.
- **Third-Party Integration:** Designing and supplying a WEG MV VSD specifically engineered to control a motor from a different manufacturer.

Both scenarios are standard practice for the department, which leverages Europe's most advanced MV VSD and motor testing laboratory to ensure seamless compatibility. We characterize this infrastructure in Section 3.1.

This flexibility in VSD-motor pairing is substantiated by adherence to international power system standards, such as IEC 60038 and the North American ANSI C84.1. These standards harmonize nominal voltage levels, thereby facilitating the global trade and interoperability of electrical equipment [6, 21].

WEG's MVW3000 exemplifies this adaptability, offering a wide array of rated output voltage options, ranging from 1.15 to 13.8 kV [50]. This extensive range allows the VSD to be configured for various regional grid requirements and specific industrial applications. Complementary to the VSD's versatility, motor designs are aligned with these standards. For instance, the WEG's W60 motor series is available in 3.3 kV, 4.16 kV and 6.6 kV versions. Similarly, ABB's AXR motor series offers 3 kV, 6 kV and 10 kV for 50 Hz systems, as well as 4.16 kV and 6.6 kV for 60 Hz environments. The availability of these specific voltage levels in the WEG MVW3000 demonstrates a clear alignment between manufacturer specifications and the benchmarks established by international voltage standards [2, 54].

Chapter 3

Current Testing Methodology and Infrastructure

We start this chapter by reviewing global manufacturers' testing practices, followed by a characterization of WEG's testing laboratory. Subsequently, we evaluate the MVW3000 testing procedure, drawing on a detailed analysis of official documentation and direct shop floor observations. Finally, we identify strategic opportunities for automation, looking to enhance consistency between tests and operational safety, as well as overall process efficiency.

We conducted an extensive search to identify current trends and methodologies employed by major manufacturers in testing MV VSDs, such as Siemens, ABB, Rockwell Automation, and Schneider Electric. We selected these specific companies because they are considered primary global competitors. This systematic review was performed across manufacturers' websites and major academic and technical databases, specifically Google Scholar and IEEE Xplore, focusing on publications from 2015 onwards. The search utilized specific query strings, including combinations of terms such as "medium-voltage drive testing", "VSD automated testing", and "VSD routine testing".

While the reviewed manufacturers' websites lacked information regarding internal testing methodologies or laboratory setups, the search across the selected academic and technical databases identified three relevant works directly addressing MV VSD testing. One of these focuses primarily on the analysis of operational electrical variables, such as output voltage and current waveforms [9, 28]. The remaining two explore automation of tests. However, both are centered on Hardware-in-Loop (HiL)[1] configurations utilizing real-time simulators [15, 19]. While these HiL studies provide valuable insights into control stage validation, they diverge from the scope of this research. This dissertation focuses on the automation of a detailed and extensive testing protocol performed on physical hardware, requiring a framework capable of managing real-world industrial laboratory constraints that simulation-based HiL environments do not address.

[1] HiL is a testing technique where a real controller is connected to a real-time simulator that executes the mathematical model of the physical system. This approach allows for the validation of control algorithms and protection logic under diverse scenarios without the risks and costs associated with HP laboratory setups.

While all market players must adhere to universal regulatory frameworks, the specific operational execution of these tests is considered highly sensitive proprietary information. The internal workflows, specialized software tools and data management systems used by manufacturers are guarded as significant competitive advantages.

Due to this lack of transparency regarding specific automation trends in MV VSD testing, a direct comparative analysis with other manufacturers is not feasible. Consequently, this work is built based only on WEG's internal documentation and on the characteristics of its SOTA testing infrastructure.

3.1 WEG's Laboratory Characterization

Testing MV VSDs and motors demands a fundamentally different laboratory approach than standard LV systems. Beyond their larger physical scale and greater structural complexity, MV units require significantly higher voltage and current capacities during testing. This forces the existence of specific laboratory infrastructure, requiring substantial physical space and dedicated equipment. Furthermore, the inherent safety risks of high-power testing demand a highly specialized workforce to manage the procedures. These unique technical constraints directly shape the specialized infrastructure detailed below.

3.1.1 Laboratory Infrastructure

Testing equipment like a MV VSD or a motor involves evaluating it under various operating conditions—most notably real load conditions—as well as verifying overall component integrity. WEG's laboratory features three primary test benches with a total testing capacity of 12 MVA. Occupying a substantial area of the factory floor, the architecture is highly versatile, supporting various configurations of existing motors and generators in the laboratory to meet diverse testing requirements and voltage levels up to 15 kV.

The architecture of a generic configuration is shown in Figure 3.1. The supply motor (SM) is controlled by an MVW01. Although it features a different topology from the MVW3000, the MVW01 is designed for motor voltages ranging from 2.3 to 6.9 kV and a standard product power range between 400 kW and 41.1 MW [49]. This enables the synchronous generator (G) to produce a pure sinusoidal wave at a specific voltage and frequency, thereby operating independently of the fixed 50 Hz supply network.

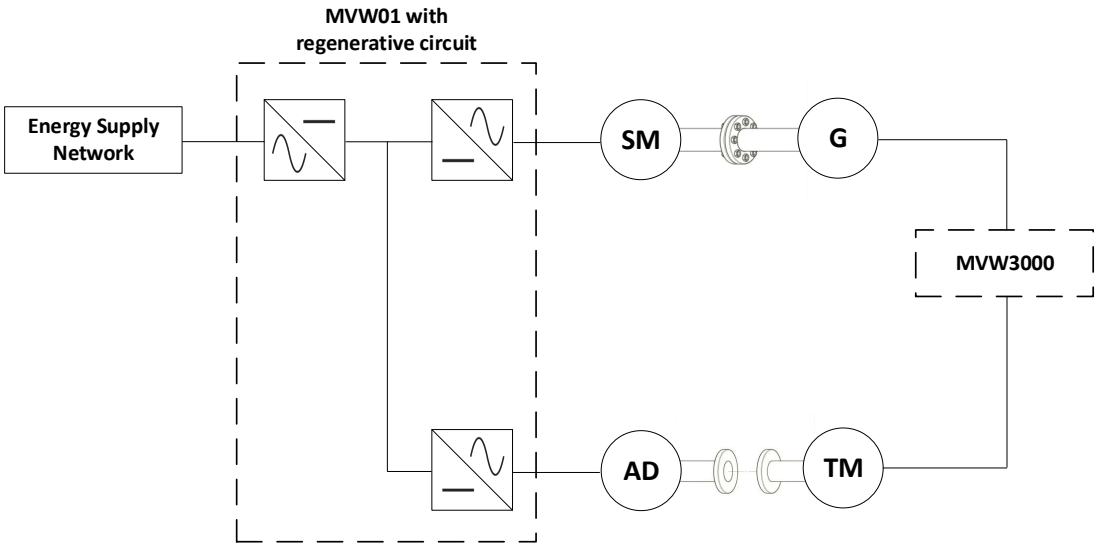


Figure 3.1: Laboratory generic configuration architecture (**SM:** Supply Motor, **G**: Synchronous Generator, **AD**: Absorption Dynamometer, **TM**: Test Motor).

A fundamental component of this architecture is the regenerative circuit of the MVW01, allowing the recirculation and reuse of electrical energy within the system instead of dissipating it as heat. The motor under test (TM) is coupled to an absorption dynamometer (AD) to create real load conditions, which absorbs the mechanical power generated by the motor so that it is possible to measure its torque, speed, and power [12]. This absorption dynamometer operates as an AC generator and it is connected to a rectifier module of the MVW01, which converts the energy to DC and injects it back into the DC bus for reuse. Consequently, the system only consumes the equivalent of the total system losses from the supply network, as the majority of the energy is recirculated. It is estimated that 80% of the energy is reused in this process, with only the remaining 20% being drawn from the grid to compensate for losses.

The experimental setup varies depending on the equipment under test. For standard motor testing, the machine is typically tested under DOL conditions. However, when a VSD such as the MVW3000 is being tested, the device is positioned between the synchronous generator (G) and the test motor (TM). This flexible arrangement allows to handle three distinct testing scenarios: validating a VSD using a dedicated laboratory motor purely for testing, testing individual motors, or testing the previously mentioned integrated WEG solutions—where both the VSD and the motor are manufactured by WEG and tested together. It is worth noting that not all tests performed on the MVW3000 require this specific configuration. However, for any evaluation that involves actively running the motor, this setup is utilized.

To maintain an appropriate working environment, the facility includes an isolated machine room (Figure 3.2) designed for acoustic insulation against the high noise levels generated by the equipment. This area houses the supply motors (SM), generators (G), and dynamometers (AD).



Figure 3.2: Machine room.

Furthermore, the laboratory features an upper floor with a technical corridor (shown in Figure 3.3) dedicated exclusively to control cabinets. These cabinets manage and supervise the infrastructure during testing processes through a specific SCADA software developed internally, WEG PLC500 controllers, and several RUW100 remote units for Input/Output (I/O) expansion, providing a modular control environment.



Figure 3.3: Technical corridor.

Regarding the physical placement of the equipment during the testing phase, the MVW3000 is positioned within a dedicated section of its assembly area rather than inside the main laboratory space. The electrical connection between the VSD and the testing laboratory's infrastructure is

securely established via an underground cabling system, linking the manufacturing floor to the testing facilities. Figure 3.4 illustrates one of the test control and monitoring benches available in the laboratory.

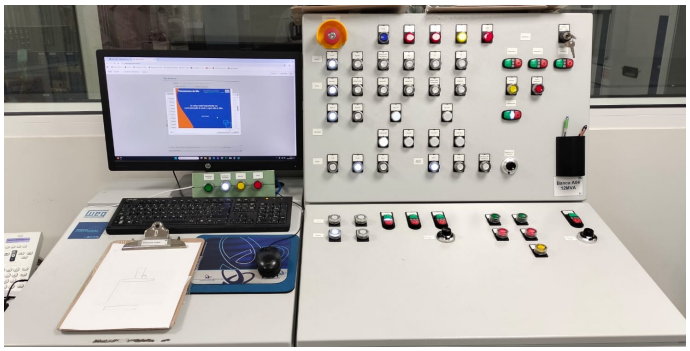


Figure 3.4: Laboratory bench.

3.1.2 Testing Instrumentation

The reliability of the experimental data is ensured by an advanced instrumentation framework designed for the precise validation of manufactured products. Due to the high voltage and power levels handled in the laboratory, the testing instrumentation must be capable of safely and accurately measuring elevated electrical values. This setup requires precise readings of voltage, current, and power—both from the equipment under test and the supply network—, as well as the assessment of harmonic distortions, insulation resistances and temperatures.

Voltage is acquired through voltage transformers on each phase at the generator output, which are connected to a ZES ZIMMER HST voltage divider, used to expand voltage measuring ranges of precision powermeters for use at nominal voltages over 1000 V (Figure 3.5) [58]. Current is measured by current transformers connected to a ZES ZIMMER PCTSIU-4-1U transducer (Figure 3.6) [59]. Although they differ in working principle, both voltage and current transformers are instruments designed to scale down or up these electrical quantities.



Figure 3.5: ZES ZIMMER HST [58].



Figure 3.6: ZES ZIMMER PCTSIU-4-1U [59].

These signals are processed by a YOKOGAWA WT1806E (Figure 3.7) digital power analyzer, which offers a high precision. In addition to monitoring standard electrical parameters, the instrument performs internal calculations to derive real-time information such as instantaneous power, frequency, torque, speed, and energy efficiency.

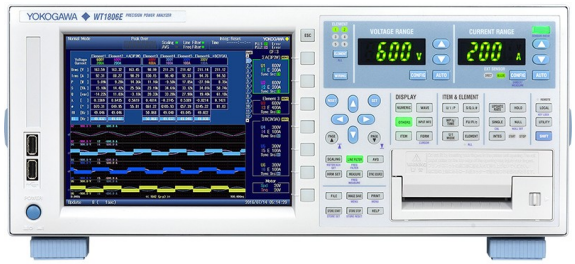


Figure 3.7: YOKOGAWA WT1806E [56].

This power analyzer is integrated into a technical panel that also houses HMIs for monitoring, as shown in Figure 3.8.



Figure 3.8: Laboratory's technical panel.

Temperature acquisition is performed via PT100 thermoresistors installed in the motor windings and bearings. These are linked to a 60-channel acquisition unit, which routes the signals to a

YOKOGAWA MW100 data acquisition unit, shown in Figure 3.9.



Figure 3.9: Electrical panel with a YOKOGAWA MW100 temperature acquisition unit.

For the measurement of insulation resistance during the dielectric tests—detailed in Subsection 3.2.2—a Megger MIT 515/2 is utilized, illustrated in Figure 3.10.



Figure 3.10: Megger MIT515/2 insulation resistance tester [29].

In addition, a Fulltest 3 by HT Instruments, shown in Figure 3.11, is employed as a multi-function instrument for safety verifications on machinery and electrical panels. Beyond insulation resistance, it is capable of testing other critical parameters such as continuity, thermomagnetic protections, residual voltages, phase rotation sequence, among others.



Figure 3.11: HT Instruments Fulltest 3 multi-function safety tester [20].

3.2 MVW3000 Testing Procedure

3.2.1 Testing Phase within the Production Cycle

The production cycle of the MVW3000 follows a structured workflow, from the initial commercial demand to the commissioning at the project site. The sequential stages of this process are illustrated in Figure 3.12.

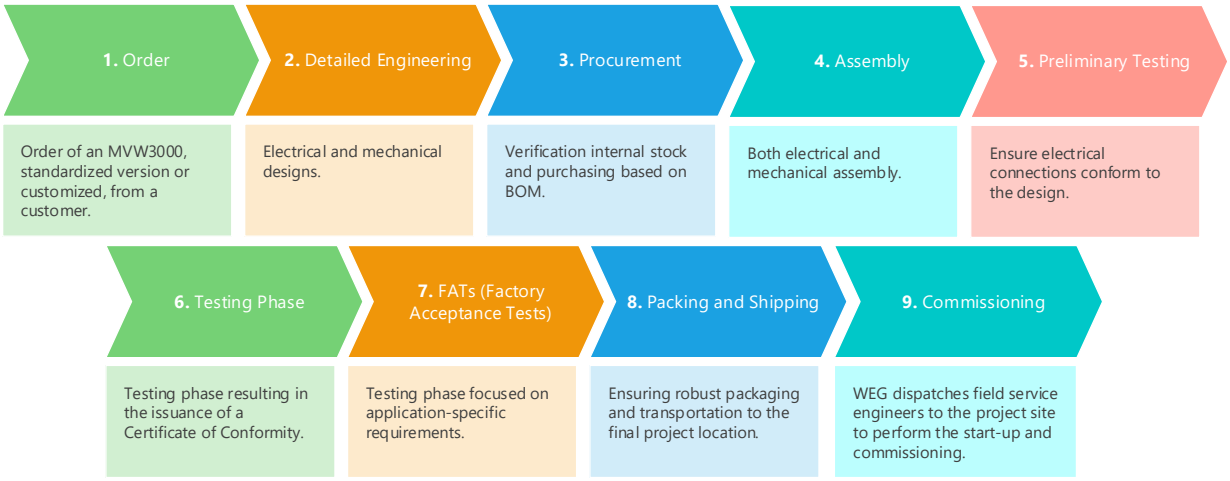


Figure 3.12: Sequential stages of the MVW3000 production cycle, illustrating the workflow from the initial customer order through engineering, assembly, testing, and final site commissioning.

The cycle begins with the Order (1), consisting of the customer's request for an MVW3000. This stage can range from a standard product configuration to highly customized solutions that may significantly impact the engineering workload. Following the order, the Detailed Engineering

(2) phase takes place, involving the concurrent development of electrical and mechanical designs. Constant communication between both disciplines is essential; for instance, mechanical engineers must align the cabinets' design with the specific electrical requirements. This phase culminates in the generation of the Bill of Materials (BOM) and requires formal customer approval before proceeding.

Once the design is finalized, the Procurement (3) is initiated, involving both an inventory check to verify stock and the purchasing of components as required by the design. This phase and the subsequent Assembly (4)—where the mechanical and electrical assemblies of the VSD are performed according to the engineering design—frequently operate in parallel. Rather than waiting for the entire BOM to be fulfilled, the assembly process can start as soon as the structural components are available, thereby optimizing the overall production timeline.

Before the unit enters the testing zone, it undergoes Preliminary Testing (5). In this step, technicians perform point-to-point continuity checks with a multimeter to verify that all electrical connections align with the design, ensuring that the necessary conditions are met to begin energized tests.

Due to its significant dimensions and weight the MVW3000 is transported to the testing zone using a specialized wheeled platform. This zone is a dedicated area within the assembly floor, physically separated from the main laboratory infrastructure. The VSD is typically mounted on this platform early in the assembly process to facilitate its movement across the factory floor. Upon arrival at the testing station, the equipment is accompanied by its respective electrical schematics. Simultaneously, the testing technicians retrieve the specific project parameters' file via SAP[2] system. Once the physical and digital setup is complete, the formal testing begins.

This work focuses primarily on the Testing Phase (6). The VSD is subjected to the specific electrical and functional tests detailed in Subsection 3.2.2. The normal time to test an MVW3000 is around 42 hours, varying according to the complexity of the anomalies encountered throughout the process. As previously stated, the assembly area layout is designed to allow the concurrent manufacture of several VSDs. However, despite the capacity of the laboratory infrastructure, the designated testing area is limited to testing one unit at a time. This creates a queue of VSDs waiting for testing, which can grow significantly during periods of high order volume or if the possible anomalies encountered take longer to solve. The duration of the testing phase may seem small compared to the overall production cycle of about seven months. However, this phase can easily extend its duration if waiting times grow. Addressing this bottleneck is therefore of paramount importance. Optimizing this stage speeds up the testing procedures themselves without requiring further capital investment in laboratory capacity. Furthermore, it frees up valuable assembly floor space, as fully assembled VSDs currently remain in the production area while waiting their turn to be tested, delaying project billing and affecting the production flow.

This is followed by the Factory Acceptance Tests (FATs) (7), which are focused on specific requirements for the application. The FATs may be conducted as a witnessed or non-witnessed test, depending on whether the customer sends a representative to oversee the procedures. At this

[2]SAP is the Enterprise Resource Planning (ERP) software system used at the company.

stage, the customer formally approves or rejects the test results. After all technical validations are met, the Packing and Shipping (8) stage ensures that the MVW3000 is provided with robust packaging to withstand transport to the final destination. The cycle concludes with Commissioning (9). During this phase, WEG dispatches field service engineers to the project site to perform the equipment's startup and commissioning.

3.2.2 Procedure Structure and Analysis

The MVW3000 testing procedure is an internal WEG document that establishes specific instructions for executing tests on the MVW3000 4th Generation MV VSDs. This instructional guide serves as the foundational document for the present work. Due to the high structural complexity and physical scale of the product, the testing procedure is exhaustive and detailed. As described in Subsection 2.4.2, an MV system of this nature integrates a vast number of power and control components and hundreds of programmable parameters. Consequently, a well-structured document is necessary to navigate this complexity and guarantee that no verification is overlooked.

The document is organized chronologically, reflecting the step-by-step sequence of operations required during a complete test of the equipment. It undergoes revisions whenever, for example, there are updates to the applicable regulatory standards. These standards define the mandatory nature of the tests, explicitly categorizing them into routine tests, mandatory for all production units to achieve product certification, and type tests, validating design integrity on initial prototypes. Furthermore, standards also reference special tests, that may be conducted if explicitly agreed upon between the manufacturer and the client, generally to validate the equipment for extreme operational conditions like harsh temperatures or exceptional loads. The document under analysis is specifically dedicated to the execution of routine tests. The applicable standards include:

- **IEC 61800-2:** Defines the general requirements and rating specifications for adjustable speed AC power drive systems [24].
- **IEC 61800-5-1:** Specifies the strict safety requirements concerning the electrical, fire, mechanical, energy and other relevant hazards of the VSD system [25].
- **IEC 61800-5-2:** Addresses requirements and makes recommendations for the design and development, integration and validation of safety-related power drive systems in terms of functional safety considerations [26].
- **IEC 60146-1-1:** Establishes performance requirements for the performance of all semiconductor power converters and semiconductor power switches using controllable and/or non-controllable electronic valve devices [22].
- **IEC 60146-2:** Details the requirements for self-commutated[3] semiconductor inverters and semiconductor converters that contain at least one part of a self-commutated type [23].

[3] Self-commutation refers to converters utilizing power semiconductors (for instance, IGBTs) that can be actively switched on and off using a control signal. This capability is, as previously shown, essential for controlling the VSD's output voltage and frequency using PWM.

While these standards establish test conditions and approval criteria, such as mathematical formulas for testing voltages or maximum allowable thresholds, they remain inherently both product- and manufacturer-agnostic. Consequently, the internal WEG procedure serves to translate these normative requirements into concrete operational steps. Throughout its various sections, the procedure references specific clauses from these standards, citing them directly next to the practical tests they justify and creating a direct link between test execution and normative framework.

In addition to the mentioned International Electrotechnical Commission (IEC) framework, the procedure also accommodates requirements from Underwriters Laboratory (UL). While IEC standards are globally recognized and generally adopt a performance-based approach to safety, UL standards (whose compliance is demanded primarily from clients operating within North American markets) are more design-specific, defining comprehensive technical details in terms of product safety and application [40]. However, within the analyzed document, explicit references to UL standards are minimal. The procedure incorporates specific initial verifications for UL compliance (detailed further below), but only references a specific standard in one particular test (also detailed below), as UL and IEC standards impose different test voltages for it.

For the remaining tests, UL standards are not explicitly cited. This absence suggests that the rigorous functional evaluations established by the IEC framework are comprehensive enough to satisfy general operational integrity, meaning that specific UL routine test equivalents either overlap entirely with the IEC procedures or are not applicable to the remaining steps of this specific factory routine.

The complete testing procedure workflow is visually synthesized in Figure 3.13. In the first phase, laboratory technicians access the SAP system to retrieve all relevant project information, including the parameter files, engineering drawings, and electrical schematics that will impact the test procedure.

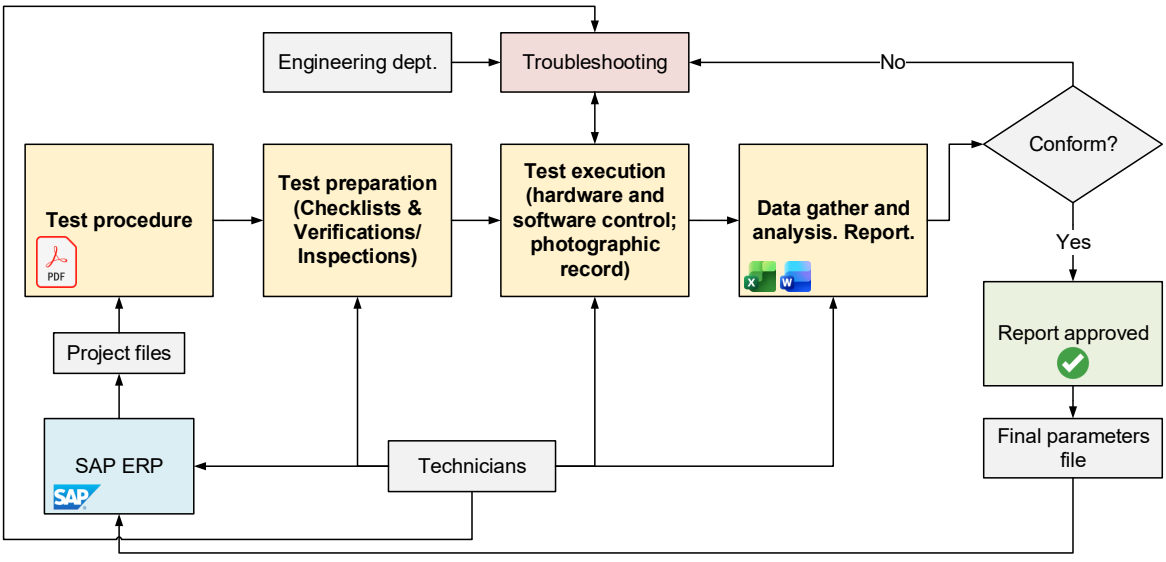


Figure 3.13: Testing procedure workflow, including technicians performing the tests, departments, data sources, information produced, and decisions made.

To enable the practical application of the procedure, the document begins with a list of required materials and instruments:

- Compatible motor and absorption dynamometer;
- Power supply compatible with the VSD's input voltage and current;
- Three-phase power source (50 or 60 Hz), power rating of 20 kVA and one of the following voltages: 220, 380, 400, 415, 440, 460, or 480 V;
- 4-channel oscilloscope with 4 voltage and 3 current probes;
- Clamp meter, 2 multimeters, thermometer, and 1 kV megohmmeter;
- Applied voltage source and a 3 kV DC or 2 kV AC voltage source;
- Laptop and camera flash.

The test procedure maintains a certain level of abstraction regarding the required instrumentation. By specifying categories of equipment instead of specific models, the procedure remains flexible and adaptable. This ensures the standardization of testing routines across international branches, allowing the same procedure to be executed consistently even when different laboratory equipment brands are utilized.

The practical execution of the procedure begins with an initial verification and visual inspection that instructs the technicians to:

- Verify the VSD's connections against the electrical design;
- Verify the integrity of the power connections within the panel;
- Verify the application of contact grease on the clamps;
- If the VSD requires UL Certification, the presence of mandatory UL labels, nameplates, and specific "Line of Sight" louvers must be verified;
- Verify bolted connections, components, Ingress Protection (IP) Ratings, layout/dimensions, insulations, and product identification.

This initial checklist is shown in the *Test preparation (Checklists & Verifications/Inspections)* block in Figure 3.13.

Following this initial verification, the procedure advances to the *Test Execution* block of Figure 3.13, starting with the applied voltage tests, commonly referred to as dielectric tests. During this phase, test voltages up to 36 kV are applied in sequential steps between the secondary windings of the transformer, between groups of these secondary windings, and against the LV control

circuits. In the first step, the test voltage is determined by the transformer's insulation level[4]. In the second step, it depends on both the VSD's supply voltage (the transformer's rated voltage) and the applicable standard (IEC 61800-5 or UL 347A), though the difference between the required voltages is minimal. Finally, in the remaining steps, the test voltage is set to a fixed value. The primary objective of these tests is to certify the insulation resistance and dielectric strength of the panel's internal components. The minimum value of insulation resistances is imposed by IEC 60146-1-1. This step is of utmost importance to guarantee that the equipment withstands its nominal and transient voltages without suffering disruptive discharges. Therefore, a nonconformity in these tests blocks the continuity of the procedure.

Once the insulation integrity is confirmed, the focus is shifted to the logical, control, and auxiliary circuits, which are tested without energizing the main power stage. This involves the initial energization of the control rack, verification of firmware versions, verification of the fiber optic cable connections (where any malfunction blocks the continuity of the procedure), and the calibration of voltage and current acquisition cards. Additionally, essential auxiliary functions—such as the optional variable speed ventilation systems, arc flash protection, and thermal protection relays—are evaluated to confirm that the system correctly triggers the expected faults and alarms. The importance of this phase lies in validating the VSD's control circuit and its safety functions, ensuring that all equipment protection measures and interlocks are fully operational prior to the introduction of MV. Subsequently, the procedure advances to the initial energization of the power circuit using the pre-charge system, intended to smoothly and safely establish the DC bus voltages in the power cell capacitors, avoiding inrush current peaks. This phase is followed by no-load or light-load operation, in which the VSD runs a motor to verify the correct functioning of the modulation, current feedbacks, output voltage consistency, and phase balance of the entire system.

The culmination of the routine procedures involves maximum voltage, dynamic load, and temperature rise tests. Utilizing the dynamometer coupled to the motor, the VSD is subjected to its nominal voltage and current conditions for prolonged periods (up to four uninterrupted hours or until the thermal stabilization of the power cells is achieved). These tests are vital to assess the actual thermal and electrical performance of the equipment, ensuring that critical components such as the power cell semiconductors, phase-shifting transformers, and reactors do not exceed the safe temperature limits outlined in the design under maximum load conditions. Simultaneously, the active protections of the control system, which include current limitation and DC bus overvoltage regulation, are deliberately tested under load to confirm the equipment's ability to protect itself by limiting power or disabling the motor in the face of severe grid or application anomalies. Finally, grid parameters are measured, such as the input transformer's inrush current, to guarantee that the mechanical and thermal stress generated at the moment of energization does not compromise the end-user's installation.

Within the normative framework, the temperature rise test, for instance, is classified as a type

[4]The insulation level of a transformer is the ability of its dielectric system (i.e., insulating materials such as oil, paper, resin, or varnish) to withstand overvoltages without experiencing a failure or electrical arc as a consequence of an insulation breakdown.

test rather than a routine test. However, it is deliberately incorporated into this execution procedure. This inclusion is justified by the highly customizable nature of the MVW3000. Consequently, by subjecting these systems to such an evaluation as if they were a new prototype, the manufacturer establishes a rigorous quality assurance baseline, fostering trust from clients.

This workflow ends with a structured documentation and certification phase. The data collected is entered manually into an Excel spreadsheet during the testing process. The raw data itself consists of a wide range of information, from simple check marks for visual inspections and calibration validations to critical quantitative measurements such as the applied test voltages, currents, temperatures, power factors, powers, and insulation resistances. Note that only a specific subset of this comprehensive Excel record is finally extracted to fill out the official WEG MVW3000 test report template. This step aligns with the *Data gather and analysis. Report.* block of Figure 3.13. The testing procedure document rarely provides explicit instructions on exactly which data points must be recorded to fill out this final report. Clarity regarding the required data collection is typically only achieved by cross-referencing the instructional document with the blank test report template itself. For newly onboarded technicians, this implicit reliance on cross-referencing can be highly confusing and prone to logging omissions. Beyond the generation of this written report, the procedure also explicitly mandates that the final VSD parameter file—reflecting all tuning and adjustments established during the calibration phases—must be uploaded to the SAP system to be permanently archived alongside the main project documentation.

Besides data collection, technicians routinely take pictures of instrument displays. Although not stated in the official written procedure, these images are undeniable evidence of the values obtained and protect the manufacturer from any future customer claims. When the official report is ready and when all the summarized results are confirmed to meet the required standards, the product quality certification is issued.

Throughout the execution of tests, nonconformities may be encountered regarding either the overall operation of the equipment or specific components. If the anomaly compromises safety or operational integrity—which is the case, for instance, in dielectric tests—, the process immediately transitions to the *Troubleshooting* phase in cooperation with the *Engineering dept.*, as shown in Figure 3.13. Since certain test parameters lack rigidly fixed thresholds, some stages are permitted to continue. In these cases, once the data is collected and the test report is filled out, the results undergo a formal technical discussion. If it is determined that specific readings constitute a nonconformity, the system re-enters the *Troubleshooting* loop, which ultimately leads to the modification and necessary repetition of those specific testing sequences.

The analysis reveals similarity across the various stages. With the exception of the applied voltage tests, the vast majority of the tests include parameterizing the VSD, executing specific operational steps and reading values from status VSD parameters (via HMI) or from measuring instruments. Whether a test isolates a specific subsection of the VSD (such as the control rack) or evaluates the equipment as a whole (such as the temperature rise test), it almost always demands continuous physical interaction. Technicians are constantly required to modify, for instance, electrical connections, shorting transformer secondaries, grounding primaries, removing

surge arresters, inserting jumpers, opening cubicles, and applying test voltages. To manage this workload, the testing procedure is typically performed by a team of two to three technicians.

A significant characteristic of the test procedure is that several tests, limits, and parameter adjustments are not fixed, but, instead, depend explicitly on the configuration of the equipment under test. The document repeatedly varies its instructions based on factors such as:

- The number of input transformers (e.g., different calibration and protection parameters for one, two, or three transformers);
- The nominal output voltage of the inverter;
- The number of power cells per phase, including optional redundancy configurations;
- Transformer tap positions[5];
- The presence (and quantity) of inverters in parallel;
- Specific motor ratings used during load and functional tests.

Although the document includes several tables to standardize this variability, these do not cover all cases where configuration affects the procedure. This means that, despite the existence of standardizing tables, several instructions assume implicit knowledge.

While specific calculations are provided, the procedure relies entirely on the technician to manually compute and compare the results. From a procedural and automation perspective, this introduces a risk of inconsistency, as different technicians may have different interpretations.

Another limitation of the document is the complete absence of comprehensive troubleshooting guidelines or contingency protocols. When unexpected behavior, faults, or alarms occur, technicians are not provided with diagnostic steps. Instead, they must rely on external resources, such as the faults/alarms descriptions found in the separate programming manual or their own empirical experience. More importantly, the testing specification does not explicitly define the procedural consequences of a test failure. In some cases it is not clearly set whether encountering a specific nonconformity dictates an immediate halt to the entire testing process or if the procedure can safely continue while the anomaly is merely logged for subsequent resolution. This lack of defined failure paths further reinforces the current system's reliance on the technicians' subjective judgment.

3.3 Digitalization and Formalization Opportunities

The limitations identified in the current manual process present significant opportunities for digitalization and the formalization of the testing procedures. By shifting from implicit, technician-dependent knowledge to explicit algorithmic rules, the testing framework can eliminate subjective interpretations and ensure full reproducibility.

[5]Transformer tap positions are selectable winding connections used to adjust the voltage transformation ratio.

This transition begins with the automated configuration detection, where the system identifies the equipment's characteristics by parsing the project parameters' file. This approach is highly effective since the VSD's offline programming is typically finalized before the testing phase begins. While the VSD's identification code only provides limited information, utilizing the parameters' file enables a far more detailed characterization. For instance, the number of transformers can be found in the project parameters' file—a critical detail since some testing phases depend on this value—although it remains unavailable in the identification code (explained in Appendix B), which only presents their nominal frequency and winding material.

Building on this automated detection, the developed software can dynamically select the appropriate test values, acceptance thresholds, and protection limits based on the identified characteristics. This eliminates the need for manual calculations and the constant consultation of the standardized tables in the procedure, significantly reducing the probability of human error during parametrization. Furthermore, automation allows for the formalization of ambiguous instructions. Subjective terms, such "low reference speed", can be translated into mathematical rules—for example, by establishing a fixed percentage of the motor's nominal speed. This ensures the procedure is entirely independent of the technician's individual experience, thereby redirecting the technician's expertise toward resolving any problems that may arise during the test.

A significant opportunity also exists to leverage data from integrated WEG solutions, particularly when both the motor and VSD are WEG-made. In these scenarios, as the VSD is usually tested with its designated motor, the tool should extract the nominal motor characteristics directly from the project parameters' file. However, for configurations involving testing the VSD with laboratory or third-party motors, the application should include a dedicated interface where these specifications can be manually introduced.

Finally, since MV VSD testing often spans multiple work shifts and, consequently, involves the use of individual laptops assigned to each technician, a robust mechanism for session persistence and state management is essential. This mechanism protects the integrity of collected data and ensures that testing can be resumed exactly where it was interrupted, preventing data loss and the need to repeat completed phases.

Chapter 4

System Development and Integration

Moving from the analysis of the testing process to practical implementation of a supporting tool requires its conceptualization, as well as translating procedural rules into a functional software solution. We address this challenge by developing the automated test logic and establishing a robust communication architecture between the MVW3000 and the dedicated PC application. Furthermore, validating the system allowed us to identify and implement adjustments, ensuring a reliable and fully optimized platform for the factory floor.

4.1 Conceptualization of the Supporting Tool

The conceptualization of the supporting tool was driven by factory floor observations during the actual testing procedures. It became evident that technicians already keep a laptop next to the VSD for the majority of the testing process, using it to consult project programs and perform firmware updates, among other tasks.

A crucial factor in modern industrial automation is user acceptance. Introducing new automated processes carries the responsibility of easing factory floor personnel into new working dynamics. It is essential to convince technicians, who are deeply accustomed to established routines, that the automation tools are designed to assist and enhance their daily tasks, rather than to replace them or unnecessarily complicate their environment. In this context, fostering user acceptance was a primary design goal. Following a proposal presented to the technicians, it was determined that a computer application designed to ease certain testing steps would be well-received. Naturally, their active participation in the development of this tool at a critical level would make it even more welcome. Consequently, the platform was conceptualized to be deployed on the same computer, running alongside the WPS software that the technicians already keep open.

4.2 Software Tools and Communications

The development of the application, given the name MVW3000 Test Wizard, was carried out using Python, chosen for its versatility, fast prototyping capabilities, and extensive ecosystem

for industrial communication and graphical interface design. Visual Studio Code served as the Integrated Development Environment (IDE), providing a lightweight yet powerful workspace with built-in debugging and version control integration.

The software depends on a chosen stack of core Python libraries to meet its functional needs. The built-in Tkinter library was used to run the first proof-of-concept tests for a very simple application. However, since the goal of the project was to create a modern, attractive, and professional GUI, Tkinter's basic styling was not sufficient. So, the focus moved to frameworks based on Qt. While alternatives like PySide6 were considered, it shares almost the same capabilities and syntax with PyQt6. At its core, PyQt6 acts as a bridge for the sixth Qt version framework. Instead of trying to render graphical elements purely within Python, it translates Python instructions down to the underlying Qt library, which is built in C++ [16, 36, 37].

Pydantic Settings library was used for managing application configurations, such as communication ports and default test limits. This tool enforces strict data validation upfront, significantly reducing the risk of runtime errors caused by bad inputs. Finally, to make deployment as seamless as possible, PyInstaller was used to package the entire Python application and all its dependencies into a ready-to-run executable [33, 34].

The components are integrated through a communication architecture based on the Modbus TCP/IP protocol (Figure 4.1). This industrial networking standard ensures reliable, rapid data exchange over an Ethernet infrastructure. In this architecture, the MVW3000 functions as the Modbus server. In this role, it houses the registers containing operational data (the VSD parameters), which are made available for external monitoring and control.

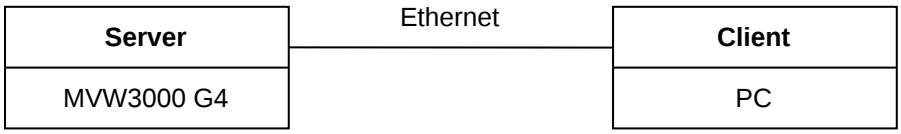


Figure 4.1: Modbus TCP/IP communications architecture.

Operating as the Modbus client, the dedicated PC application communicates with the VSD by making periodic or event-triggered requests. This client-server relationship enables real-time data visualization, manual adjustments, and the execution of automated parametrization sequences directly from the computer. Consequently, it guarantees that the graphical interface remains continuously synchronized with the internal state of the VSD.

To establish communication with the VSD, the PyModbus library was integrated, which served as a reliable bridge for reading and writing internal VSD parameters over the Modbus protocol [35].

4.3 System Requirements

To ensure the reliable execution of the developed testing tool, the host computer must meet a set of baseline hardware and software requirements. The software is designed to run on Windows 10 or 11 (64-bit) operating systems, utilizing x64-compatible processors. Since the application was compiled into a standalone executable via PyInstaller, there is no requirement for a local Python installation on the host machine.

In terms of hardware, a minimum of 4 GB of RAM is required, although 8 GB is recommended for optimal performance. The application requires approximately 80 MB of available disk space to accommodate the executable file and temporary logs. For the graphical interface, a minimum display resolution of 1280x820 is necessary, while a Full HD resolution is recommended to ensure the best visualization of the dashboard and its real-time data.

Regarding connectivity, the PC must be equipped with an Ethernet port. Furthermore, the Modbus TCP port (typically 502) must be open and accessible on the network. It is crucial to ensure that no firewall restrictions block the communication between the PC and the VSD to guarantee stable and uninterrupted data exchange during the testing procedures.

When it comes to future code development for the application, additional requirements are detailed in the produced user manual, which can be found in Appendix D.

4.4 Software Architecture

The architecture of the MVW3000 Test Wizard application was structured in layers with the purpose of isolating and specializing the different responsibilities of the system. The system gains flexibility by separating the GUI, navigation logic, state management, hardware communication, and data persistence. This organization facilitates maintenance interventions and allows the ecosystem to evolve incrementally without the risk of generating unintended side effects in the rest of the codebase. The conceptual block diagram of this architecture is illustrated in Figure 4.2.

Responsible for the main windows, side panels, and forms, the user interface layer serves as the direct bridge with the operator, collecting data and reflecting the visual progress of the test on the screen. However, to ensure the safety and integrity of the process, the interface does not dictate the operational rules independently. Instead, it captures user actions and delegates validations and step transitions to the underlying control logic. The behavior resembles a page-oriented platform, where each screen processes and safeguards its own partial state independently. To visually illustrate this design approach, Figure 4.3 presents a representative test page, as well as the standard layout maintained throughout the application. The interface is organized into distinct functional zones. A lateral tree on the left provides overall navigation, while the bottom section contains sequential control buttons alongside triggers for pop-up windows dedicated to monitoring active faults and alarms, as well as saving or loading test progress. At the top, the layout features a specific panel for communication configuration, along with a button that opens a sliding window.

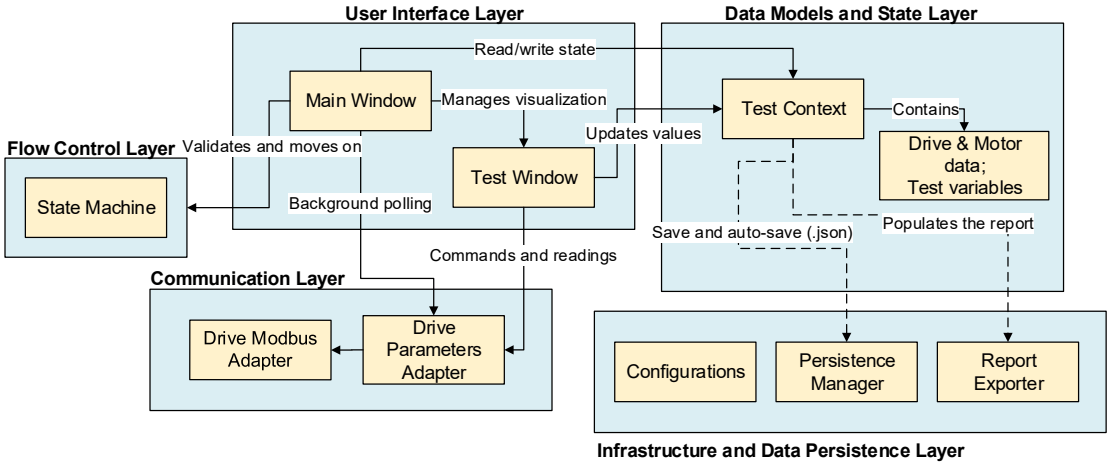


Figure 4.2: Software architecture. Solid lines represent frequent actions, while dashed lines indicate more sporadic operations.

The application's flow is governed by a flow control layer, which functions as the "skeleton" of the process. It dictates the sequence of steps and validates which transitions are permitted at any given moment. So, navigation is not unrestricted: advancing to the next page strictly requires fulfilling the current screen's requirements. However, the system incorporates an administrative override mechanism. By inputting a specific administrator password, authorized personnel can deliberately bypass these strict validation constraints.

The centralization of the test's operational knowledge resides in the data and state layer. This is where the application maintains all live and structured information: nominal VSD parameters, motor specifications, test recipes[1], event logs and the progress of each stage. The core of this layer is the test context object. By acting as a shared session repository, this object allows each page to query or modify only the variables within its specific scope, eliminating direct dependencies between screens and keeping the information flow clean and organized.

To interact with the MVW3000, the system relies on a communication and integration layer that encapsulates all hardware access. Rather than allowing the interface to deal directly with complex protocols or low-level network details, the application utilizes specific adapters to isolate these operations. Concretely, this layer is implemented via two primary adapters: the Drive Modbus Adapter, which manages low-level Modbus TCP connectivity (connect/disconnect, register read/write, probing, and error handling), and the WPS Adapter, a higher-level domain adapter that composes the VSD adapter and maps TestRecipe objects to VSD operations (for example, applying and validating VSD parameters). This design choice protects the core of the wizard against changes in communication mediums and standardizes error handling using exceptions. Thus, connectivity functions as an autonomous service, triggered on demand whenever the technician needs to monitor states, read data, or modify parameters.

[1]Consists of a reusable configuration bundle containing technician metadata, motor nominal parameters, and test limits. It pre-fills user interface fields, can be applied to the VSD and is persisted with the test context.

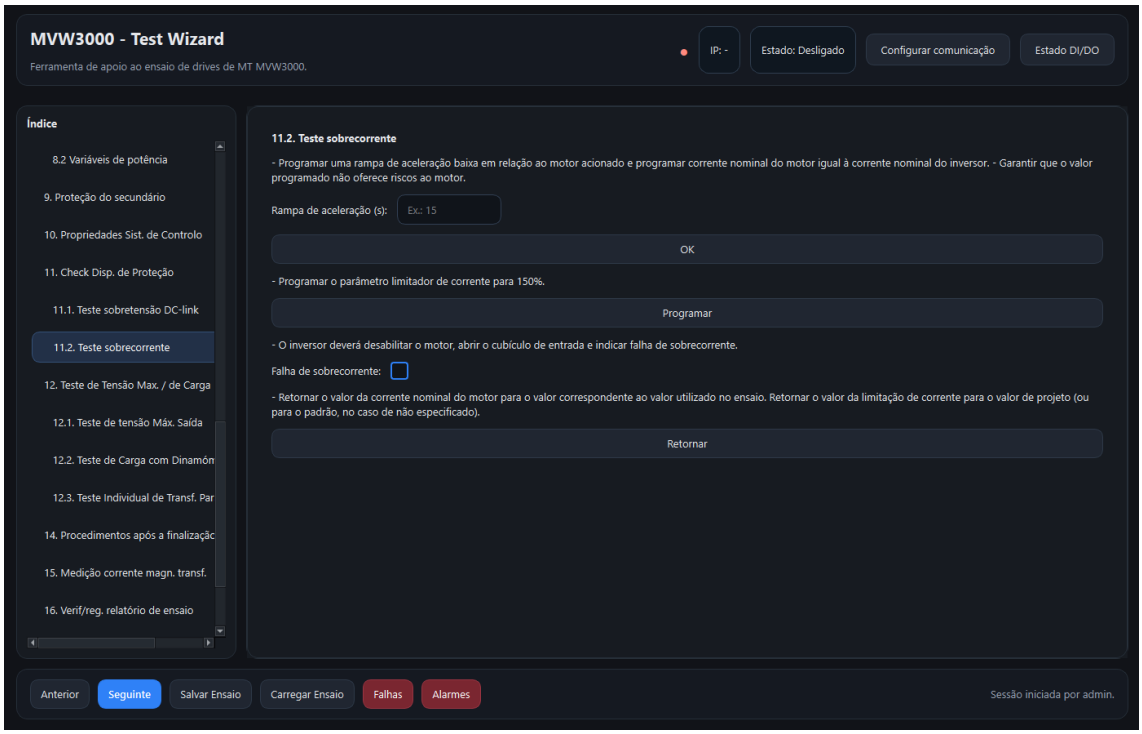


Figure 4.3: MVW3000 Test Wizard: representative page illustrating the general GUI layout.

Finally, the system's foundational support rests on the infrastructure and persistence layer, responsible for recording progress and structuring results. The testing progress is serialized into JSON files, supporting a periodic auto-save mechanism that prevents data loss in the event of an interruption. At the end of the testing cycle, this same structure fuels the automatic generation of reports, extracting consolidated data directly from the test context.

4.5 Test Execution Example

The very first page displayed upon launching the application is the authentication interface, illustrated in Figure 4.4. On this screen, users must input the specific username and password predefined in the source code for the laboratory technicians' use.

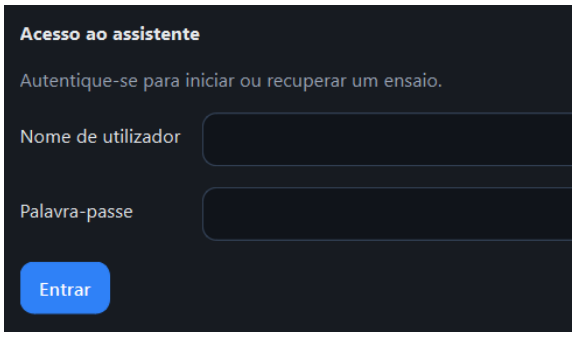


Figure 4.4: Test execution example: user authentication.

The subsequent page, shown in Figure 4.5 allows the user to choose between starting a new testing phase or resuming a previously saved session. Selecting the latter option prompts the user to load the JSON file that contains the exact progress data and testing history for that specific MVW3000.

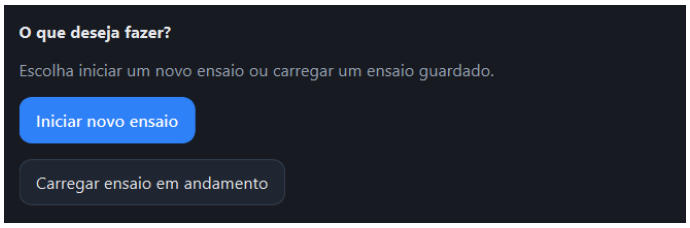


Figure 4.5: Test execution example: choose between starting a new testing phase or resuming a saved session.

Conversely, choosing to start a new testing phase leads directly to the next screen, illustrated in Figure 4.6, where the MVW3000 identification code and the parameters' file must be provided to the application. There are other essential fields to be completed, such as the serial number, the number of columns, and the client's name, which will subsequently be used to fill the final test report. Furthermore, upon entering the identification code, the system automatically processes it and displays the extracted data at the bottom of the page.

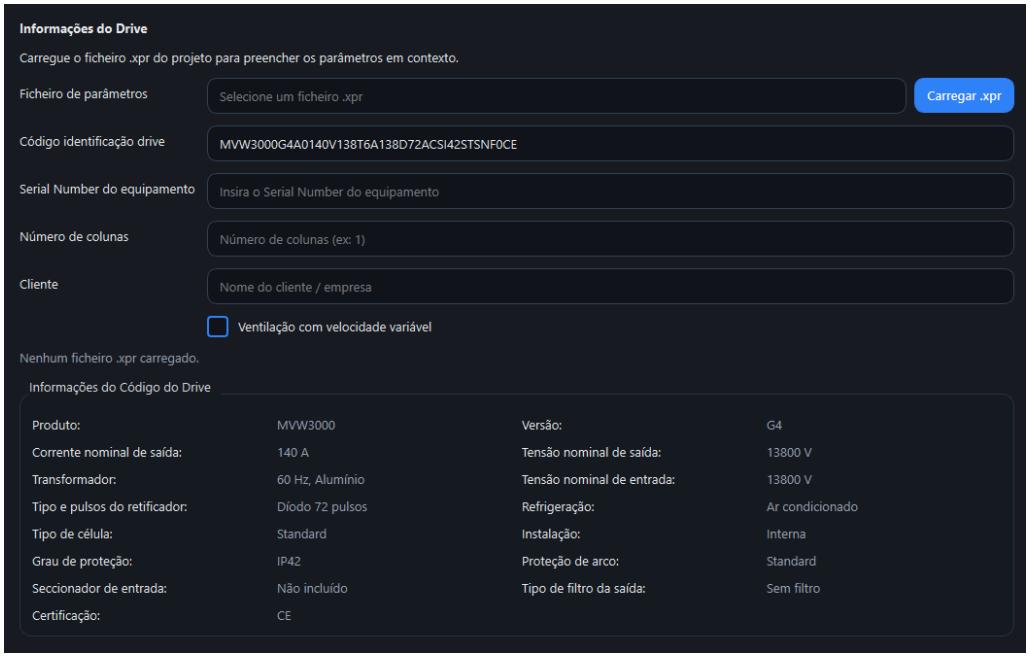


Figure 4.6: Test execution example: identification code and parameters' file upload page.

To provide a clearer understanding of how the application handles this data extraction, an excerpt of a parameters' file is presented below (Listing 4.1). Given the file's highly consistent structural organization, the underlying code can reliably parse the document, mapping each specific parameter to its corresponding value.

```
<?xml version="1.0" encoding="UTF-8" standalone="yes"?>
<user_parameters>
(...)
   <user_parameter parameter_ref="P205" user_value="0"/>
(...)
   <user_parameter parameter_ref="P1683" user_value="10"/>
   <user_parameter parameter_ref="P1684" user_value="15"/>
   <user_parameter parameter_ref="P1685" user_value="5"/>
   <user_parameter parameter_ref="P1686" user_value="5"/>
(...)
</user_parameters>
```

Listing 4.1: Excerpt of a standard parameter file showing the structured parameter-value pairs.

As can be observed, the file is structured using a standard XML format. The document features a single root element, **<user_parameters>**, which encompasses the complete list of parameter settings. Each configuration line is defined by an individual **<user_parameter />** tag. The data organization relies on two main attributes: **parameter_ref**, which explicitly denotes the identifier of the target parameter, and **user_value**, which contains the value assigned to it.

Taking the motor type parameter discussed in Subsection 2.4.2 as an example, while its official five-digit designation is P00205, it appears within this file simply as P205, omitting the leading zeros. The numerical suffix remaining after the "P" prefix directly corresponds to the VSD's communication address (in this case, register 205).

On the other hand, parsing the VSD identification code relies on splitting the character string based on the information detailed in Appendix B. Because every identification code has a fixed length and shares the exact same segment structure, the parsing logic can consistently extract the required information. Furthermore, this rigid structure allows the developed software to instantly validate whether the identification code was entered correctly, preventing typos or invalid configurations from progressing.

Once the information regarding the MVW3000 under test is submitted, details about the motor used in the testing routine must be entered on the following page, illustrated in Figure 4.7. If the motor used on the laboratory is the actual unit intended for the client's final installation, the user can select this option directly in the interface. Consequently, the application automatically retrieves the motor characteristics from the project parameters' file. Otherwise, the operator must manually input the required fields regarding the motor's characteristics.



Figure 4.7: Test execution example: characterization of the motor used for testing the MVW3000.

To demonstrate the practical operation of the application, the "Initial Energization: Pre-Charge System / DC Bus Voltage Feedbacks" test was selected as an example. The objective is to ensure the safe initial energization of the equipment before subjecting it to full-load testing. An excerpt detailing this procedure can be found in Appendix C.

The testing procedure begins by requiring the VSD test mode to be inactive. As detailed in the programming manual, this mode is configured through parameter C1.2.2 (Figure 4.8). Furthermore, either the manual or the WPS provides the specific parameter address, allowing it to be read and modified using an available communication protocol [52].

C1.2 Inverter use

C1.2.2 Inverter test mode

Range: 0 ... 3 **Default:** 0

Properties:

Description:
Enables and configures the inverter operation to operate in test mode.

Indication	Description
0 = Inactive	Test mode inactive. All communications, protections and inverter functions are enabled.
1 = No cells and no measurements	Test mode active. The inverter operates with cell communications and measurements disabled.
2 = Cellless	Test mode active. The inverter operates with cell communications disabled.
3 = No measurements	Test mode active. The inverter operates with measurements disabled.

Figure 4.8: Inverter test mode parameter details in the programming manual [52].

If this test mode is inactive—i.e., if the parameter value is zero—,this status is displayed within the application. Conversely, if the mode is active, a dedicated button appears, enabling the technician to input the correct value to the parameter. Furthermore, the procedure requires logging the ambient temperature and relative humidity, obtained from a calibrated laboratory thermometer, which is shown in Figure 4.9.



Figure 4.9: Calibrated reference thermometer used for ambient temperature validation.

For this logging, the application provides appropriate editable input fields (Figure 4.10). It is worth noting that, if the test mode remains active or if the environmental data fields are not properly filled out, the application's validation logic prevents the technician from advancing to the subsequent step.

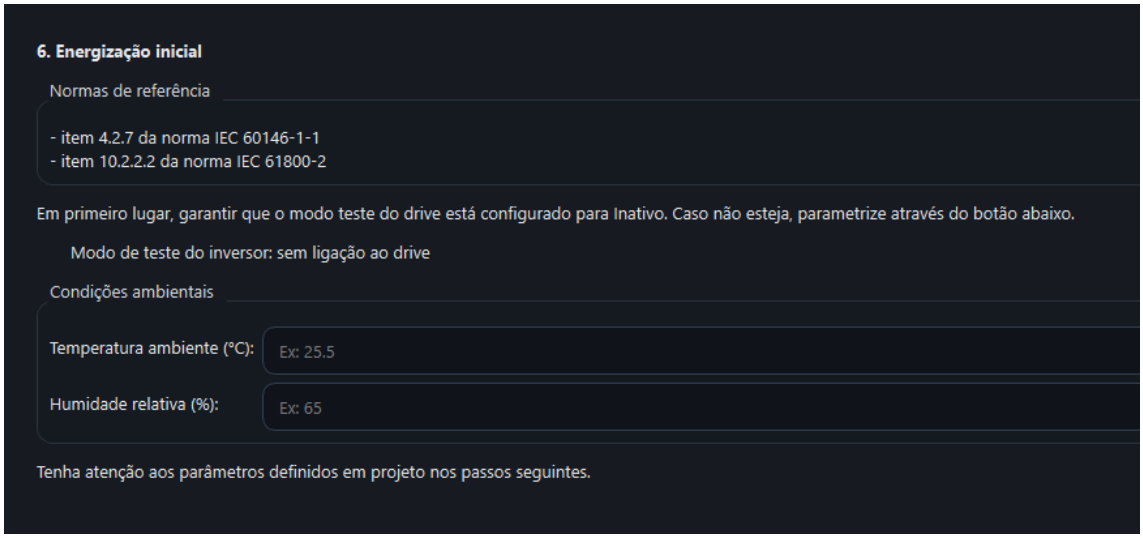


Figure 4.10: Test execution example: initial verifications page, displaying normative framework, VSD mode and input fields.

Following this, the pre-charge VSD requires a basic parameterization. Initially, the procedure dictates loading the default parameters for 60 Hz operation, which is achieved by setting parameter P0204 (Load/Save Parameters) to 5 (Load WEG 60 Hz). Subsequently, the "Oriented Start-up"

must be enabled by configuring P0317 to 1 (Yes). Since the required settings vary depending on the specific pre-charge VSD in use, the GUI dynamically updates the displayed instructions based on the technician's selection (Figure 4.11).

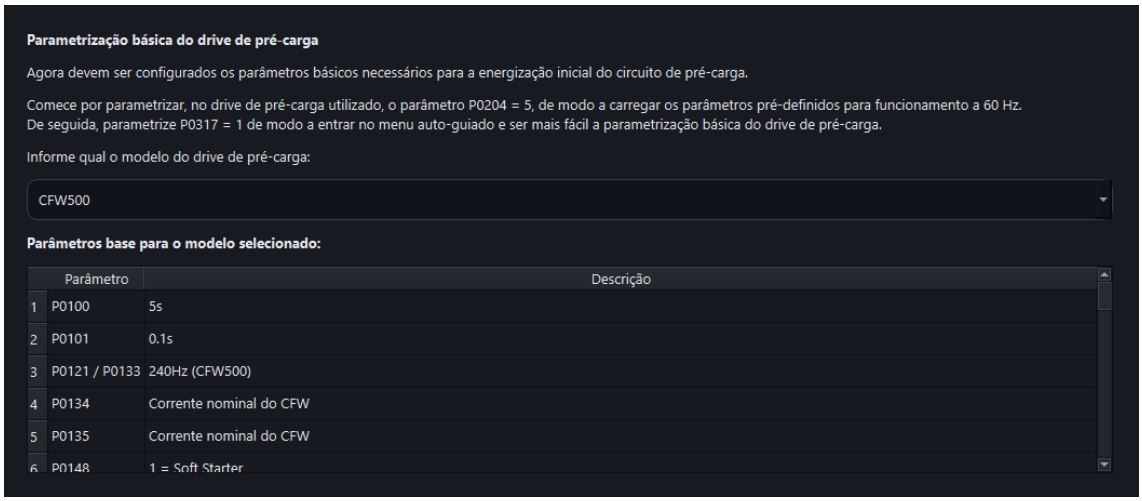


Figure 4.11: Test execution example: basic parameterization of the used pre-charge VSD.

The pre-charge unit is a LV VSD (CFW500, CFW501, CFW700 or CFW900 from WEG) internally mounted within the MVW3000 panel. Automating this parameterization would require switching the active communication channels to target this specific internal VSD. Combined with the VSD's built-in oriented startup, it was concluded that the operational gain of implementing an automated parameterization for this specific step was considered unjustified.

The procedure then moves to the basic parameterization of the MVW3000. Table 8 of the testing procedure (provided in Appendix C) outlines the specific parameters required for this phase. As previously mentioned, the application features a dedicated initialization page where the operator inputs the drive's foundational data, namely its identification code and the corresponding parameter file. Consequently, during this parameterization step, the software accesses the Test Context (refer back to the software architecture in Figure 4.2) to retrieve the required parameter values, which were extracted and stored in memory upon the initial file upload.

The procedure specifies that if the VSD features a sine-wave filter with an output contactor, parameter C5.11.3.1 must be set to 1. This information is automatically extracted from the MVW3000's identification code (corresponds to the case where the output filter is type 2) and is factored into the parameterization process executed by the tool.

The basic parameterization of the MVW3000 can then be executed simply by pressing the dedicated button shown in Figure 4.12. After writing to the registers corresponding to these parameters, the application automatically performs a read operation to verify the success of the procedure. Consistent with the system's safety design, further progress within the application is prohibited until a successful write confirmation is achieved from the hardware.

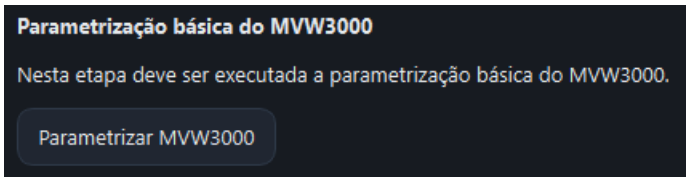


Figure 4.12: Test execution example: basic parameterization of the MVW3000.

Following the basic parameterization phase, the procedure outlines the steps for the initial energization of the MVW3000. Broadly, this process entails powering up the VSD's control electronics, release the emergency button, executing the pre-charge sequence, and continuously monitoring the operation. The application polls the specific status register of the MVW3000 to track its status and display this real-time feedback on the screen. To safeguard the equipment, the application blocks navigation to subsequent steps until the drive explicitly reports a "Ready" status (Figure 4.13).

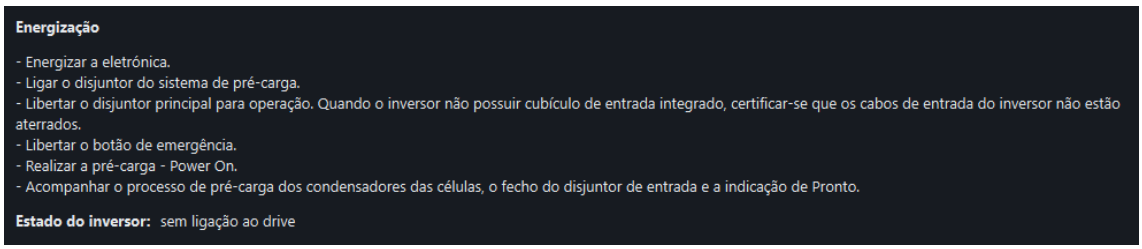


Figure 4.13: Test execution example: energization instructions.

Subsequently, the operator is prompted to insert the grid voltage and the transformer's secondary-to-primary voltage ratio. These variables are exogenous to the automated framework, as they are not contained within either the uploaded parameter file or the VSD identification code. As stipulated in the testing procedure, the allowable tolerance for the DC bus voltage of each power cell is $\pm 5\%$ relative to the theoretical ideal value calculated using Equation 4.1:

$$V_{\text{DC bus}} = V_{\text{grid}} \times \left(\frac{V_{\text{sec}}}{V_{\text{prim}}} \right) \times \sqrt{2} \tag{4.1}$$

Similarly, the cell temperature measurements are subject to an allowable tolerance of $\pm 5\%$ relative to the reference reading inserted in the beginning of the test. Since the number of power cells per phase is another variable omitted from both the parameters' file and the VSD identification code, the technician must input this value manually. This action dynamically adjusts the number of rows in the data acquisition table displayed on the application screen (Figure 4.14). If any of the cell temperatures or voltages read via the parameters fall outside their respective acceptable thresholds, the issue must be corrected. To ensure process integrity, the application's validation logic strictly blocks any further progress in the test sequence until all parameters fall within the compliant range.



Figure 4.14: Test execution example: power cells temperature and DC bus voltage monitoring.

Once the power cell temperatures and voltages are successfully validated, the testing procedure requires applying a reduced speed reference, exemplified in the original documentation as "Set a reduced speed reference (e.g., 200 rpm for a 4-pole motor)".

The synchronous speed of an induction motor is given by:

$$n_s = \frac{120 \cdot f}{P} \tag{4.2}$$

Where,

- n_s is the synchronous speed [rpm];
- f is the frequency of electrical voltage supply [Hz];
- P is the total number of magnetic poles in the motor;

The original procedure was developed in Brazil, where there is a standard 60 Hz grid frequency environment. The synchronous speed, n_s, for a 4-pole motor is, accordingly:

$$n_s = \frac{120 \times 60}{4} = 1800\,\text{rpm} \tag{4.3}$$

So, the suggested 200 rpm reference corresponds to approximately 11.1% of the synchronous speed, n_s:

$$\frac{200}{1800} \cdot 100 \approx 11.1\% \tag{4.4}$$

This requirement was implemented into an automated logic to dynamically calculate and parameterize a reduced speed reference equivalent to 10% of the motor's synchronous speed. This action is executed via the dedicated button illustrated in Figure 4.15. Once the reduced speed reference is successfully parameterized, the VSD must be enabled to initiate operation. During this

phase, the testing procedure requires monitoring the output voltage and current, both of which are displayed as real-time feedback directly on the GUI.

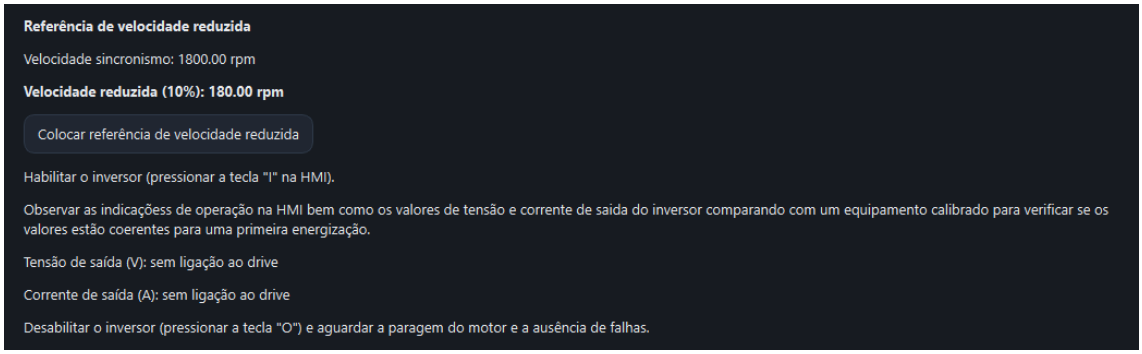


Figure 4.15: Test execution example: reduced speed reference and output voltage/current assessment.

To wrap up the testing workflow, the application features a dedicated export page with two distinct buttons: one for the updated parameters' file and another for the final test report (Figure 4.16).

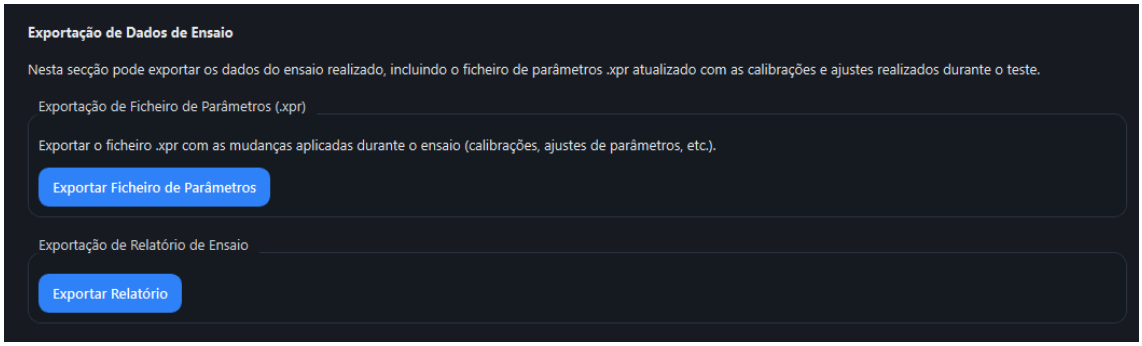


Figure 4.16: Final parameters' file and test report exportation.

First, technicians can export the updated parameters' file, which automatically integrates all calibrations and adjustments performed throughout the process into the original file. Second, the system generates a fully filled test report by leveraging WEG's official internal report template. This template is embedded within the application using specific placeholders for each required data field, as shown in Figure 4.17. Upon triggering the report exportation, the software automatically replaces these placeholders—that consist of text strings formatted as **{{variable_name}}**—with the actual data gathered during the test sequences, instantly delivering a final document in PDF format.

2. Transformer Secondary Insulation and Dielectric Test: Ambient Tem

2.1 Isolation and Dielectric Test Between Secondaries			
Isolation Resistance Measured		Dielectric (4 kVac)	
Before Dielectric Test	After Dielectric Test	Leakage Current	Result
TR1 {{rb_1}} MΩ	TR1 {{ra_1}} MΩ	TR1 {{lc_1}} mA	{{R41_1}}
TR2 {{rb_2}} MΩ	TR2 {{ra_2}} MΩ	TR2 {{lc_2}} mA	{{R41_2}}
TR3 {{rb_3}} MΩ	TR3 {{ra_3}} MΩ	TR3 {{lc_3}} mA	{{R41_3}}

Figure 4.17: Excerpt from the WEG's internal report template with placeholders.

4.6 Experimental Validation

The validation of the tool began concurrently with its development. Due to the unavailability of an actual MVW3000 during the initial proof-of-concept phase, we had to utilize a server simulator directly on the development computer.

To achieve this, we used Modbus Slave from Modbus Tools, a Modbus server simulator whose interface is shown in Figure 4.18 [47]. To establish a connection, the server was simulated on the local IP address 127.0.0.1 via port 502, which serves as a local host for the computer to communicate with itself. We then configured this specific IP within the communication settings of the developed tool.

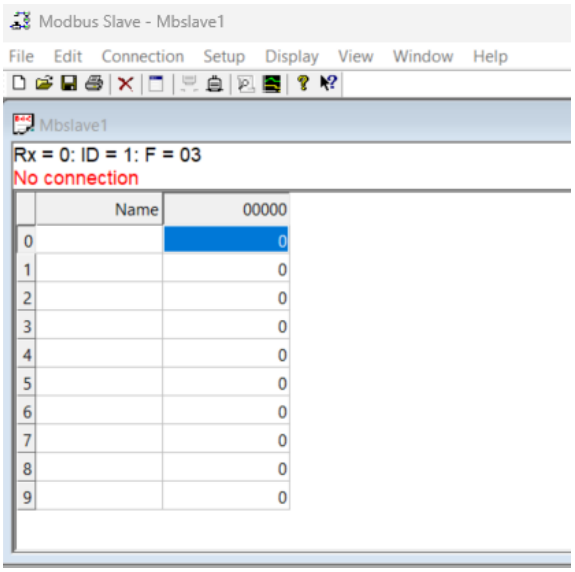


Figure 4.18: Modbus Slave interface.

By creating a dedicated register for each MVW3000 parameter, it was possible to simulate the tool usage with an actual equipment, ensuring a secure and reliable development environment. Furthermore, since the Modbus Slave interface allows direct modification of register values, we successfully simulated and verified the parameter-reading functions.

To test the tool's performance with physical hardware, we used the automation training unit illustrated in Figure 4.19. This unit primarily comprises a 0.18 kW induction motor manufactured by WEG equipped with an encoder, alongside a control panel featuring a main switch, speed reference controls, output current and speed monitoring, and an emergency stop button. Additionally, the setup integrates a CFW900 LV VSD, also manufactured by WEG.

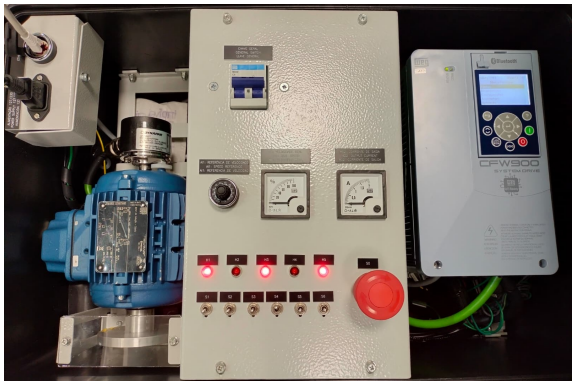


Figure 4.19: Automation training unit used to validate the MVW3000 Test Wizard, comprising a 0.18 kW induction motor with encoder, control panel, and a CFW900 LV VSD.

We selected this validation setup because CFW900's processing unit is highly identical to that of the MVW3000. Notably, the communication part is exactly the same. Although the specific parameters and their addresses are not identical, they share similarities and follow a nearly identical parameter structure. The main difference lies in the CFW900 featuring an additional level, W (Wizards), which allows setting the parameters related to the oriented startup and self-tuning processes. Consequently, this setup provided a representative validation environment for the communication layer and core read/write mechanisms.

In this regard, we began by configuring the IP address setup parameter directly through the CFW900's HMI, setting it to the mode where the IP address, subnet mask, and gateway configurations are defined via the product's internal parameters instead of receiving this information dynamically over the network. Following this configuration, we navigated the HMI to set the equipment's IP address to 192.168.0.1 (Figure 4.20) and the Modbus TCP port to 502 (Figure 4.21).

Consequently, we configured the same IP address and port within the developed application, as illustrated in Figure 4.22. This setup allowed the communication link with the hardware to be successfully established.

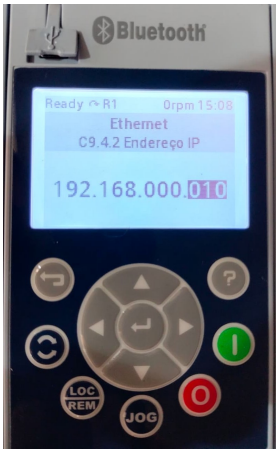


Figure 4.20: Configuration of CFW900's IP address.



Figure 4.21: Configuration of CFW900's Modbus TCP port.



Figure 4.22: Connection settings screen within the developed tool configured for the used validation setup.

Additionally, we connected the WPS software to the CFW900. As shown in Figure 4.23, its corresponding status parameter confirmed two active Modbus TCP/IP connections simultaneously: one originating from the WPS software itself and the other from the developed tool.

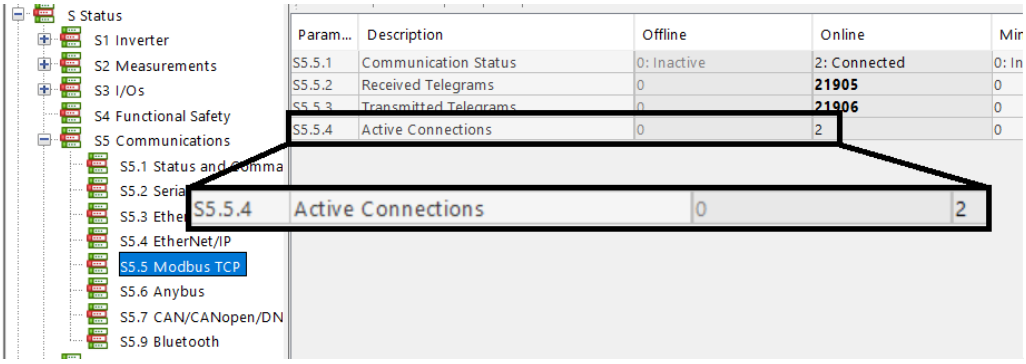


Figure 4.23: VSD status parameter indicating two active Modbus TCP/IP connections.

To validate the parameter reading and modification functions, we temporarily adjusted the developed application to test these core capabilities. The tool includes a dedicated developer mode,

which can be activated directly through the source code before recompiling the software. This developer mode bypasses the standard procedural sequence of the software. After successful authentication, it allows the user to navigate freely through any section of the application, eliminating the requirement to validate a specific testing step before proceeding to the next. This approach allowed us to successfully test and verify both the reading and modification of parameters.

Chapter 5

Impact Assessment and Discussion

This chapter assesses the effectiveness of the developed supporting tool by means of a dedicated impact study. In addition, it discusses the key challenges encountered during the development process, as well as the operational limitations of the resulting application.

5.1 Impact Assessment

The impact assessment began by comparing the time required for each type of task in a full MVW3000 testing process with the time required to perform the same tasks using the MVW3000 Test Wizard. This comparison is detailed in Table 5.1. The impact of the developed tool can be assessed based on several criteria, including process efficiency, workload distribution, reliability of execution, and potential financial benefits.

The original testing procedure has a total duration of 42 hours and 30 minutes, based on data provided by the laboratory team. With the MVW3000 Test Wizard, the testing time is reduced to 34 hours and 15 minutes, saving 8 hours and 15 minutes—a reduction in the total testing time of 19.41%. These results demonstrate the tool's direct and measurable impact on testing efficiency, reducing the time required to complete the same scope of work by almost one fifth. These durations serve as a typical reference for a standard test profile, as the actual timeframe can fluctuate based on the MVW3000 configuration, troubleshooting of anomalies, client-specific demands, FAT execution, or the necessity of repeating test stages.

Although this reduction is already significant within a single test cycle, its relevance becomes even more evident when translated into laboratory capacity. Considering the standard routine testing time reported by WEG, the laboratory currently has an installed capacity of 24 units per year under a single-shift operation. This capacity is not determined solely by the testing time itself, but also includes supporting activities such as moving equipment, which can reach 20 tonnes; changing the power supply connections; installing the test motor, supply motor, and dynamometer; preparing the test platform; and carrying out other setup activities required before and after test execution. By applying the time reduction achieved with the MVW3000 Test Wizard, the available capacity of the laboratory can be recalculated. Under the same operating conditions, the

reduction in testing time allows an increase of approximately five additional units per year, per shift. Therefore, based on industrial processes' team calculations, the annual capacity increases from 24 to, approximately, 29 units per year. This represents a 20% increase in installed testing capacity, without requiring additional investment in major laboratory infrastructure. This is particularly relevant because the laboratory represents one of the most important operational assets in the production flow. It is also one of the assets with the highest associated investment and, as discussed in Subsection 3.2.1, the most prone to becoming a bottleneck. Therefore, a capacity increase of this magnitude should not be understood merely as a reduction in labour hours. Rather, it reflects a more efficient use of an existing asset, enabling higher output while preserving the same physical infrastructure and basic shift structure.

Table 5.1: Time comparison of the routine testing procedure for an MVW3000 without the tool, with the tool, and the resulting time savings (ΔT).

Type of task	**Time without tool (h)**	**Time with tool (h)**	ΔT **(h)**
Inspections and Verifications	1.5	1.5	0
Measurement of electrical variables, speeds, and torques, among others	**4.5**	**4**	**-0.5**
Parameterization associated with variable reading	0.5	0	-0.5
Measurement of variables during temperature rise test	4	4	0
Verification of fault/alarm occurrences on the HMI	3	0	-3
Parameterization of the MVW3000, including during calibration phases	1.5	0	-1.5
Parameterization of the pre-charge VSD	0.25	0.25	0
Consulting reference tables and calculating test voltages	0.25	0	-0.25
Setting up the various tests outlined in the procedure	26	26	0
Exporting the final parameters' file	0.5	0	-0.5
Final test report	**5**	**2.5**	**-2.5**
Final inspection	1.75	1.75	0
Serial Numbers registration	0.75	0.75	0
Organize data	1	0	-1
Filling the report	1.5	0	-1.5
Total Testing Time	**42.5**	**34.25**	**-8.25**

From WEG's historical order profile, the annual capacity of the laboratory appears to be generally well dimensioned in terms of average yearly demand. The main challenge is that several orders are linked to specific project packages, potentially creating significant workload peaks within relatively short periods. In these situations, even if the annual capacity is adequate, the short-term concentration of tests can create operational pressure and may require exceptional measures to meet customer delivery dates.

One of the most common responses to these workload peaks is the use of additional working

hours, such as Saturday work. In this context, the approximately 20% capacity gain provided by the tool becomes highly relevant by being comparable to the additional capacity obtained by extending the working week with Saturday work. In other words, the use of the tool may allow the same amount of testing work to be completed within the normal five working days of the week, reducing the need for overtime and improving workload balance for the laboratory team.

In cases where Saturday work is not sufficient to absorb the workload peak, another possible operational response is the temporary opening of a second shift, requiring an additional team. The capacity increase enabled may, in some cases, be sufficient to avoid or delay the need for this second shift. Alternatively, if Saturday work is maintained during peak periods, the use of the tool further increases the laboratory's ability to respond to short-term demand without immediately requiring a structural increase in resources. The financial impact of this improvement is therefore broader than the direct saving in labour hours. The developed tool can reduce the need for overtime, decrease the probability of additional shift activation, support compliance with customer deadlines, and improve the laboratory's ability to respond to project-driven demand peaks.

In addition to the capacity and productivity benefits, the MVW3000 Test Wizard also introduces qualitative improvements in the testing methodology. By increasing the level of automation, the tool reduces operator dependency during repetitive tasks and minimizes the probability of human error. The automated acquisition and organization of test records also improves consistency and documentation quality. These aspects are particularly important in a testing environment where reliability is crucial.

As discussed in Section 4.1, involving laboratory technicians during the development phase is essential to ensure smooth downstream integration into the testing workflow and adequate alignment with technicians' needs. This collaborative approach kept the technicians engaged, and their inputs directly shaped the final software. Consequently, the user feedback was positive. Although adopting the application requires breaking old habits and adapting to a new routine, the team perceives it as a significant improvement to their work. Technicians highlighted that the interface is straightforward and intuitive, making it excellent for training new personnel. A major factor behind this is how the application eliminates paper workflows by embedding specific data entry fields directly within the digital testing instructions, removing any ambiguity about which variables to record. Furthermore, the company highly values the MVW3000 Test Wizard and fully supports its implementation.

These results directly address the three research questions established in Section 1.2. Regarding the first research question, which questioned whether converting manual operations and configuration rules into software logic could partially automate the routine and reduce reliance on technicians' interpretations, the data confirms a successful transition. By embedding the testing constraints and automating verifications directly into the software, the procedure was standardized, ensuring uniform execution and removing the ambiguity of individual technical criteria. In relation to the second research question, which questioned if establishing direct communication with the VSD could minimize manual effort and transcription errors, the impact is clearly reflected in the time reductions. Tasks that previously required continuous, manual navigation through the

HMI and paper-based tracking were optimized into automated digital routines, eliminating transcription errors and reducing manual workload. Finally, concerning the third research question, which assessed whether the developed tool could deliver measurable improvements to the overall workflow, the evidence shows a considerable reduction in total testing time. Beyond this acceleration, workflow consistency and multi-shift session continuity were structurally secured through the application's reporting and state-persistence features.

5.2 Challenges and Limitations

Throughout the development of this dissertation, challenges were encountered that directly impacted the initial research phase. The existing written testing procedures proved to be highly complex and exceptionally difficult to interpret. Due to the sophisticated engineering and project-specific nature of MV VSDs, the documentation frequently led to procedural ambiguities. Obtaining objective guidelines was a recurring challenge throughout the project, requiring continuous clarification and technical discussion with specialized engineering personnel.

While the MVW3000 Test Wizard successfully automates an important part of the testing, it possesses clear boundary limitations regarding its operational scope and long-term maintenance. The software focuses predominantly on automated parameter updates, enforcing configurations required by the ruleset, and creating specific calibration routines such as measuring cards. However, the application does not interface with voltage application systems, nor does it connect digitally to external physical laboratory instruments. Consequently, the acquisition of external measurements does not occur automatically, relying entirely on the technician to manually read the instruments and transcribe the values into the software interface.

In addition, any future modification to the testing procedure, whether driven by hardware upgrades, client customization, or international standard updates, will likely require direct intervention in the application's source code. Therefore, ensuring the long-term viability and autonomy of this tool within the company demands that engineering personnel maintain basic algorithmic and programming knowledge to implement these necessary adjustments. Finally, the entire software architecture is strictly tailored and limited to one specific equipment line, meaning it is exclusively restricted to the MVW3000 and cannot be deployed across other product lines without significant redevelopment. This is because testing protocols are highly product-specific; although similarities certainly exist, the procedures for the MVW3000 differ fundamentally from those of other WEG equipment, such as the MVW01.

These limitations correspond to expected boundaries established at the beginning of the work. Throughout the experimental validation phase, no operational malfunctions were encountered within the software tool. The initial concept for the project recognized that to break the barrier between a completely manual process and an automated one, the work should focus primarily on parameterization routines, status monitoring, and report generation, thereby establishing a solid baseline for subsequent developments. In summary, although the tool features clear operational boundaries (meaning it does not fully automate the physical components of the testing routine)

and will require ongoing maintenance like any other software application, it successfully delivers on its foundational objectives.

Chapter 6

Conclusions and Development Perspectives

6.1 Conclusions

The primary objective of this dissertation was to conceptualize, develop, and deploy an automated software tool designed to optimize the routine testing procedure for WEG's MVW3000 MV VSD. Following the completion of the development cycle and experimental validation, it can be concluded that the project successfully achieved its core objectives, while also receiving positive feedback from its target users.

The analysis of the traditional testing workflow revealed significant inefficiencies, characterized by a high volume of manual data transcription and repetitive navigation through the VSD's physical HMI. By leveraging the equipment's communication capabilities, this tool broke the barrier between a completely manual testing procedure and an automated one. The developed software has a reduced amount of manual data entry fields because it automatically parses project parameters' files and decodes identification codes, as well as effectively mitigates the risk of human error and reduces procedural ambiguities.

Furthermore, the integration of automated calibration routines, dynamic safety verification sequences, and real-time monitoring of variables represented a major modernization of the factory floor's testing infrastructure. The implementation of a structured state-persistence mechanism ensured operational continuity across multi-shift testing, while the automated exportation of finalized test reports in PDF format significantly enhanced data traceability and quality assurance protocols.

Overall, the implementation of the MVW3000 Test Wizard produces a measurable reduction in routine testing time and a significant increase in the effective capacity of the MVW3000 laboratory. The reduction of 8 hours and 15 minutes per tested unit translates into an annual capacity increase from 24 to approximately 29 units per shift per year, representing a gain in the order of 20%. Beyond the numerical improvement, the tool contributes to a more efficient, less tiring, and less error-prone testing process. It also strengthens the laboratory's role as a strategic asset for

WEG, supporting future activity growth in an operation where the testing laboratory can represent one of the main production constraints.

6.2 Development Perspectives

Despite the advancement in the optimization of the testing procedure, there are several opportunities for future improvement.

The first major area of evolution involves the direct integration of measurement equipment into the software. However, achieving this goal will require a detailed and thorough study of the testing laboratory's physical layout. It will be necessary to evaluate the impact of additional cabling on the ergonomics and safety of the space, the physical availability to accommodate new infrastructure, and the transition from point-to-point connections to an integrated network architecture.

Another critical aspect refers to the automation of voltage application. Although the current instrumentation possesses the technical capacity for this, an evaluation of laboratory supervisors concluded that this implementation currently lacks the required robustness and safety. Thus, improving the safety protocols associated with the automatic injection of voltage constitutes future work. In parallel, the inherently physical nature of several testing tasks imposes a limit on complete automation. Overcoming this barrier would require a substantial redesign of the MVW3000's hardware, incorporating automatic and controllable switching systems that operate robustly and safely.

Regarding the data and documentation flow, the process currently ends with the manual upload of the report and final parameters file to the SAP system. Automating this export and archiving step would eliminate the final remaining workload. Additionally, linking the tool with a central database would allow for the creation of a real-time dashboard, providing the department with immediate visibility into the status and progress of tests.

As previously mentioned, although this work is focused specifically on the MVW3000, the supporting tool could have targeted other products. Therefore, expanding the scope of the tool is also a natural progression. The software could be adapted to support the testing procedure of other equipment, such as the MVW01 MV VSD or the mounted panel soft-starter ASW900 series.

Furthermore, an interactive troubleshooting guide could be integrated into the application. This feature would function as a step-by-step diagnostic wizard, prompting the user with symptom-based questions and offering selectable options to effectively guide them through a structured problem-solving process.

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Appendix A

Parameter Structure

The following page of this appendix contains an excerpt from the product programming manual, illustrating the structure of the MVW3000's parameters [52].

1 PARAMETER STRUCTURE

S Status

- S1 Inverter
  - S1.1 Status
  - S1.2 Software version
  - S1.4 Accessory data
    - S1.4.1 Backplane
    - S1.4.2 Slot A
    - S1.4.3 Slot B
    - S1.4.4 Slot C
    - S1.4.5 Slot D
    - S1.4.6 Slot E
    - S1.4.7 Slot F
    - S1.4.8 Slot G
    - S1.4.9 Control board
  - S1.5 Date/Hour
  - S1.6 Control words
  - S1.8 Cells
- S2 Measurements
  - S2.1 Motor speed
  - S2.2 Motor torque
  - S2.3 Inverter output
  - S2.4 Temperatures
    - S2.4.1 Temperature accessory
    - S2.4.2 Thermal protection relay
    - S2.4.3 Air temperature
    - S2.4.4 Cells
  - S2.6 Inverter input
  - S2.7 DC link
  - S2.8 Torque current limitation
- S3 I/Os
  - S3.1 Slot X status
    - S3.1.1 Analog inputs
    - S3.1.2 Analog outputs
    - S3.1.3 Digital inputs
    - S3.1.4 Digital outputs
    - S3.1.5 Encoder
  - S3.2 Slot A status
    - S3.2.1 Analog inputs
    - S3.2.2 Analog outputs
    - S3.2.3 Digital inputs
    - S3.2.4 Digital outputs
    - S3.2.5 Encoder
    - S3.2.6 Temperatures
  - S3.3 Slot B status

S Status (cont.)

- S3 I/Os (cont.)
  - S3.4 Slot C status
  - S3.5 Slot D status
  - S3.6 Slot E status
  - S3.7 Slot F status
  - S3.8 Slot G status
  - S3.9 Control board
    - S3.9.1 Analog outputs
    - S3.9.2 Digital inputs
    - S3.9.3 Digital outputs
    - S3.9.4 Encoder
- S5 Communications
  - S5.1 Status and commands
  - S5.2 Serial RS485
  - S5.3 Ethernet
  - S5.4 EtherNet/IP
  - S5.5 Modbus TCP
  - S5.6 Anybus
  - S5.7 CAN/CANopen/DNet
- S6 SoftPLC
  - S6.1 Program execution
  - S6.2 Control and references

D Diagnostics

- D1 Faults
  - D1.1 Current
  - D1.3 History
- D2 Alarms
  - D2.1 Actual
  - D2.3 History
- D3 Hour control
- D4 Inverter and access.
  - D4.1 Inverter
    - D4.1.1 Measurements
    - D4.1.4 Control voltages
    - D4.1.5 Mot.overl.fault
    - D4.1.11 Configuration
    - D4.1.12 Advanced
  - D4.2 Accessories
    - D4.2.1 Diag. Slot A
    - D4.2.2 Diag. Slot B
    - D4.2.3 Diag. Slot C
    - D4.2.4 Diag. Slot D

D Diagnostics (cont.)

- D4 Inverter and access. (cont.)
  - D4.2 Accessories (cont.)
    - D4.2.5 Diag. Slot E
    - D4.2.6 Diag. Slot F
    - D4.2.7 Diag. Slot G

C Configurations

- C1 Inverter and power supply
  - C1.2 Inverter use
  - C1.6 Other inverter settings
  - C1.8 Measurements
  - C1.9 Precharge
  - C1.10 Calibrations
- C2 Motor
  - C2.1 Motor data
  - C2.2 Motor model
- C3 Control
  - C3.1 Configuration
  - C3.2 Scalar control
    - C3.2.1 V/f curve
    - C3.2.2 Optimization
      - C3.2.2.1 Induction motor
      - C3.2.2.2 Synchronous motor
      - C3.2.2.3 Sync.mot.external excitation
    - C3.2.3 Current stabilization
    - C3.2.4 Pre-magnetization
    - C3.2.5 I/F control
  - C3.3 Vector control
    - C3.3.1 Configuration
    - C3.3.2 Regulators
      - C3.3.2.1 Speed regulator
      - C3.3.2.2 Torque regulator
      - C3.3.2.3 Flux regulator
      - C3.3.2.4 Current regulator
      - C3.3.2.6 Regulators self-tuning
    - C3.3.3 Output voltage limiter
    - C3.3.4 Torque mode
      - C3.3.4.1 Speed limiter
    - C3.3.5 Speed mode
      - C3.3.5.1 Torque limiter
    - C3.3.7 Speed steady state estimator
    - C3.3.10 Maximum torque per ampere
  - C3.4 Current limiter

PARAMETER STRUCTURE

C Configurations (cont.)

- C3 Control (cont.)
  - C3.5 DC link
    - C3.5.1 Voltage limit
    - C3.5.2 Scalar control
    - C3.5.3 Vector control
    - C3.5.4 Modulation compensation
  - C3.8 Flying Start
    - C3.8.1 Configuration
    - C3.8.2 Scalar control
    - C3.8.3 Vector control
  - C3.9 Ride-Through
    - C3.9.1 Configuration
    - C3.9.2 Scalar control
    - C3.9.3 Vector control
  - C3.11 Synchronous transfer
  - C3.12 Bypass
  - C3.14 Zero speed disable
- C4 Commands and references
  - C4.1 LOC/REM mode config.
  - C4.2 Commands
    - C4.2.1 Remote R1
    - C4.2.2 Remote R2
    - C4.2.3 DI for commands
    - C4.2.4 Local HMI
  - C4.3 References
    - C4.3.1 Speed
      - C4.3.1.1 Reference range
      - C4.3.1.2 Reference source
      - C4.3.1.3 Ref. HMI, AIs and FIs
      - C4.3.1.4 Electronic pot. ref.
      - C4.3.1.5 Multispeed reference
      - C4.3.1.6 Skip speed
    - C4.3.2 JOG speed
    - C4.3.3 Torque
- C5 I/Os
  - C5.1 Slot X
    - C5.1.1 Analog inputs
    - C5.1.2 Analog outputs
    - C5.1.3 Digital inputs
    - C5.1.4 Digital outputs
    - C5.1.5 Encoder
  - C5.2 Slot A
    - C5.2.1 Analog inputs

C Configurations (cont.)

- C5 I/Os (cont.)
  - C5.2 Slot A (cont.)
    - C5.2.2 Analog outputs
    - C5.2.4 Digital outputs
    - C5.2.5 Encoder
    - C5.2.6 Temperatures
  - C5.3 Slot B
    - C5.3.1 Analog inputs
    - C5.3.2 Analog outputs
    - C5.3.4 Digital outputs
    - C5.3.5 Encoder
    - C5.3.6 Temperatures
  - C5.4 Slot C
    - C5.4.1 Analog inputs
    - C5.4.2 Analog outputs
    - C5.4.4 Digital outputs
    - C5.4.5 Encoder
    - C5.4.6 Temperatures
  - C5.5 Slot D
    - C5.5.1 Analog inputs
    - C5.5.2 Analog outputs
    - C5.5.4 Digital outputs
    - C5.5.5 Encoder
    - C5.5.6 Temperatures
  - C5.6 Slot E
    - C5.6.1 Analog inputs
    - C5.6.2 Analog outputs
    - C5.6.4 Digital outputs
    - C5.6.5 Encoder
    - C5.6.6 Temperatures
  - C5.7 Slot F
    - C5.7.1 Analog inputs
    - C5.7.2 Analog outputs
    - C5.7.4 Digital outputs
    - C5.7.5 Encoder
    - C5.7.6 Temperatures
  - C5.8 Slot G
    - C5.8.1 Analog inputs
    - C5.8.2 Analog outputs
    - C5.8.4 Digital outputs
    - C5.8.5 Encoder
    - C5.8.6 Temperatures
  - C5.9 DO operation levels

C Configurations (cont.)

- C5 I/Os (cont.)
  - C5.10 DOs delay
  - C5.11 Control board
    - C5.11.1 Analog inputs
    - C5.11.2 Analog outputs
    - C5.11.3 Digital outputs
    - C5.11.4 Encoder
- C6 Ramps
  - C6.1 Speed control
  - C6.2 Torque control
- C7 Prot.
  - C7.1 Power supply
  - C7.2 Ground fault
  - C7.3 Motor current
  - C7.4 Motor overload fault
  - C7.5 Over/Undertemperature
  - C7.6 DC link
  - C7.7 Motor overspeed
  - C7.9 Auto-Reset
  - C7.10 External fault/Alarm
  - C7.11 Thermal management
  - C7.13 Input transformer
  - C7.14 Encoder
  - C7.15 History
- C9 Communications
  - C9.1 Communication errors
    - C9.1.1 Master offline
    - C9.1.2 Master idle/Prog
  - C9.2 I/O data
    - C9.2.1 Reading data
    - C9.2.2 Writing data
  - C9.3 Serial RS485
  - C9.4 Ethernet
  - C9.5 EtherNet/IP
  - C9.6 Modbus TCP
  - C9.7 Anybus
  - C9.8 CAN/CANopen/DNet
  - C9.10 SymbiNet
- C10 SoftPLC
  - C10.1 Configuration
  - C10.2 Engineering unit
- C12 Backup
- C13 Nominal data

C Configurations (cont.)

- C13 Nominal data (cont.)
  - C13.1 Inverter
  - C13.2 Transformer
  - C13.3 Encoder
    - C13.3.1 Absoluto
    - C13.3.2 Incremental

A Application

- A1 User parameters
- A2 PID controller
  - A2.1 Monitoring
  - A2.2 Regulation
    - A2.2.1 Setpoint
    - A2.2.2 Ganhos
  - A2.3 Configuration
    - A2.3.1 Controle
    - A2.3.2 Setpoint
    - A2.3.3 Process variable
    - A2.3.4 Operation mode
    - A2.3.5 Command sources
    - A2.3.6 Falhas e alarmes
    - A2.3.7 Sleep mode
- A3 Mill
  - A3.1 Configurations
  - A3.2 Frozen charge detection
  - A3.3 Frozen charge release

Appendix B

MVW3000 Identification Code

The following page of this appendix contains an excerpt from the product catalog, illustrating the structure of the MVW3000 identification code and the information that can be extracted from it [50].

Coding[1)]

1	2	3	4	5	6	7	8
MVW3000	G4	A0140	V138	T6A	138	D72	AC

9	10	11	12	13	14	15
S	I	42	ST	SN	F0	CE

1 - Product line
2 - Generation
3 - Rated output current[2)], according to the table below

40 A	A0040	400 A	A0400
50 A	A0050	450 A	A0450
60 A	A0060	500 A	A0500
70 A	A0070	550 A	A0550
80 A	A0080	600 A	A0600
90 A	A0090	650 A	A0650
100 A	A0100	700 A	A0700
110 A	A0110	750 A	A0750
125 A	A0125	800 A	A0800
140 A	A0140	855 A	A0855
160 A	A0160	950 A	A0950
180 A	A0180	1,045 A	A1045
200 A	A0200	1,140 A	A1140
225 A	A0225	1,235 A	A1235
265 A	A0265	1,330 A	A1330
310 A	A0310	1,425 A	A1425
340 A	A0340	1,520 A	A1520

4 - Rated output voltage

1,150 V	V011	7,200 V	V072
2,300 V	V023	8,000 V	V080
3,300 V	V033	9,000 V	V090
4,160 V	V041	10,000 V	V100
5,500 V	V055	11,000 V	V110
6,000 V	V060	12,000 V	V120
6,300 V	V063	13,200 V	V132
6,600 V	V066	13,800 V	V138
6,900 V	V069		

5 - Input transformer

Al 50 Hz	T5A
Al 60 Hz	T6A
Cu 50 Hz	T5C
Cu 60 Hz	T6C

6 - Rated input voltage

1,150 V	011	6,900 V	069
2,300 V	023	7,200 V	072
3,000 V	030	8,000 V	080
3,300 V	033	8,400 V	084
4,160 V	041	10,000 V	100
4,800 V	048	11,000 V	110
5,500 V	055	12,000 V	120
6,000 V	060	12,400 V	124
6,300 V	063	13,200 V	132
6,600 V	066	13,800 V	138

7 - Rectifier type and pulses

Diode 18 pulses	D18	Diode 72 pulses	D72
Diode 24 pulses	D24	Diode 90 pulses	D90
Diode 30 pulses	D30	Diode 108 pulses	D108
Diode 36 pulses	D36	Diode 126 pulses	D126
Diode 42 pulses	D42	Diode 144 pulses	D144
Diode 48 pulses	D48	Diode 162 pulses	D162
Diode 54 pulses	D54	Diode 180 pulses	D180
Diode 60 pulses	D60	Diode 198 pulses	D198
Diode 66 pulses	D66	Diode 216 pulses	D216

8 - Cooling type

Air cooled	AC

9 - Cell type

Default	S
Bypass	B
Redundant	R

10 - Installation type

Indoor	I

11 - Protection degree

IP21	21
IP41	41
IP42	42

12 - Arc protection

Standard (without)	ST

13 - Input switchgear

Not included	SN
Included	SI

14 - Output filter type

Without	F0
Type 1	F1
Type 2	F2
Type 3	F3

15 - Certification

CE
UL

Notes: 1) Other configurations available under request.
2) Overload capacity: ND = Normal Duty: 115% for 60 seconds every 10 minutes.
3) Table with standard mounted references in section MVW3000 G4 - Standard versions.
4) The interfaces incorporated into the control and optional modules are listed in the Technical Data table.

Appendix C

Test Example

The following pages in this appendix contain an excerpt from WEG's internal document regarding the testing procedure for the MVW3000 MV VSDs. It details the Initial Energization test, which is used as an operational example of the MVW3000 Test Wizard in Section 4.5.

6 Energização Inicial: Sistema de Pré-Carga/Realimentações de Tensão dos barramentos CC

(itens 4.2.7 – IEC 60146-1-1/ 10.2.2.2 – IEC 61800-2)

- Ao prosseguir para os testes de média tensão, garantir que o **modo de teste do inversor** esteja configurado para “0 - Inativo”:
  - Configurar o “Modo de teste do inversor” C1.2.2 / P00297 = “0 – Inativo”.
- Antes de iniciar a primeira energização do circuito de média tensão a lista de parâmetros da Tabela 8 deverá ser conferida. Também devem ser verificados os parâmetros registrados no projeto.

Tabela 7 – Parâmetros básicos do inversor usado para pré-carga (CFW50x, CFW11 ou CFW700)

Antes de iniciar a configuração carregar U/F 60Hz (P0204 = 5 Carrega WEG 60 Hz).
Para fazer a programação, parametrizar P317=1 de forma a entrar pelo menu autoguiado.

Parâmetro	Descrição
P0100	5s
P0101	0.1s
P0121	1800rpm (CFW501, CFW11) 240Hz (CFW500)
P0133	
P0134	
P0135	Corrente nominal do CFW
P0148	1 = Soft Starter
P150	2 = hold_Ud e hold_LC
P0156	Programar para 110% da corrente nominal do CFW
P0157	
P0158	
P0202	0 = V/F
P0205	3 = Corrente do Motor
P0206	7 = Tensão Saída (CFW50x) 6 = Tensão Saída (CFW11)
P0208	100% (CFW50x) 1800rpm (CFW11)
P0209 (1)	2 = A
P0220	1 = Sempre Remoto

Parâmetro	Descrição
P0222	0 = Tecla HMI
P0226	0 = Horário
P0227	1 = DIx
P0263	1 = Gira/Para
P0264	2 = Habilita Geral
P0275	13 = Sem Falha
P0296	1 (acessar pelo menu autoguiado)
P0320	0 = Inativas
P0340	3s (auto reset)
P0400	440V
P0401	Corrente nominal do CFW
P0402	1800rpm
P0403	240Hz
P0588	0 %
P1001	0 = Para Aplicação

(1) Somente para CFW50x

Tabela 8 – Parâmetros básicos necessários para operação do inversor

Parâmetro	Descrição
C6.1.1/P00100	Tempo da rampa de aceleração.
C6.1.2/P00101	Tempo da rampa de desaceleração.
C4.3.1.1.1/P00133	Referência Velocidade Mínima
C4.3.1.1.2/P00134	Referência Velocidade Máxima
C11.1.3/P00201	Seleção do Idioma
C3.1.1/P00202	Tipo de controle do inversor

Parâmetro	Descrição
C3.12.1/P01660	Função bypass automático
C13.2.5/P01554	Relação TCs de entrada do Trafo 1
C13.2.4/P01553	Relação entre tensão de entrada (primário) e saída auxiliar
C13.2.8/P01557	Tap do transf. 1 de entrada
C13.2.2/P01551	Tensão nominal de entrada
C13.2.11/P01560	Potencial nominal transf. 1 entrada

C13.1.2/P01295	Corrente do inversor	C13.2.3/P01552	Frequência nominal transf. entrada
C13.1.1/P00296	Tensão de Saída Nominal Inversor	C13.2.6/P01555(1)	Relação TCs de entrada do Trafo 2
C7.11.13/P00390	Relé 1 de proteção térmica	C13.2.9/P01558(1)	Tap do transf. 2 de entrada
C7.11.14/P00391	Relé 2 de proteção térmica	C13.2.12/P01561(1)	Potencial nominal transf. 2 entrada
C7.11.15/P00392	Relé 3 de proteção térmica	C13.2.7/P01556(2)	Relação TCs de entrada do Trafo 3
C2.1.4/P00400	Tensão nominal do motor	C13.2.10/P01559(2)	Tap do transf. 3 de entrada
C2.1.5/P00401	Corrente nominal do motor	C13.2.13/P01562(2)	Potencial nominal transf. 3 entrada
C2.1.8/P00402	Velocidade nominal do motor	C13.1.4/P01569	Número de células redundantes
C2.1.6/P00403	Frequência nominal do motor	C13.1.3/P01563	Células em paralelo
C1.9.1/P01683	1s maior que P0331 do CFW	C13.2.1/P01550	Quantidade transf. entrada
C1.9.2/P01684			

(1) – Somente em inversores com 2 ou mais transformadores de entrada (C13.2.1 = 1 ou 2)
(2) – Somente em inversores com 3 transformadores de entrada (C13.2.1 = 2)
Observações:

Se o Inversor possuir filtro senoidal com contator de saída, parametrizar C5.11.3.1/P00587 = “1 = Operação com filtro tipo 2”.

Se o inversor possuir células redundantes por fase, (Ex.: 4,16kV com 5 células por fase), o parâmetro C13.1.1/P00296 deve ser configurado conforme a tensão nominal do inversor e informar no C13.1.4/P01569 a quantidade de células redundantes por fase. Para mais detalhes ver Tabela 9

Tabela 9 – Número de células por fase para cada modelo de inversor (exceto paralelo)

Tensão saída do inversor C13.1.1/P00296	Modelo padrão		Modelo com células (N+1)	
	C13.1.4/ P01569	N° células / fase	C13.1.4/ P01569	N° células / fase
0 (1150V)	0	1 (690V)	1	2 (690V)
1 (2300V)		2 (690V)		3 (690V)
2 (3300V)		3 (690V)		4 (690V)
3 (4160V)		4 (690V)		5 (690V)
4 (5500V)		5 (690V)		6 (690V)
5 (6300V)		6 (690V)		7 (690V)
6 (6900V)		6 (690V)		7 (690V)
7 (7200V)		7 (690V)		8 (690V)
8 (8000V)		7 (690V)		8 (690V)
9 (9000V)		8 (690V)		9 (690V)
10(10000V)		9 (690V)		10 (690V)
11 (11000V)		10 (690V)	0	10 (**710V**)
12 (12000V)		11 (690V)		11 (**710V**)
13 (13200V)		12 (690V)		12 (**710V**)
14 (13800V)		12 (690V)	- (1)	- (1)

(1) Inversores com tensão 13800V não permitem a opção de célula redundante

Para inversores paralelos (C13.1.3(P01563) ≠ 0) a quantidade de células informada na Tabela 9 deve ser multiplicada pelo número de inversores em paralelo.

- Energizar eletrônica.
- Ligar o disjuntor do sistema de pré-carga.
- Liberar o disjuntor principal para operação (Quando o inversor não possuir cubículo de entrada integrado, certificar-se que os cabos de entrada do inversor NÃO estejam aterrados).
- Liberar o botão de emergência
- Realizar a pré carga – ***Power On.***
- Acompanhar o processo de pré carga dos capacitores das células, o fechamento do disjuntor de entrada e a indicação de **Inv. Ready** no status do inversor.
- O valor da tensão nos barramentos CCs das células com o PWM desligado e transformador de entrada com tap na posição 0%, deve apresentar uma variação máxima de **5%** para mais ou para menos a partir do valor calculado pela **equação (** 1**).**

$$V_{BARRAMENTO\_CC} = V_{Rede} \times (V_{sec} / V_{prim}) \times 1{,}41 \qquad (1)$$

Tabela 10 – Indicações das tensões dos barramentos CCs das células do inversor

Qtd. Células p/ fase	Posição da Célula	Parâmetros Fase U	Parâmetros Fase V	Parâmetros Fase W
Até 1	1°	S2.7.4/P02250	S2.7.16/P02262	S2.7.28/P02274
Até 2	2°	S2.7.5/P02251	S2.7.17/P02263	S2.7.29/P02275
Até 3	3°	S2.7.6/P02252	S2.7.18/P02264	S2.7.30/P02276
Até 4	4°	S2.7.7/P02253	S2.7.19/P02265	S2.7.31/P02277
Até 5	5°	S2.7.8/P02254	S2.7.20/P02266	S2.7.32/P02278
Até 6	6°	S2.7.9/P02255	S2.7.21/P02267	S2.7.33/P02279
Até 7	7°	S2.7.10/P02256	S2.7.22/P02268	S2.7.34/P02280
Até 8	8°	S2.7.11/P02257	S2.7.23/P02269	S2.7.35/P02281
Até 9	9°	S2.7.12/P02258	S2.7.24/P02270	S2.7.36/P02282
Até 10	10°	S2.7.13/P02259	S2.7.25/P02271	S2.7.37/P02283
Até 11	11°	S2.7.14/P02260	S2.7.26/P02272	S2.7.38/P02284
Até 12	12°	S2.7.15/P02261	S2.7.27/P02273	S2.7.39/P02285

Comparar as temperaturas das células do inversor, conforme parâmetros da Tabela 11 com um termômetro calibrado. Tolerância ± 5ºC com relação à temperatura do termômetro.

Tabela 11 – Indicações de temperatura das células do inversor

Qtd. Células p/ fase	Posição da Célula	Parâmetros Fase U	Parâmetros Fase V	Parâmetros Fase W
Até 1	1°	S2.4.4.1/P02286	S2.4.4.13/P02298	S2.4.4.25/P02310
Até 2	2°	S2.4.4.2/P02287	S2.4.4.14/P02299	S2.4.4.26/P02311
Até 3	3°	S2.4.4.3/P02288	S2.4.4.15/P02300	S2.4.4.27/P02312
Até 4	4°	S2.4.4.4/P02289	S2.4.4.16/P02301	S2.4.4.28/P02313
Até 5	5°	S2.4.4.5/P02290	S2.4.4.17/P02302	S2.4.4.29/P02314
Até 6	6°	S2.4.4.6/P02291	S2.4.4.18/P02303	S2.4.4.30/P02315
Até 7	7°	S2.4.4.7/P02292	S2.4.4.19/P02304	S2.4.4.31/P02316
Até 8	8°	S2.4.4.8/P02293	S2.4.4.20/P02305	S2.4.4.31/P02317
Até 9	9°	S2.4.4.9/P02294	S2.4.4.21/P02306	S2.4.4.33/P02318
Até 10	10°	S2.4.4.10/P02295	S2.4.4.22/P02307	S2.4.4.34/P02319
Até 11	11°	S2.4.4.11/P02296	S2.4.4.23/P02308	S2.4.4.35/P02320
Até 12	12°	S2.4.4.12/P02297	S2.4.4.24/P02309	S2.4.4.36/P02321

- Colocar uma referência de velocidade reduzida (exemplo 200rpm, se for motor 4 polos)
- Habilitar o inversor (pressionar a tecla ”I”).

- Observar as indicações de operação na HMI bem como os valores de tensão e corrente de saída do inversor comparando com um equipamento calibrado para verificar se os valores estão coerentes para uma primeira energização.
- Desabilitar o inversor (pressionar a tecla “O”) e aguardar a parada do motor e a ausência de falha na HMI

Appendix D

User Manual

The following pages contain the User Manual for the MVW3000 Test Wizard, developed within the scope of this dissertation. This guide is intended to assist both end-users and those who will contribute to the future development of the application.

MVW3000 Test Wizard

Ferramenta de Suporte aos Ensaios de Rotina do VSD de Média-Tensão MVW3000G4

Esta ferramenta foi desenvolvida por Pedro Martins no âmbito da sua dissertação de Mestrado em Engenharia Mecânica – Automação pela Faculdade de Engenharia da Universidade do Porto (FEUP) no Departamento de Soluções de Automação e Quadros Elétricos (SAQE) da WEGeuro.

Revisões

Nº da revisão	Data (dd/mm/aaaa)	Efetuada por	Observações
00	05/07/2026	Pedro Martins	Primeira versão

Conteúdos

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Guia para Instalação e Desenvolvimento

Sobre o projeto

A aplicação é uma GUI em PyQt6 para guiar os ensaios do MVW3000G4 passo a passo. O utilizador faz login, preenche dados do drive e do motor, seguindo-se os ensaios. A aplicação guarda o progresso automaticamente. O fluxo da aplicação é o seguinte:

1. Login
2. Dados do drive
3. Dados do motor
4. Checklist de material
5. Verificações/inspeções iniciais
6. Geração de documentação final

Requisitos mínimos

Se apenas tiver intenção de executar a ferramenta, deve executar em Windows 10 ou superior (64-bit). Dado que a aplicação foi compilada num executável autónomo (standalone) através do Pyinstaller, não é necessária a instalação local de Python ou outras dependências na máquina. A aplicação não é exigente, mas, ainda assim, é conveniente um mínimo de 4 GB de RAM, embora se recomendem 8 GB para um melhor desempenho. A aplicação requer aproximadamente 80 MB de espaço em disco disponível para alojar o ficheiro executável e alguns registos temporários. Para a interface gráfica, é necessária uma resolução mínima de ecrã de 1280x820, sendo recomendada uma resolução Full HD para garantir a melhor visualização dos seus dados em tempo-real.

No que toca à conectividade, o PC deve estar equipado com uma porta Ethernet. Adicionalmente, a porta Modbus TCP/IP (tipicamente a 502) deve estar aberta e acessível na rede. É importante assegurar que nenhuma restrição de firewall bloqueie a comunicação entre o PC e o drive, de modo a garantir uma troca de dados estável e ininterrupta durante os ensaios.

No caso de ter intenções de desenvolvimento da ferramenta, os requisitos anteriormente mencionados devem ser cumpridos, assim como os que a seguir se apresentam.

- Python 3.11 ou superior
- Git, se pretender clonar o repositório
- Um IDE à escolha – é recomendado o Visual Studio Code
- Acesso a PowerShell (pode ser através do IDE)

Além destes requisitos, siga os passos de instalação que se seguem.

Instalação

Descarregue o .zip, extraindo-o para uma pasta simples. Não é recomendada a utilização de uma pasta no Desktop. Lembre-se que, no caso de avaria do computador, o conteúdo do Desktop é o mais difícil de recuperar, muitas vezes impossível.

Descarregue o Python em https://www.python.org/downloads/

Durante a instalação, marque a opção "Add Python to PATH". De seguida, quando a instalação estiver concluída, abra um terminal no IDE e coloque os seguintes comandos:

```
1. python --version
2. pip --version
```

Se isto falhar, é sinal de que o Python não ficou corretamente instalado. Deve efetuar a instalação novamente.

Num terminal PowerShell, navegue até à pasta do projeto e coloque os seguintes comandos de modo a ativar o ambiente virtual:

```
1. .\.venv\scripts\Activate.ps1
```

No caso de o PowerShell bloquear scripts:

```
1. Set-ExecutionPolicy -ExecutionPolicy RemoteSigned -Scope CurrentUser
```

Quando estiver correto, vai ver `(.venv)` no início de cada linha no terminal.

Agora instale as dependências. Com o ambiente virtual ativo:

```
1. python -m pip install --upgrade pip
2. pip install -r requirements.txt
```

De modo a confirmar a instalação das dependências:

```
pip list | findstr "PyQt6 pymodbus pydantic pydantic-settings python-docx docx2pdf jinja2 pyinstaller"
```

Para o interpretador Python, deve usar o ficheiro /.venv/Scripts/python.exe

Para correr a aplicação

A primeira opção é através do Python e o main script:

```
python -m src.main
```

Pode, ainda:

```
.\run_hmi.bat
```

Ou, então a partir do ficheiro executável (.exe). Para construir esse ficheiro, é necessário:

```
.\build_hmi_exe.bat
```

Note que, cada vez que fizer alguma alteração ao nível do código da aplicação e pretender ver o resultado, deve correr este último comando. Depois de ter sucesso no build, o resultado – ou seja, o ficheiro executável – fica disponível em dist/MVW3000 Test Wizard.exe, podendo, se assim entender, movê-lo.

Estrutura do projeto

```
MVW3000_Wizard_HMI/
├── src/
│   ├── main.py
│   ├── qt_wizard_hmi.py
│   ├── config.py
│   ├── adapters.py
│   ├── models.py
│   ├── persistence.py
│   ├── qt_ensaio*.py
│   └── ...
├── templates/
├── icones/
├── requirements.txt
├── run_hmi.bat
├── build_hmi_exe.bat
└── .env
```

- `src/main.py`: onde a aplicação arranca

- `src/qt_wizard_hmi.py`: janela principal, navegação e páginas que não sejam de nenhum ensaio específico
- `src/models.py`: os dados que a aplicação guarda
- `src/adapters.py`: comunicação com hardware
- `src/qt_ensaio6_pages.py` como exemplo de uma página de um ensaio mais completa

As páginas de cada ensaio seguem uma base comum. No entanto, os métodos mais importantes são os seguintes:

- `__init__(self, app)`: cria a página e guarda a referência para a aplicação
- `_build()`: monta a interface da página e adiciona os widgets
- `register_state_widget(name, widget)`: marca um widget para ser guardado e reposto automaticamente
- `save_page_state()`: guarda os valores atuais da página no contexto
- `load_page_state()`: repõe os valores guardados quando a página volta a abrir
- `on_show()`: corre quando a página fica visível; normalmente recarrega dados
- `on_hide()`: corre quando a página deixa de estar visível; usa-se para parar timers ou limpar estados temporários
- `validate_before_next()`: valida os dados antes de avançar para a próxima página

Há também uma base para páginas com navegação interna, como é o caso do ensaio 6, de Energização Inicial: `InternalNavigationPage`

Como regra geral e prática:

1. Criar a página em `__init__()`
2. Montar os widgets em `_build()`
3. Guardar campos importantes com `register_state_widget()`
4. Validar em `validate_before_next()`
5. Usar `on_show()` e `on_hide()` apenas para o que é necessário acontecer ao abrir ou ao fechar a página.

Como exemplo, apresenta-se um exemplo de uma página de um ensaio com uma estrutura mínima, num ficheiro .py em branco, importando do ficheiro da janela principal o tipo de página (no caso, uma página com scroll lateral):

```
1. from src.qt_wizard_hmi import ScrollPage
2.
```

```python
class MyTestPage(ScrollPage):
    page_key = "test_x_y"
    title = "XY. Ensaio de (...)"

    def __init__(self, app: "QtWizardWindow") -> None:
        super().__init__(app)
        self.my_input = self.register_state_widget("my_field", QLineEdit())
        self._build()

    def _build(self) -> None:
        layout = self.content_layout
        layout.addWidget(QLabel("Campo:"))
        layout.addWidget(self.my_input)
        layout.addStretch(1)

    def validate_before_next(self) -> bool:
        if not self.my_input.text().strip():
            QMessageBox.warning(self, "Erro", "Preencha o campo.")
            return False
        return True
```

Depois de criar esta classe, deve:

1. Importar a nova página em `src/qt_wizard_hmi.py`
2. Adicionar o `page_key` ao `PAGE_ORDER` em `src/qt_wizard_hmi.py`
3. Adicionar o título ao `PAGE_TITLES`
4. Criar instância em `QtWizardWindow.__init__()`

Se um determinado campo tiver de manter o valor entre sessões, use `register_state_widget()`. Assim, a aplicação irá guardar e repor esse valor automaticamente.

Persistência de dados

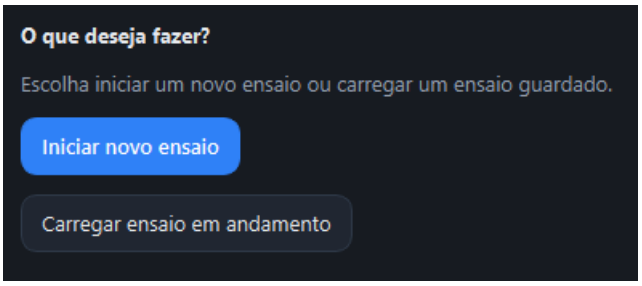
A aplicação guarda o estado do ensaio num ficheiro JSON. Este ficheiro inclui:

- Dados do recipe (que consiste num conjunto de parâmetros que a aplicação usa como base de trabalho)
- Dados do MVW3000
- Dados do motor utilizado em ensaio
- Estado de cada página de ensaio
- Página atual
- Páginas já concluídas

Como exemplo (simplificado):

```
{
  "context": {
    "page_states": {
      "test_4_1": {}
    }
  },
  "page_key": "test_4_2",
  "completed_pages": ["test_4_1"]
}
```

A nível do uso normal da aplicação, o progresso pode ser salvo/carregado através da barra inferior ou, no início da aplicação, ao escolher a opção "Carregar ensaio em andamento", se for esse o caso.



No caso de falhar a validação numa determinada página ao avançar, aparecerá um popup onde se poderá introduzir uma password de override, se quem tiver acesso à mesma assim o entender.

Password de override: `saqeadmin`

Convém referir que não substitui a validação normal dos dados, simplesmente permite continuar o ensaio se alguém experiente com acesso à password em questão entender que não existem quaisquer riscos.

Modo Developer

De modo a navegar facilmente entre as várias páginas dos ensaios enquanto estiver a trabalhar no código da ferramenta, poderá utilizar a seguinte opção no ficheiro `src/main.py`:

```
DEV_MODE = 1
```

Depois de colocar o valor 1 deve fazer o build do ficheiro executável novamente.

Comunicação com o drive – via Modbus TCP/IP

Segue-se um exemplo de código para ler um registo.

```
address = ...

if hasattr(self.app, "drive_adapter") and self.app.drive_adapter.is_connected():
    try:
        value = self.app.drive_adapter.read_register(address, unit=1)[0]
    except Exception as exc:
        QMessageBox.warning(self, "Modbus", f"Erro: {exc}")
```

Segue-se um exemplo de código para escrever um registo.

```
address = ...
value = ...

try:
    self.app.drive_adapter.write_register(address, value, unit=1)
except Exception as exc:
    QMessageBox.warning(self, "Modbus", f"Erro ao escrever: {exc}")
```

Possíveis erros e resoluções

- No caso de faltar um módulo, como o PyQt6, pode significar que o ambiente virtual não está ativo. Volte atrás neste documento, ative-o e volte a instalar as dependências.
- No caso de a conversão para PDF do relatório falhar, instale um leitor de PDF dedicado. Pode ser uma causa possível.
- …

Guia para a Utilização da Ferramenta

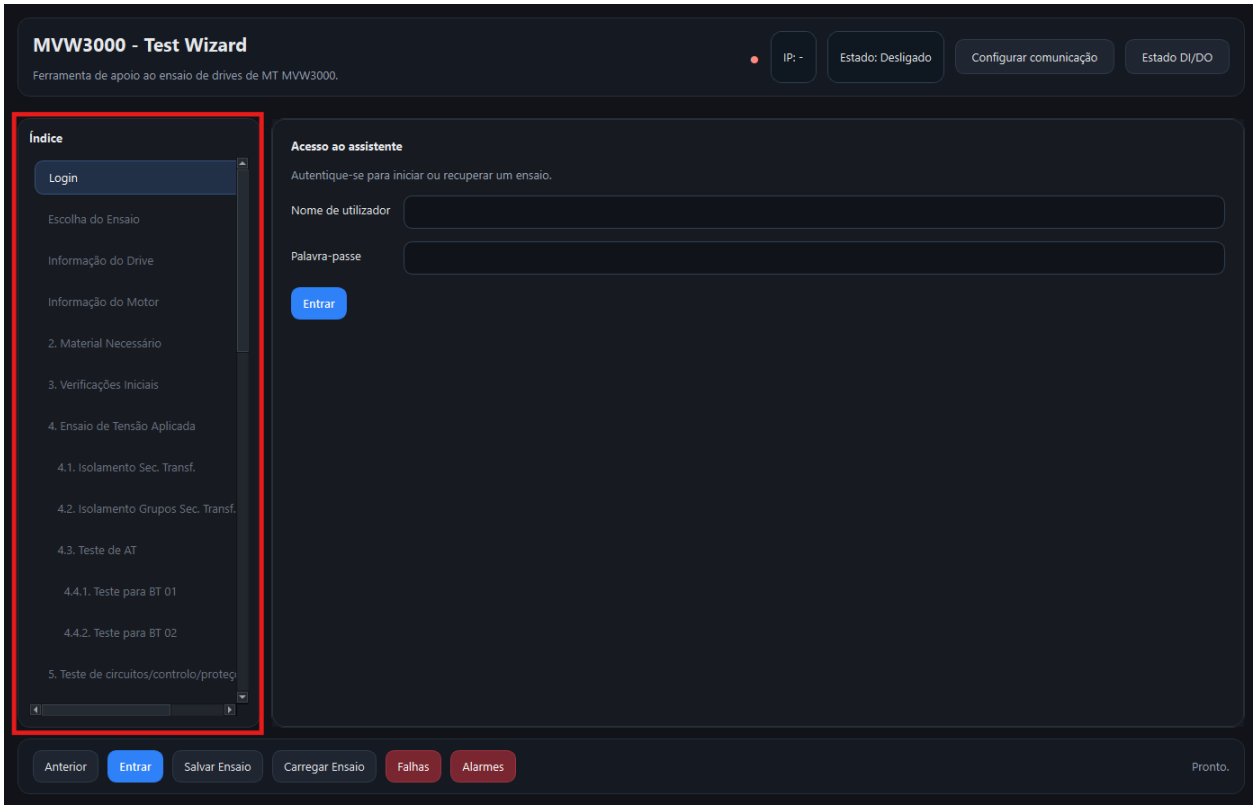
Para tornar a navegação intuitiva, a aplicação acompanha o fluxo cronológico da especificação de ensaios, apresentando as etapas na mesma ordem em que aparecem no documento de referência.

É importante notar que a ferramenta foi construída com base na versão 01 deste procedimento (emitida a 23/01/2026). Isto significa que, para manter a aplicação fidedigna, qualquer modificação ou detalhe que venha a ser alterado no processo real de ensaio terá de ser obrigatoriamente replicado na ferramenta.

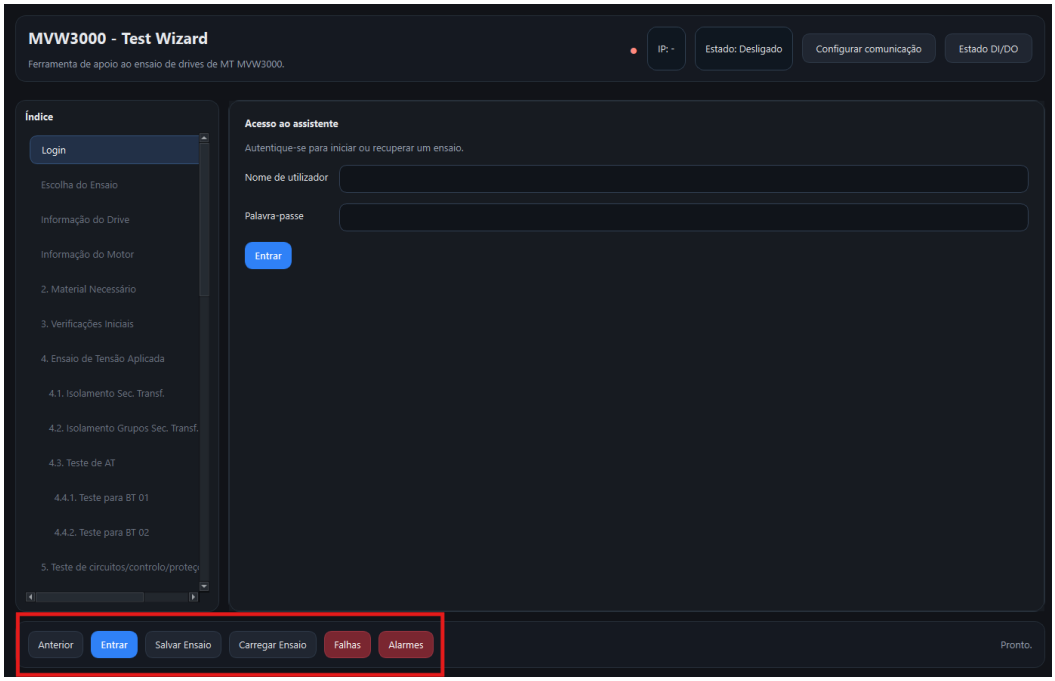
Neste documento, o número do ensaio que aparece antes do seu título corresponde ao mesmo número que está presente da especificação. Nesse sentido, um cruzamento das informações entre este documento e a especificação é mais direto e totalmente válido. Naturalmente, quando alterações forem efetuadas na ferramenta porque foram adicionados ensaios ou a organização já não é a mesma, deve ser atualizada a numeração na ferramenta, assim como neste documento, de modo a garantir esse cruzamento de informações mais prático.

Layout

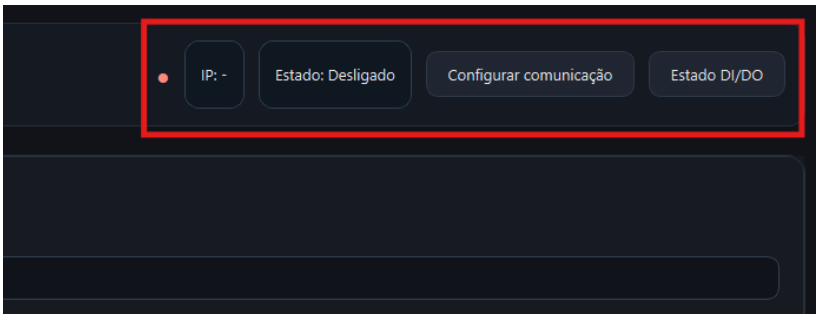
Inicia-se este guia para a utilização do MVW3000 Test Wizard apresentando o layout da aplicação. No painel lateral esquerdo encontra-se o índice da aplicação. Após a autenticação inicial (login) mencionada com mais detalhe adiante, o utilizador pode navegar para o passo seguinte (“Escolha do ensaio”). O avanço para etapas subsequentes é sequencial, ficando disponível à medida que os requisitos de cada página vão sendo devidamente cumpridos.



Na zona inferior do ecrã, encontram-se os botões de navegação, os comandos para guardar ou carregar ensaios e, adicionalmente, os botões que abrem janelas flutuantes (pop-up) com registo de falhas e alarmes ativos no equipamento.



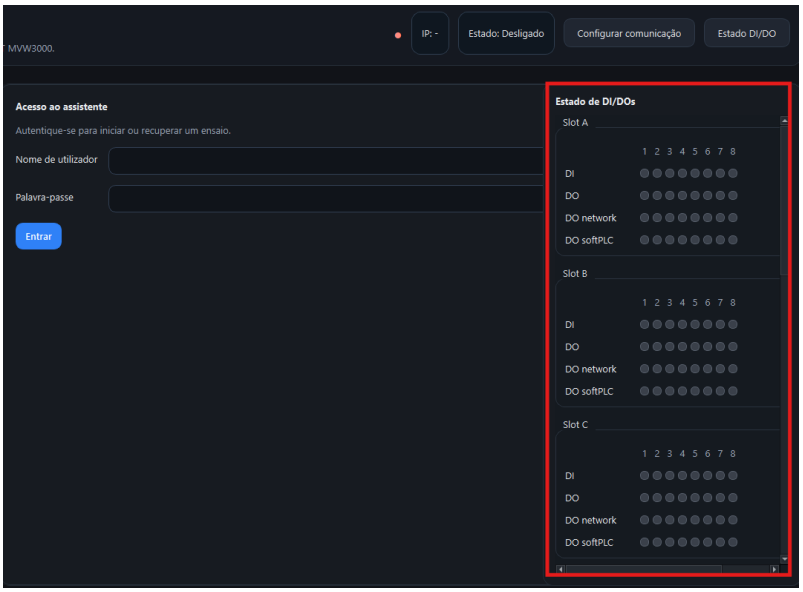
Na zona superior do ecrã, são exibidas as informações relativas ao estado das comunicações Modbus com o equipamento. Esta secção inclui dois comandos principais: um botão que aciona um painel deslizante para a configuração destas comunicações e outro que abre um painel semelhante para a verificação do estado das entradas e saídas digitais (DI/DO).



Para configurar a comunicação é necessário inserir o IP, Porta e Unit ID, pressionando, por fim, o botão “Ligar Modbus”.



Para a monitorização do estado das DI/DOs, aparecerá uma luz verde em cada DI/DO que estiver ativa.



Login

Para aceder ao conteúdo da ferramenta, deverá autenticar-se através da página de Login apresentada logo no arranque da aplicação.

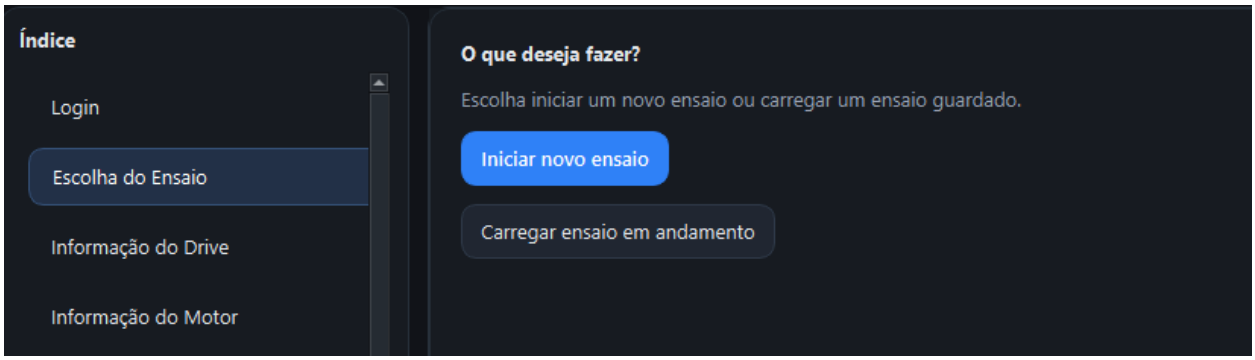


Para o efeito, deverá utilizar as seguintes credenciais:

- Nome de utilizador: **SAQEWPT**
- Password: **8739876**

Escolha do Ensaio

De seguida, e tendo em conta a persistência dos dados, é possível iniciar um ensaio completo a um MVW3000G4 ou carregar um ficheiro JSON que contenha informação sobre o procedimento em curso a algum equipamento.

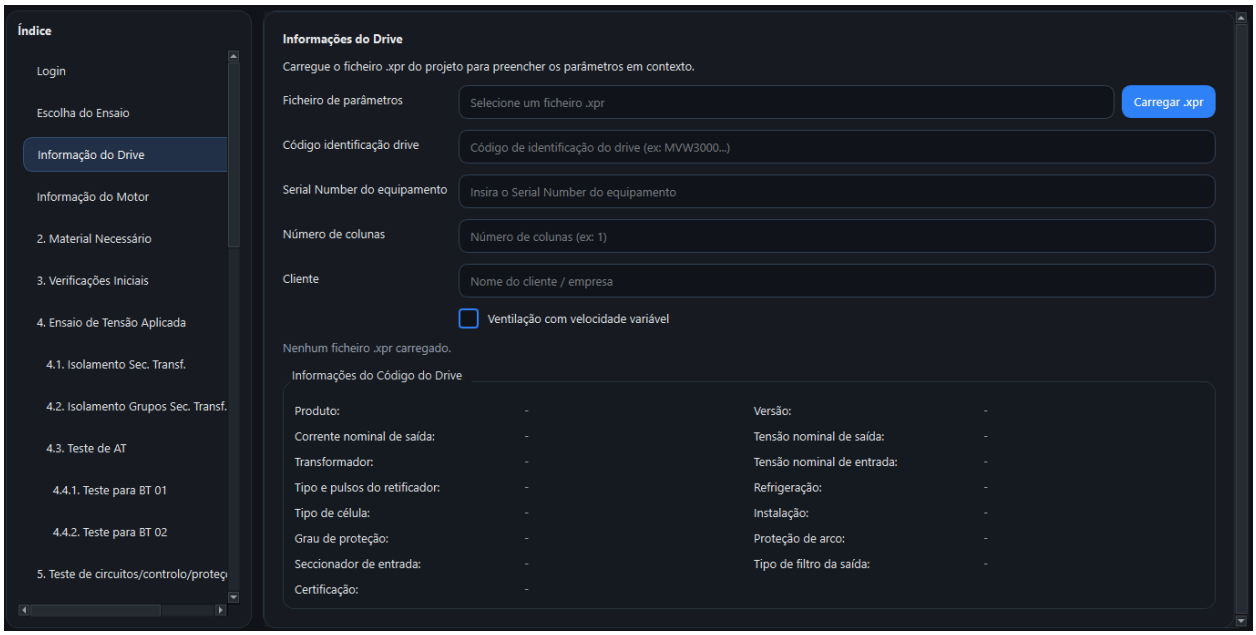


Informação do Drive

Considerando, por se tratar de um guia de utilização, que foi escolhida a opção "Iniciar novo ensaio", passamos para uma página em que é pedida informação em relação do MVW3000. No caso de ter escolhido a outra opção, foi, certamente, encaminhado diretamente para a fase do procedimento a que se chegou no equipamento.

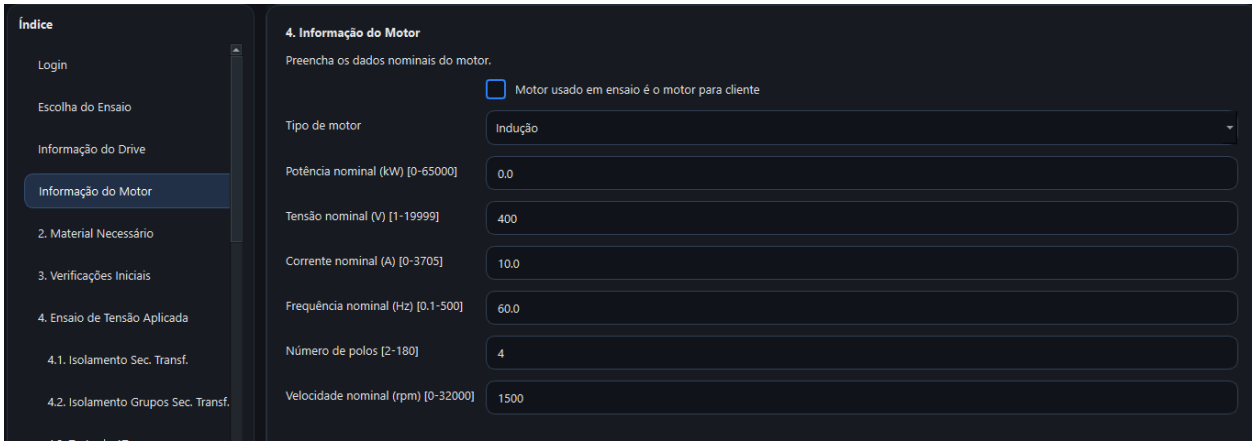
Para fornecer à aplicação a informação completa em relação ao equipamento alvo de ensaio, deve carregar o ficheiro de parâmetros .xpr, obtido na pasta do projeto WPS. Além disso, deve inserir o código inteligente do drive, composto exatamente por 41 caracteres. Tanto o ficheiro de parâmetros como o código inteligente do drive impactam o procedimento de ensaios, por isso tenha máxima atenção para inserir as informações corretamente. Na parte inferior da janela, são mostradas as informações extraídas do código inteligente do drive – use-as para confirmar que inseriu o código corretamente.

Ainda, é pedido o Serial Number do equipamento, o número de colunas, o cliente (informações que serão usadas no preenchimento automático do relatório de ensaios e exportado na fase final em formato PDF) e uma opção no caso de o equipamento ter ventilação com velocidade variável (já que a realização, ou não, do ensaio 5.2 depende da existência da mesma).



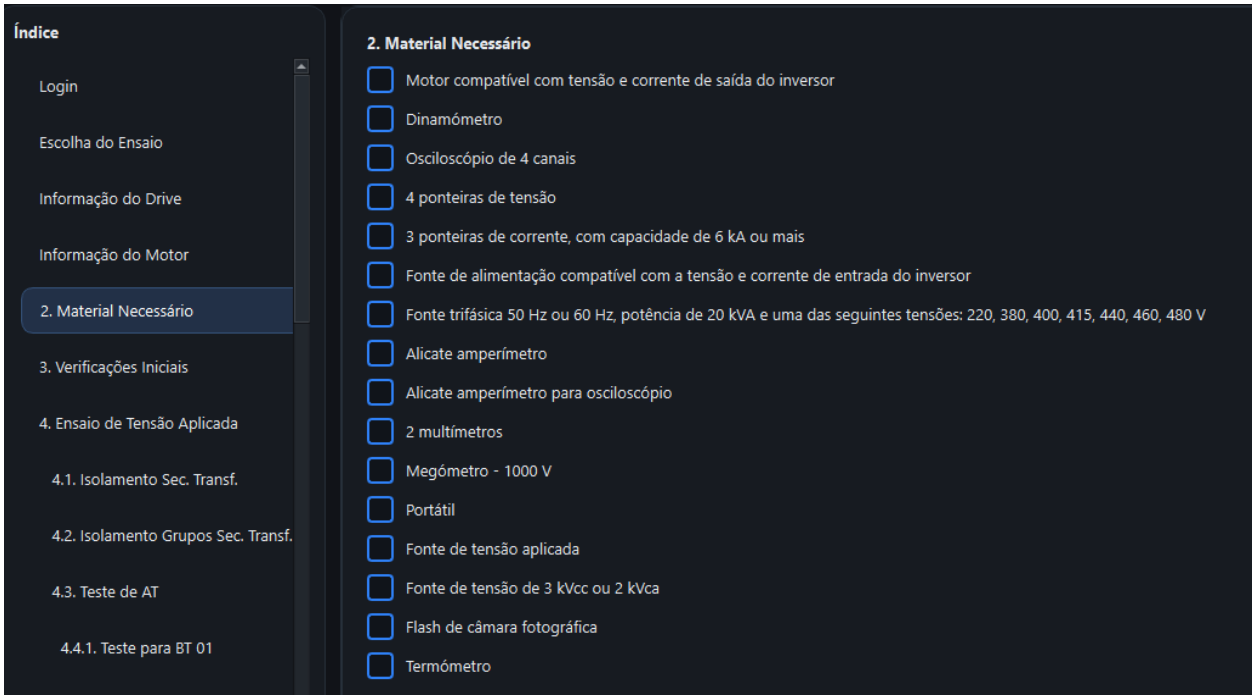
Informação do Motor

De seguida, é necessário inserir informação relativa ao motor utilizado para o ensaio deste drive. No caso de o motor utilizado ser o motor para o qual o drive foi projetado, então a opção “Motor usado em ensaio é o motor para cliente”. Nesse caso, os valores inseridos nestes campos estarão bloqueados e a aplicação usará os parâmetros correspondentes que estão no ficheiro .xpr.



2. Material Necessário

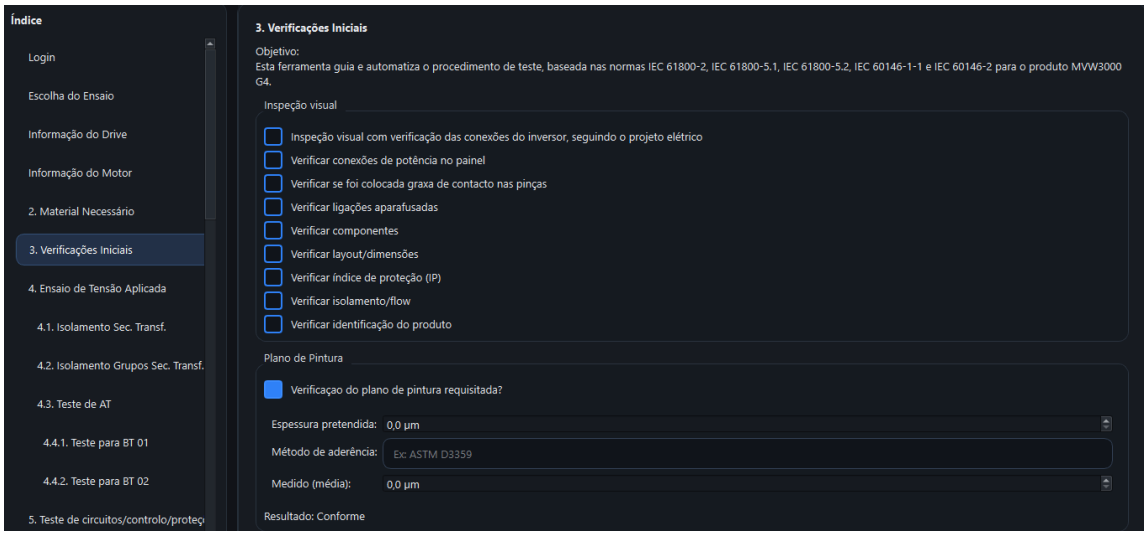
Nesta fase, é necessário reunir o material necessário conforme solicitado no procedimento. Por isso, na página "2. Material Necessário" encontra-se uma checklist que deve ser verificada na íntegra para a passagem à fase seguinte ser possível.



3. Verificação Inicial / Inspeção Visual

Agora, devem, conforme o procedimento, ser efetuadas as inspeções e verificações que constam na checklist apresentada.

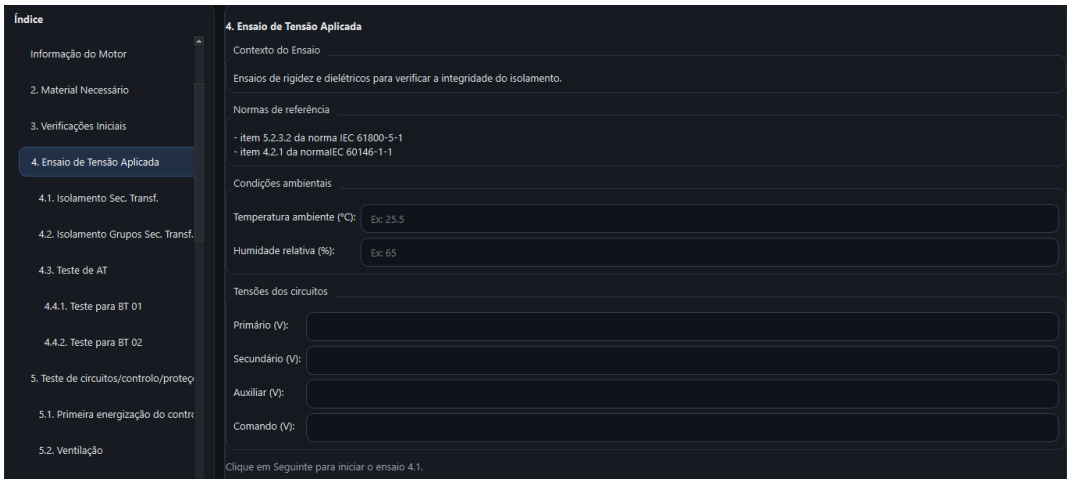
No caso de ser requisitada pelo cliente a verificação do plano de pintura, deve ser selecionada essa opção, que abre um painel para inserir a espessura pretendida, o método de aderência e a espessura medida (média). De seguida, é possível ver o resultado (conforme ou não conforme) que também aparecerá no relatório do ensaio.



4. Ensaio de Tensão Aplicada

No caso dos ensaios de tensão aplicada ainda não é necessária (nem possível) comunicação com o drive. Nesta primeira página, que é uma página apenas introdutória ao ensaio, devem ser inseridas a temperatura ambiente (ºC) e a humidade relativa (%), medidas através de um equipamento calibrado.

Devem ser informadas também as tensões dos circuitos: primário, secundário, auxiliar e comando.

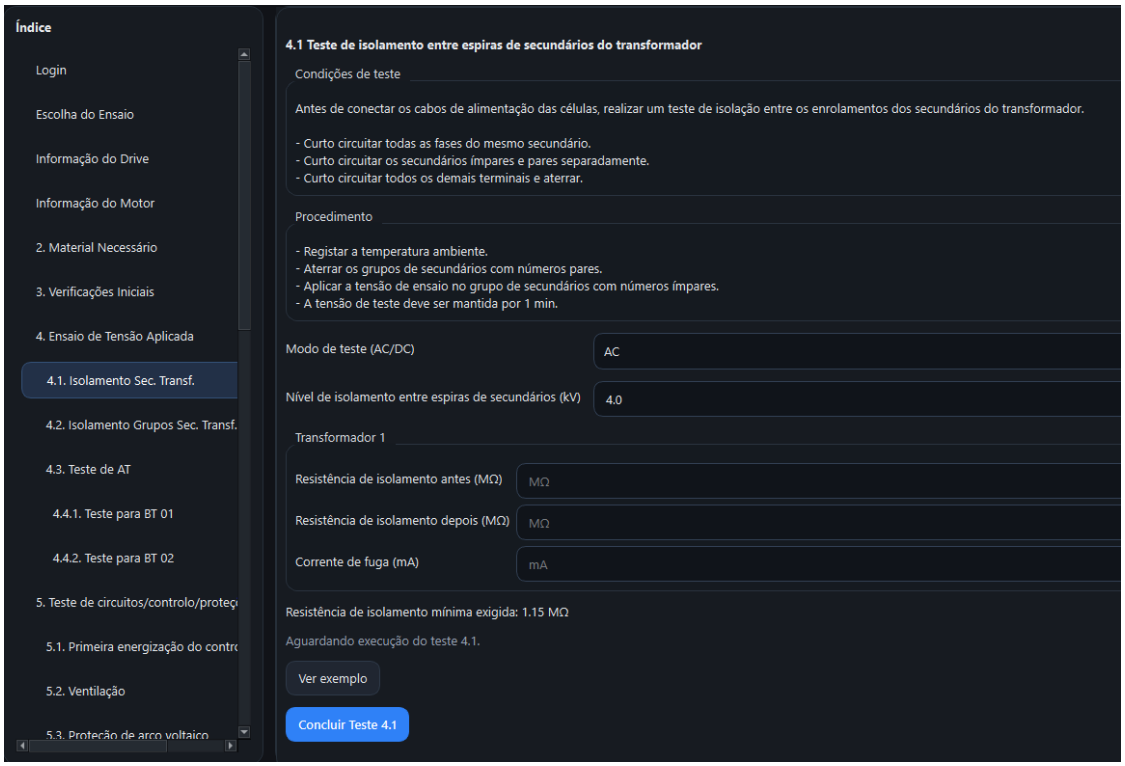


4.1. Teste de Isolamento entre Espiras de Secundários do Transformador

Nesta página são dadas as instruções para a realização do ensaio. Existe a opção de ensaio em AC ou DC. No caso de o ensaio ser realizado em AC, a corrente de fuga deverá ser medida em mA; no caso de ser realizado em DC, deverá ser medida em µA).

Existem campos específicos para preenchimento de resultados das medições, nomeadamente resistência de isolamento antes/depois e a corrente de fuga. No final da página é indicada qual a resistência de isolamento mínima tendo em conta o nível de isolamento entre espiras de secundários (kV) indicado. Para passagem à fase seguinte, os valores devem estar dentro do intervalo esperado. No caso da imagem, vê-se apenas um conjunto de resultados de medições, que é relativo a um transformador. No caso de existir mais do que um transformador, essa informação já está contemplada no ficheiro de parâmetros, pelo que aumentarão dinamicamente nesta página de ensaio os conjuntos de campos para inserir resultados de medições.

O botão “Ver Exemplo” abre a Figura 1 do procedimento em pop-up, ou seja, um exemplo das ligações para a realização do ensaio.

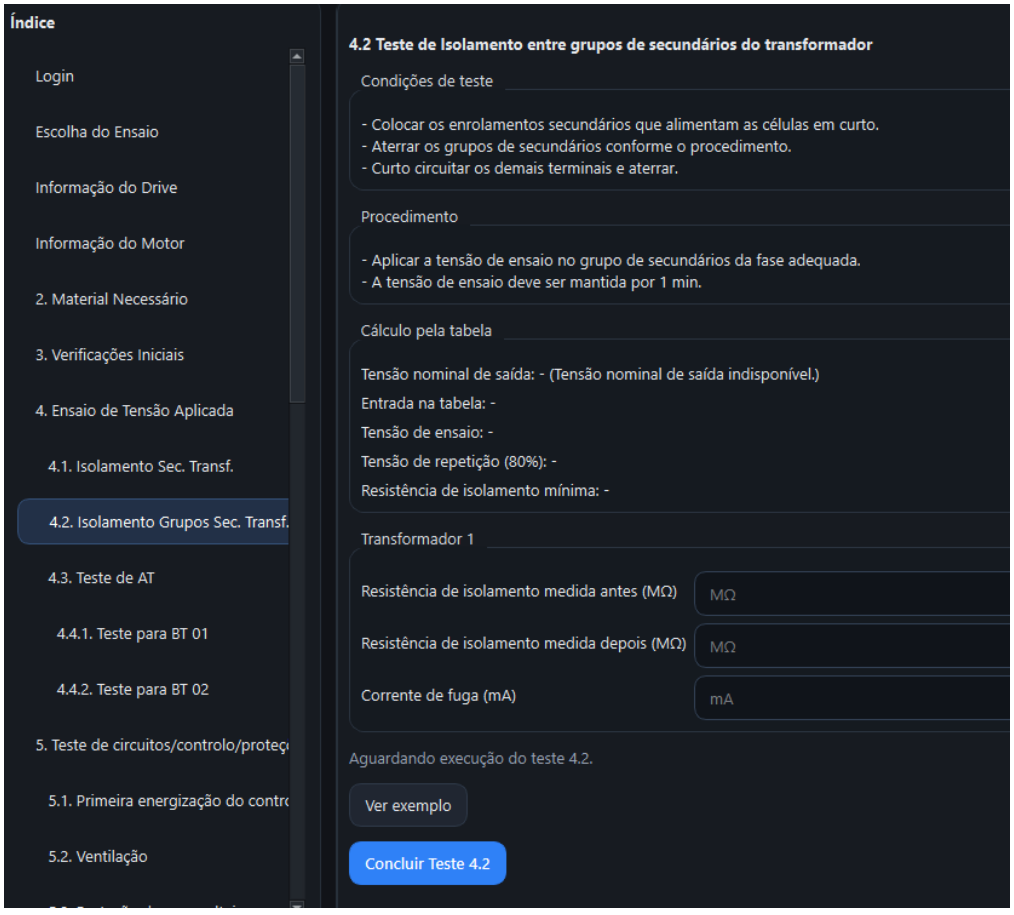


4.2. Teste de Isolamento entre Grupos de Secundários do Transformador

À semelhança do 4.1, na página deste ensaio são apresentadas as instruções para a realização do mesmo.

Tendo em conta a Tensão Nominal de Saída do equipamento (extraída do código inteligente) é calculada a tensão de entrada na Tabela 11 do procedimento, chegando à tensão de ensaio. É, ainda, calculado 80% dessa tensão de ensaio, para o caso de o ensaio necessitar de repetição. De acordo com as tensões calculadas, também é informada qual a resistência de isolamento mínima. De seguida, apresenta-se um conjunto de resultados de medições necessário de preencher que, também à semelhança do 4.1, aumenta dinamicamente conforme a quantidade de transformadores do equipamento.

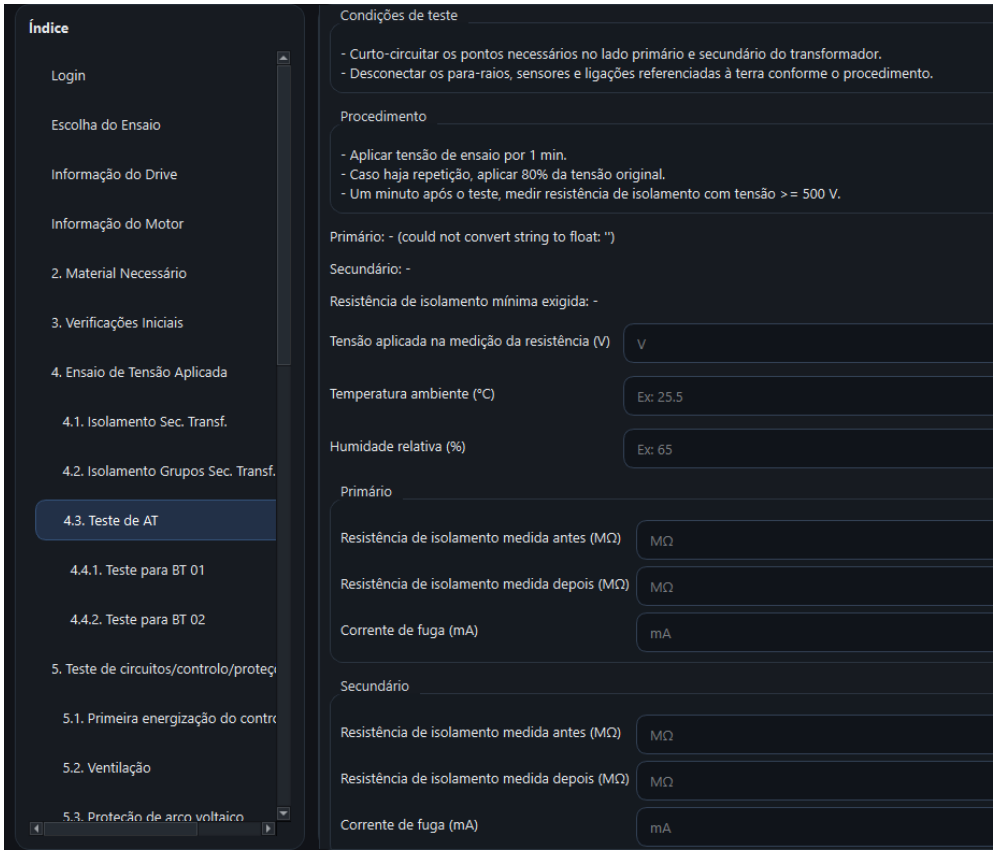
O botão "Ver Exemplo" abre a Figura 2 do procedimento em pop-up, ou seja, um exemplo das ligações para a realização do ensaio.



4.3. Teste de Alta Tensão

No caso deste ensaio, depois das instruções para a realização do mesmo, são apresentadas as tensões de ensaio no primário e no secundário do transformador. Tendo em conta o relatório, nesta fase é necessário inserir novamente a temperatura ambiente (ºC) e a humidade relativa (%).

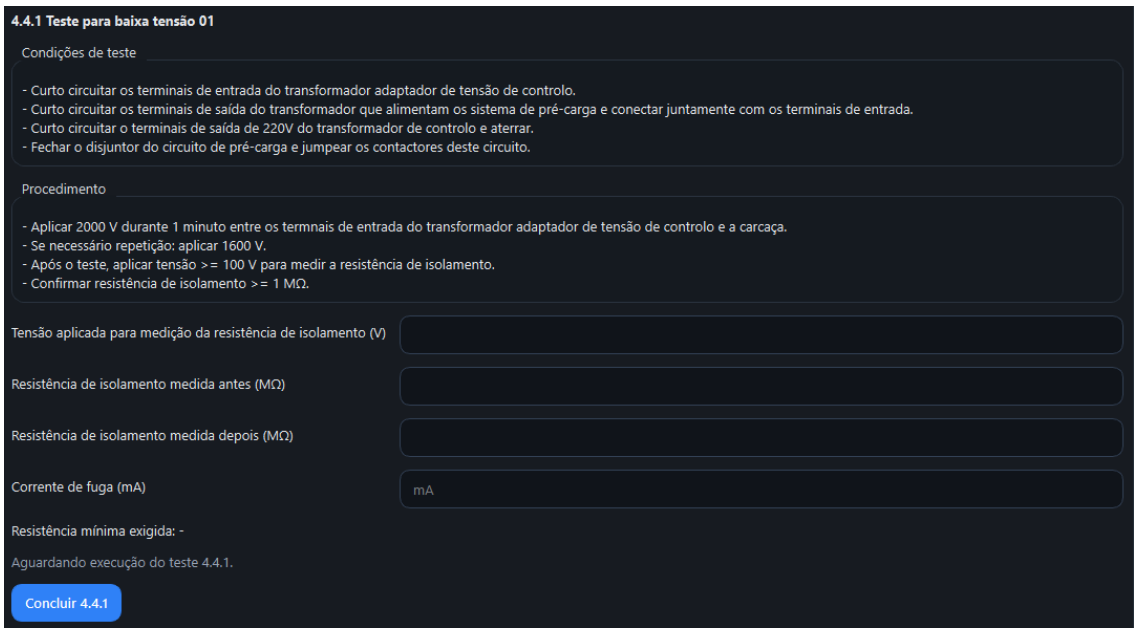
A resistência de isolamento mínima é calculada conforme a tensão aplicada na medição da mesma.



4.4.1. Teste para Baixa Tensão 1 – Entrada do Transformador de Controlo

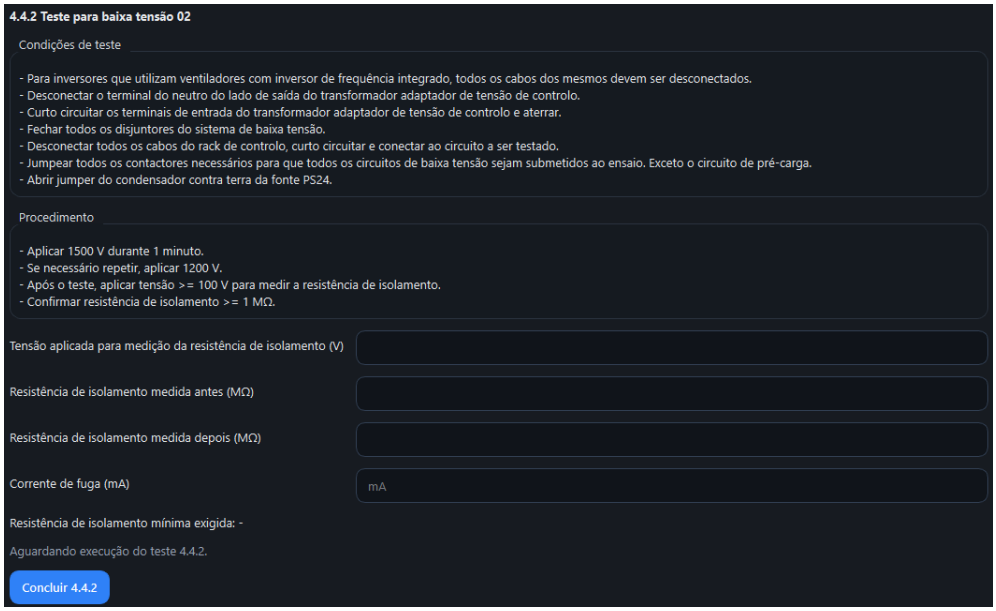
Neste ensaio, são informadas as instruções para realização mesmo e, tendo em conta a tensão utilizada para medição da resistência de isolamento, é informada a resistência de isolamento mínima.

Devem ser colocadas na aplicação os valores medidos da resistência de isolamento medida antes, resistência de isolamento medida depois e corrente de fuga.



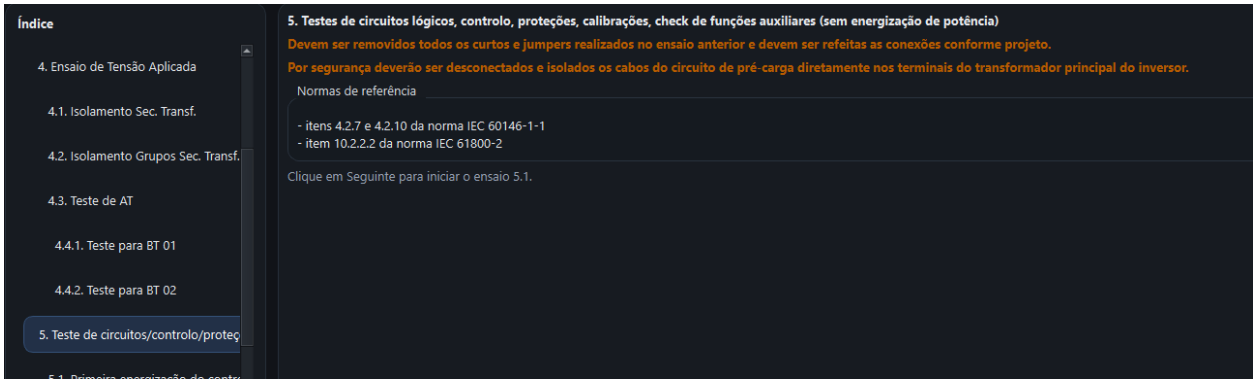
4.4.2. Teste para Baixa Tensão 2 – Saída 220 V do Transformador de Controlo

Neste ensaio, são informadas as instruções para realização mesmo e, tendo em conta a tensão utilizada para medição da resistência de isolamento, é informada a resistência de isolamento mínima. O utilizador deve colocar a resistência de isolamento medida antes, medida depois e corrente de fuga.



5. Teste de circuitos lógicos, controlo, proteções, calibrações e funções auxiliares (sem energização da potência)

São apresentadas algumas informações de segurança que estão dispostas no procedimento bem como o enquadramento normativo do ensaio. Não é necessária nenhuma verificação para conseguir avançar para a página seguinte.

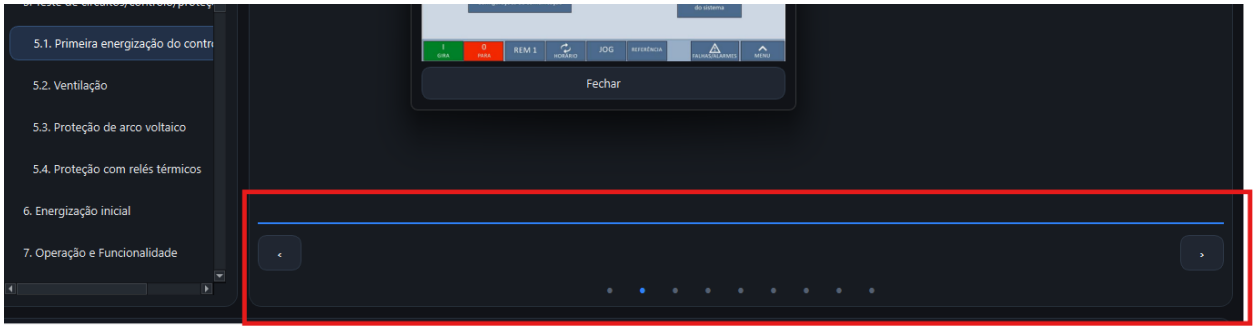


5.1 Primeira Energização do Controlo

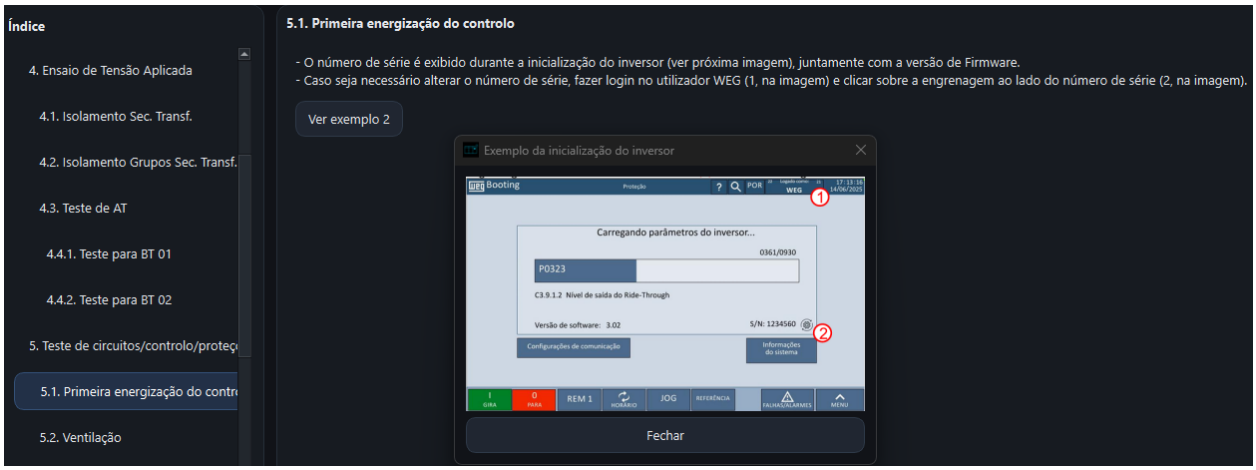
Começa-se por por dar as instruções necessárias e também, através do botão "Ver Exemplo", é aberta uma imagem exemplo do registo do Serial Number do drive na HMI – imagem essa que consta na especificação.



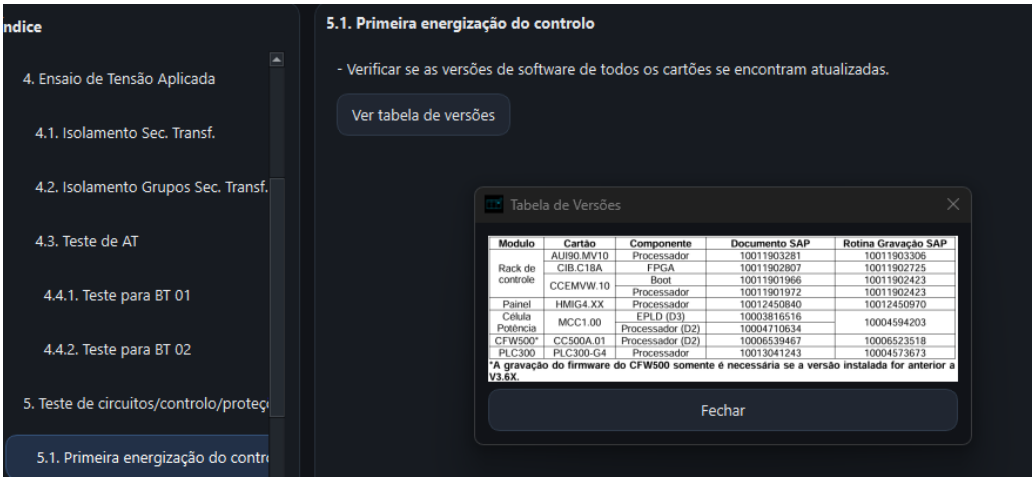
Como este ensaio é mais longo, existem botões no fundo da página para avançar para passos seguintes. Através da intensidade dos pontos azuis, é possível saber sempre em que passo estamos. Avançar para passos seguintes requer, à semelhança do que acontece com avanços para ensaios seguintes, uma validação (automaticamente feita pela aplicação) dos valores inseridos.



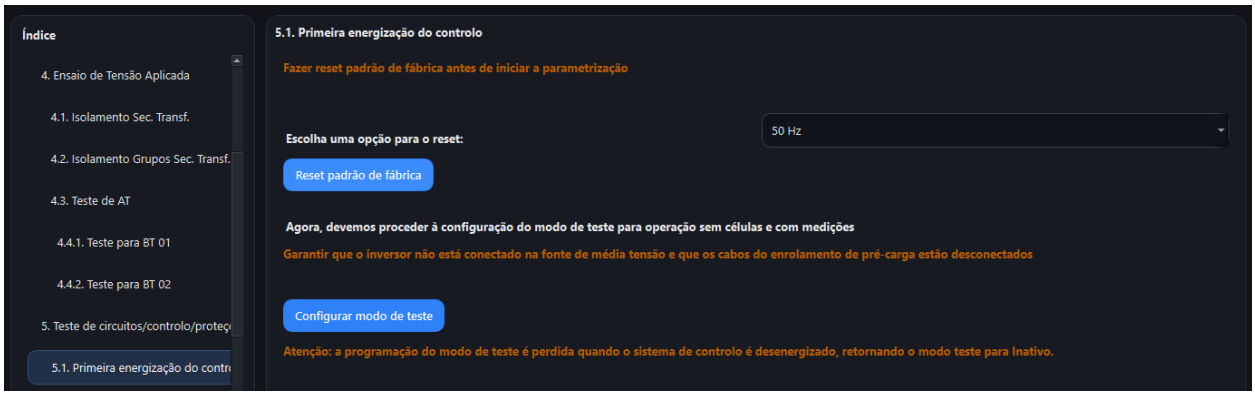
Avançando, então, para o passo seguinte, existem mais instruções e também outra figura de exemplo para. Neste caso, informações para uso inicial da HMI.



De seguida, é necessário efetuar a verificação da versão de software de todos os cartões, drives de pré-carga, PLCs, entre outros. A imagem exemplo mostra uma tabela de versões, qual o componente, documento SAP e qual o número SAP das respetivas instruções para rotinas de gravação.



O utilizador deve, na fase seguinte, escolher se pretende fazer um reset fábrica para o padrão da WEG 50 ou 60 Hz. Aqui, o parâmetro **C12.1/P00204** será programado para 1 (no caso de 60 Hz) ou para 2 (no caso de 50 Hz).



Feito o reset e seguidas as instruções seguintes, o modo de teste deverá ser configurado. No caso, será configurado para **C1.2.2/P00297 = 2**, ou seja, para operação sem células e com medições.

Note que a parametrização do modo teste é perdida quando o sistema de controlo é desenergizado, retomando o modo teste para Inativo, ou seja, **C1.2.2/P00297 = 0**.

Segue-se uma verificação aos cabos de fibra ótica. Para verificar as conexões dos cabos de fibra ótica, deve desconectar os mesmos um a um e verificar o aparecimento das falhas correspondentes. Tendo em conta que estamos a comunicar com o drive via Modbus e temos acesso na ferramenta às falhas ativas, assim que um cabo de fibra ótica for desconectado, deverá aparecer um check à frente da falha correspondente na tabela.

No caso de nenhuma falha aparecer, as causas do problema deverão ser investigadas. O programa não permite o avanço para o passo seguinte enquanto as falhas todas não tiverem um check.

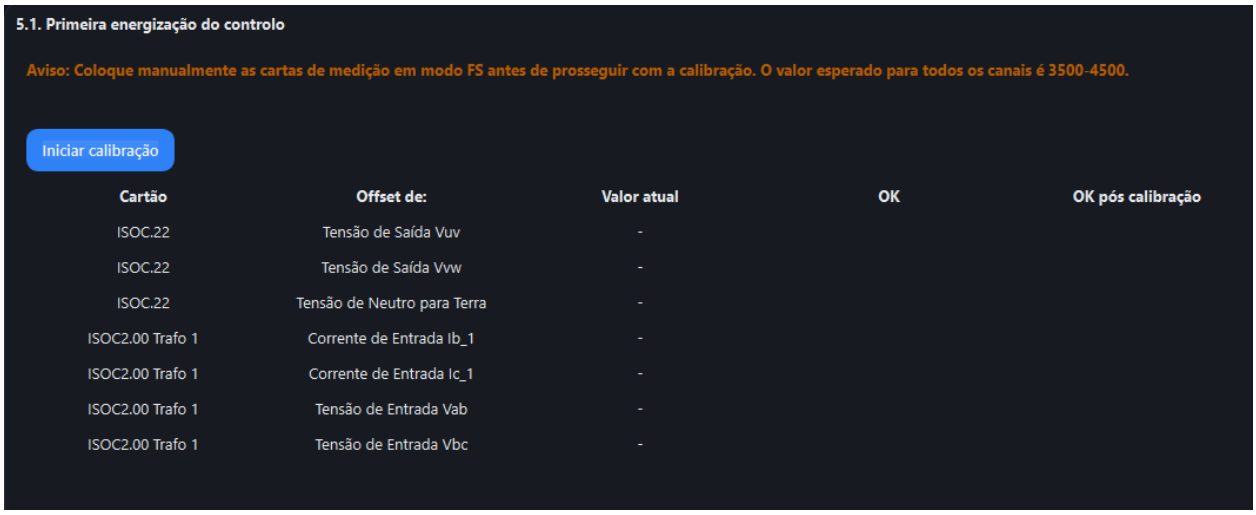


De seguida, deve colocar as cartas de medição em modo OP para fazer a sua calibração. Tenha a certeza que o modo está corretamente colocado, já que isso pode influenciar a calibração que se segue. Tendo garantido o modo OP, carregue no botão “Iniciar Calibração”.

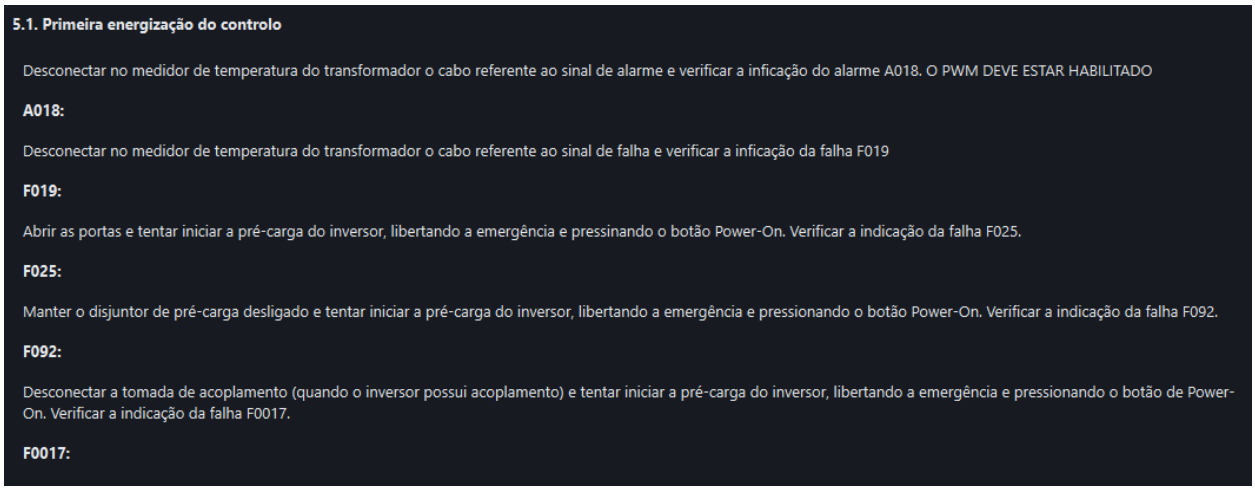
Após carregar nesse botão, será indicado o valor inicial de cada um dos parâmetros. Depois, será feito o procedimento conforme descrito na especificação, mas de forma automática. O valor resultante da calibração será apresentado e, no caso de estar dentro do valor aceitável, aparecerá um check à frente desse valor. Quando todos os valores estiverem **OK**, será permitido o avanço.



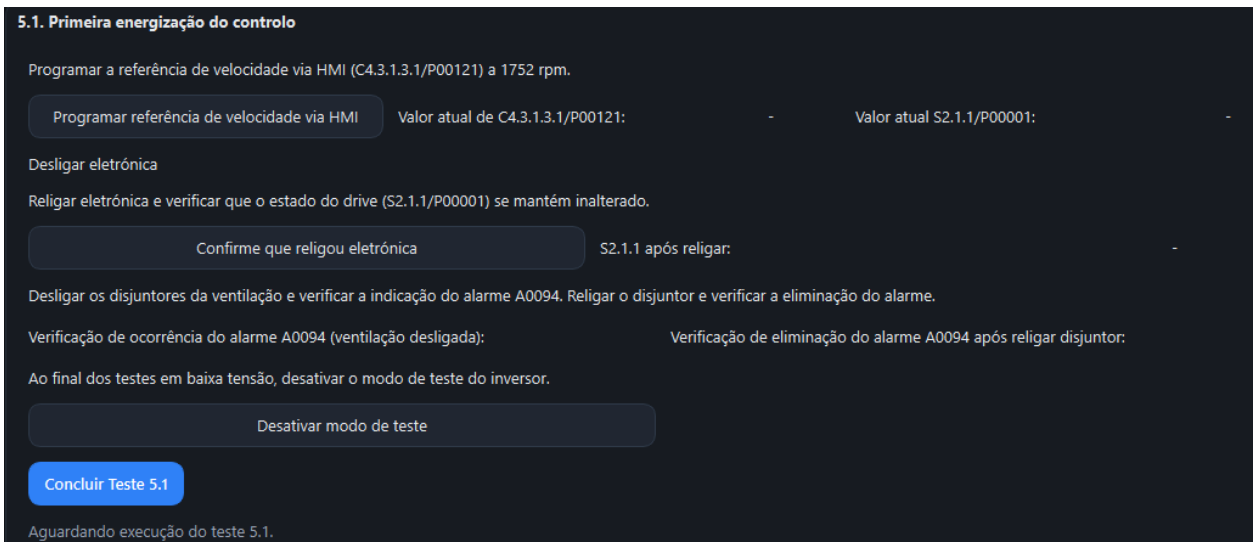
Depois do modo OP, é necessária a mudança para FS. As indicações dadas anteriormente são iguais para este caso, apesar de alterar o intervalo de valores aceitável após calibração.



Por fim, são dadas algumas instruções de tarefas manuais no equipamento que deverão levar ao aparecimento de falhas/alarmes correspondentes. À frente da falha/alarme, aparecerá um check.



Na última fase deste ensaio, é necessário programar a referência de velocidade na HMI (**C4.3.1.3.1/P001121**) a 1752 rpm. Tal é feito carregando no botão correspondente da aplicação, que indicará o valor atual desse parâmetro, bem como o valor atual do estado do drive (**S2.1.1/P00001**) – para garantir que este não sofreu alterações.



A eletrónica deverá ser desligada e religada para verificar que o estado do drive se mantém inalterado. Deverá confirmar, através do botão, que religou a eletrónica. Note-se que, naturalmente, ao desligar a eletrónica, as comunicações com o drive

serão afetadas. Tenha o cuidado de configurar novamente antes de confirmar que religou a eletrónica.

Deverá seguir as instruções que se encontram a seguir e verificar as ocorrências do alarme A0094, bem como a sua eliminação (checks automáticos aparecerão). Por fim, deverá desativar o modo de teste através do botão indicado para o efeito e dar como concluído o ensaio.

5.2. Sistema de Ventilação com Velocidade Variável

No caso de ter selecionado no início que o drive tem sistema de ventilação com velocidade variável, este ensaio estará disponível.

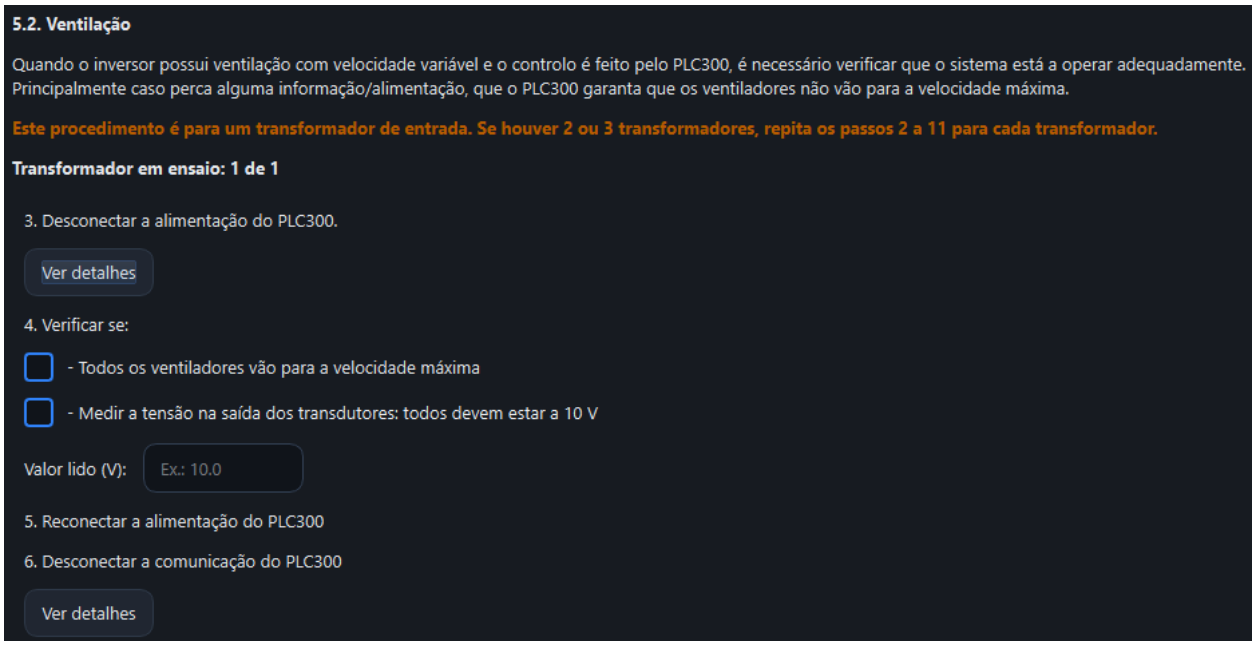
Este ensaio deve ser realizado para cada transformador. Assim, tendo em conta a quantidade de transformadores do drive extraída do ficheiro de parâmetros, aparecerá na barra lateral na direita cada um dos transformadores.

Conforme é dito na aplicação, os passos 2 a 11 deverão ser repetidos para outros transformadores. No caso de existência de mais do que um transformador, a aplicação fará esse encaminhamento de modo automático.

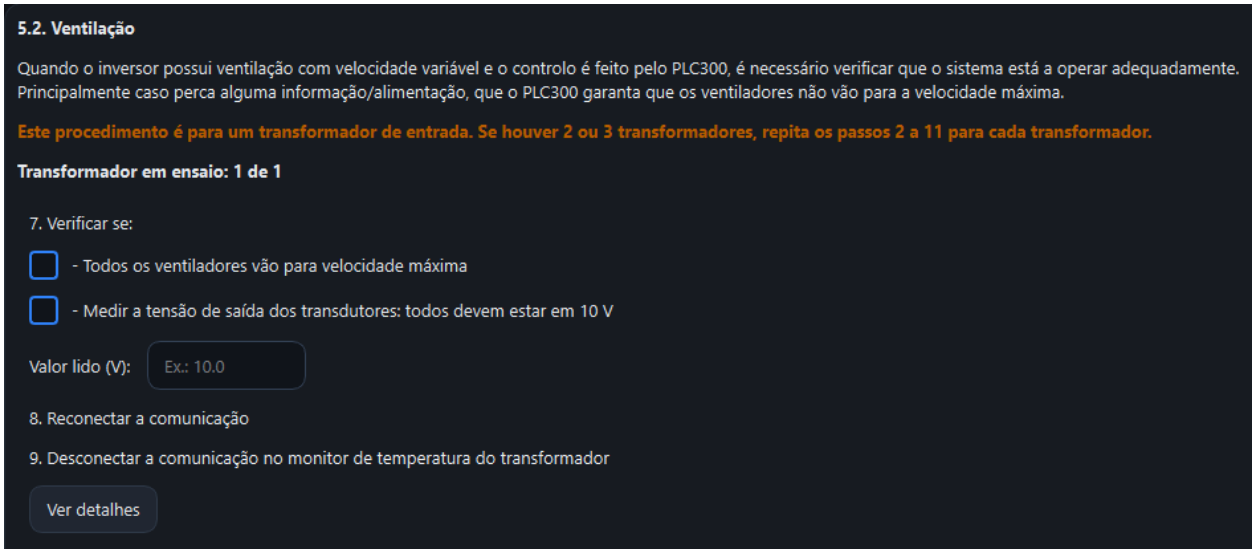


Começa-se por colocar o drive em modo de calibração, ou seja, colocando **C1.2.2/P00297 = 2**. De seguida, medem-se tensões e os resultados são inseridos no devido campo. Em "Ver detalhes", tem-se uma imagem explicativa de como devem ser feitas as medições.

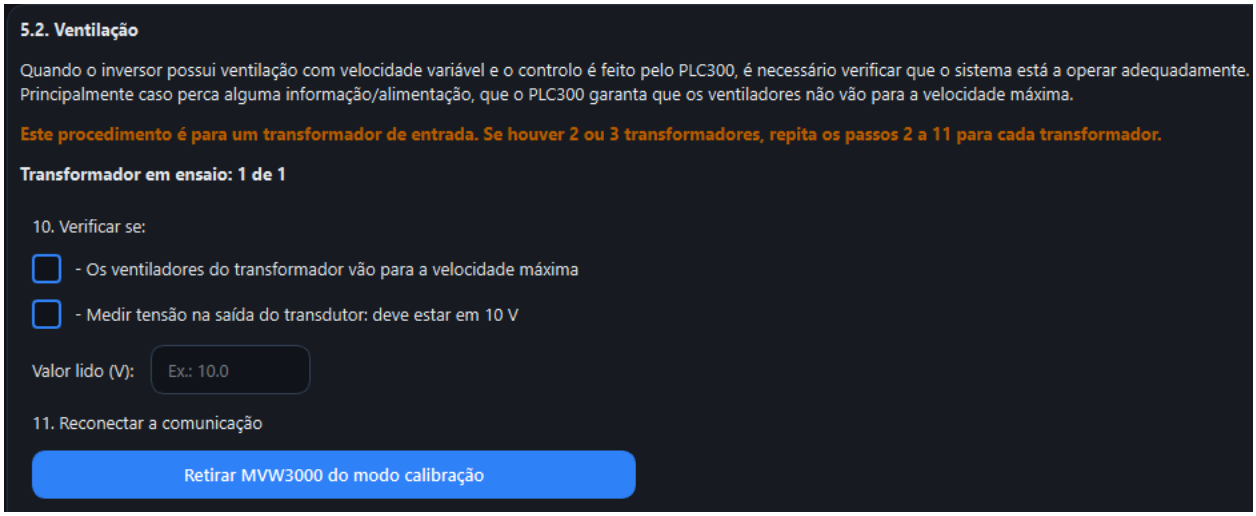
Avançando para o passo seguinte, são mostradas mais instruções. Em “Ver detalhes” tem-se uma imagem para desconectar a alimentação do PLC e, no botão seguinte com o mesmo texto, a mesma imagem.



Na fase seguinte, também existem mais instruções e campos de preenchimento. Note-se que a aplicação apenas permite avanço no caso de estar tudo preenchido conforme esperado.



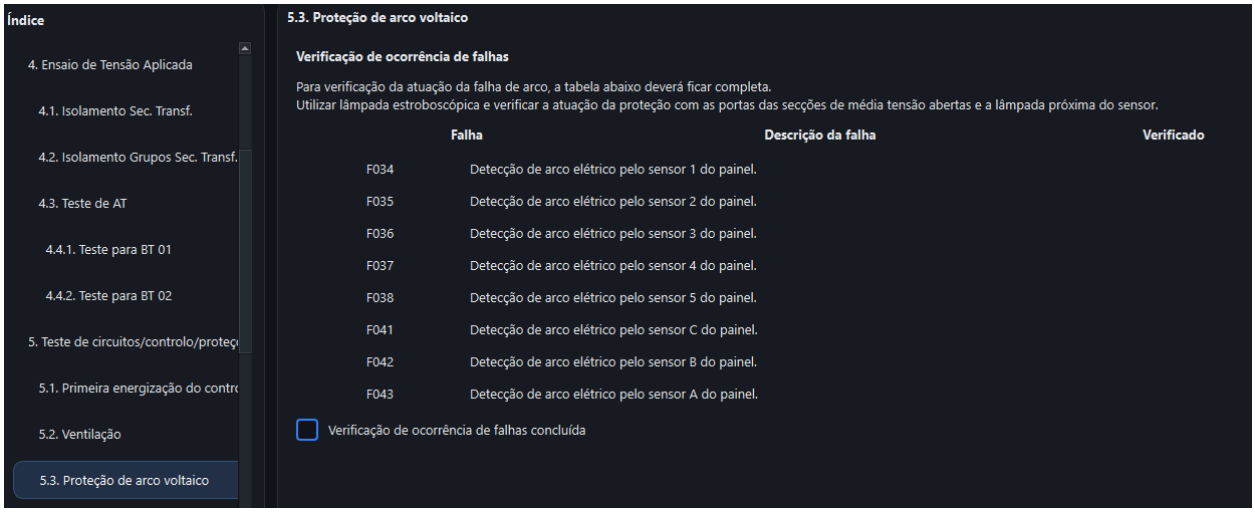
Por último, existem mais verificações e um campo para inserir resultado de uma medição; ainda, é pedido que se retire o drive do modo calibração, ou seja, **C1.2.2/P00297 = 0**.



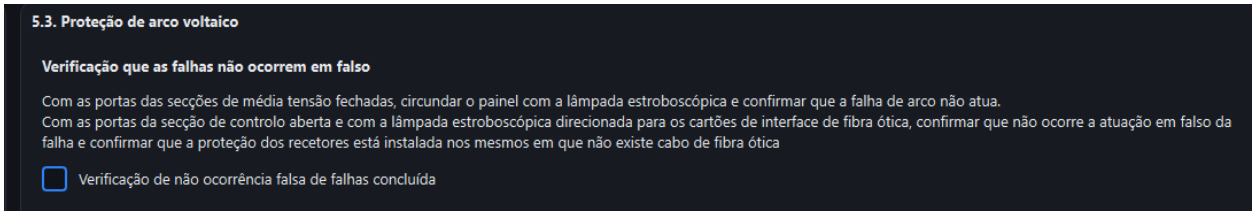
Na existência de mais transformadores, será encaminhado para o devido passo nesta fase.

5.3. Proteção de Arco Voltaico

Neste teste, a filosofia é semelhante a algo já encontrado (naturalmente, do ponto de vista da utilização da ferramenta). Deve seguir as instruções e as falhas aparecerão com um check correspondente em "Verificado" na tabela.

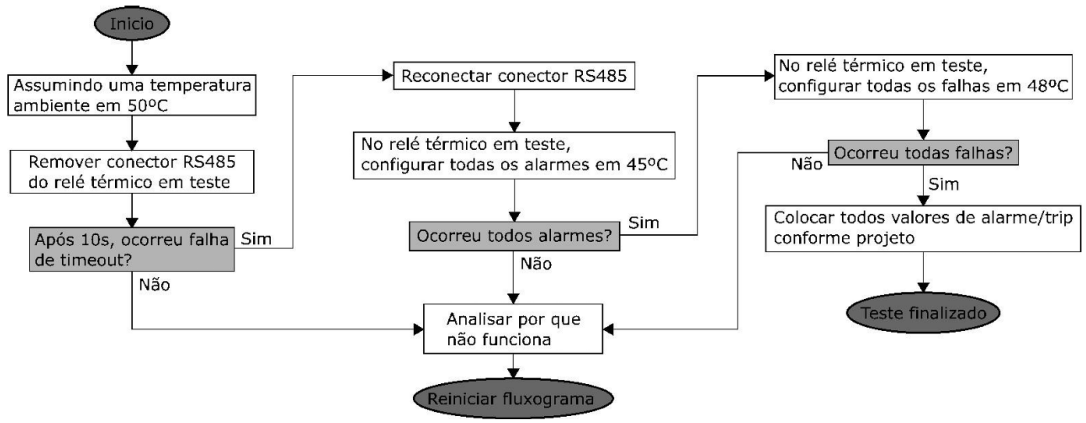


No passo seguinte, são dadas instruções e a não ocorrência de falhas deve ser verificada.

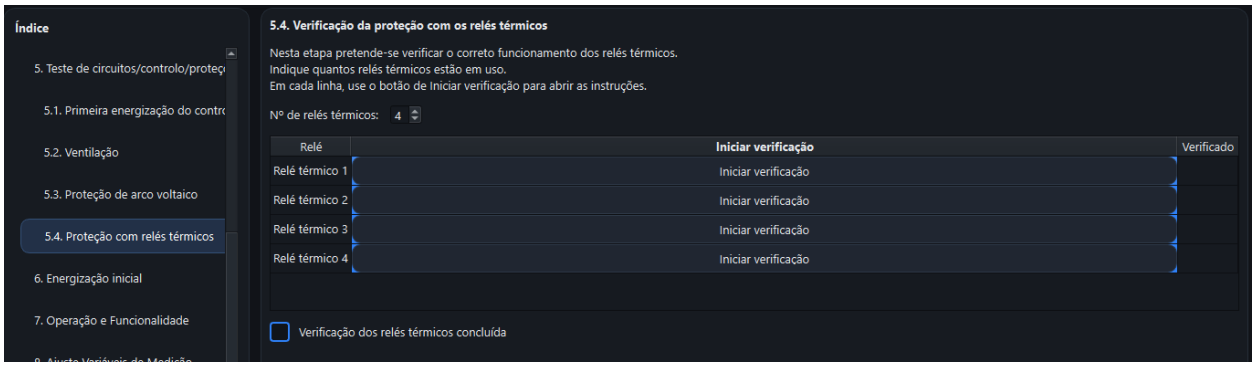


5.4. Verificação da Proteção com os Relés Térmicos

A verificação dos relés térmicos tem por base o seguinte fluxograma, que também se encontra na especificação. Assim, as respostas dadas pelo utilizador encaminharão o mesmo tendo em conta o fluxograma.



O MVW3000 tem capacidade para 1 a 6 relés térmicos. Deverá selecionar quantos relés térmicos possui o equipamento em teste.

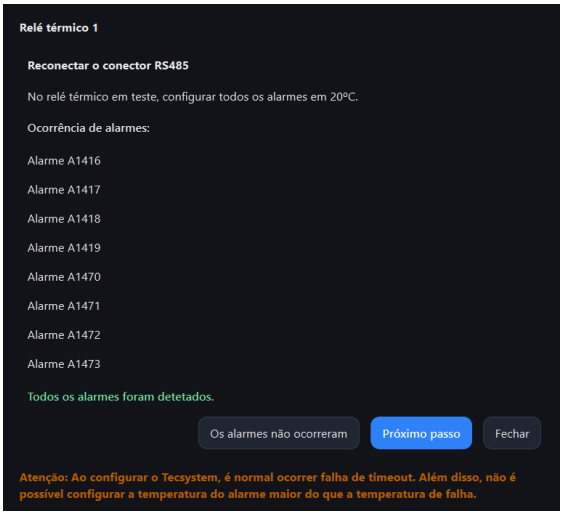


De seguida, em cada um deles dispostos na tabela, deverá efetuar o teste de acordo com a especificação. Ao pressionar "Iniciar Verificação", será aberta uma janela pop-up que guiará esse teste. A falha e o alarme aparecerão com check automaticamente quando forem detetadas. Após programar o relé para a temperatura ambiente, deverá indicar qual é essa temperatura.

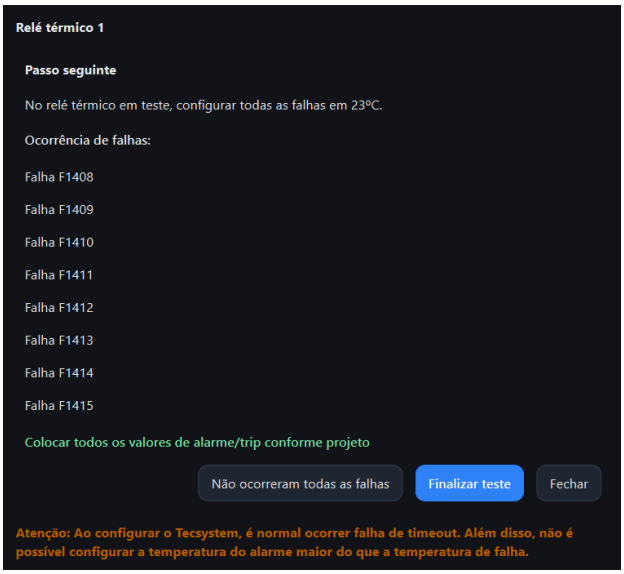


No caso de não ter ocorrido a falha e o alarme esperados, devem ser pressionado o botão "As falhas não ocorreram". Caso contrário, deverá pressionar "Próximo passo". Assumindo pressionou "Próximo passo", deve reconectar o conector RS485, conforme a instrução.

De seguida, deve configurar no relé todos os alarmes para a temperatura ambiente indicada menos 5ºC. Por exemplo, considerando que colocou uma temperatura ambiente de 25ºC, deve configurar todos os alarmes no relé para 25 – 5 = 20ºC. O exemplo apresentado na imagem é referente ao caso do relé 1. Os alarmes a verificar (automaticamente verificados pela aplicação) variam de relé para relé.



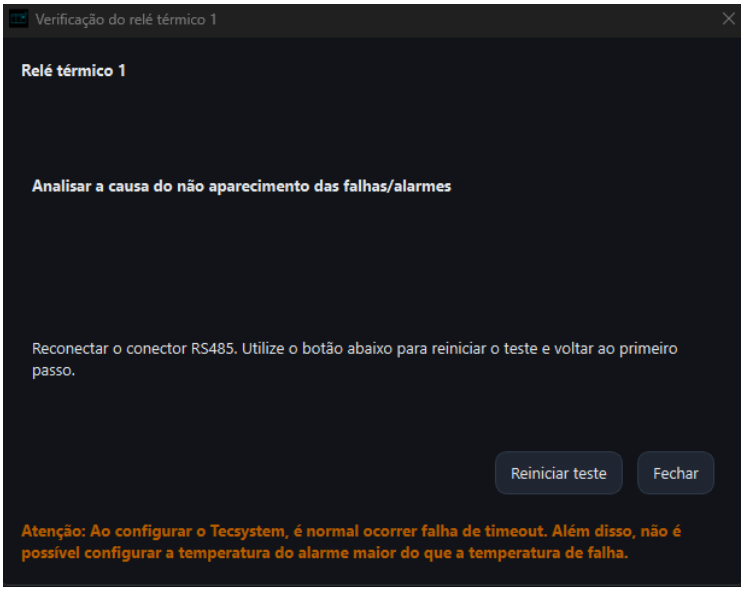
De seguida, deve configurar no relé todas falhas para a temperatura ambiente indicada menos 2ºC. Por exemplo, considerando que colocou uma temperatura ambiente de 25ºC, deve configurar todos os alarmes no relé para 25 – 2 = 23ºC. O exemplo apresentado na imagem é referente ao caso do relé 1. As falhas a verificar (automaticamente verificadas pela aplicação) variam de relé para relé.



No caso de pressionar "Finalizar teste", aparecerá um check na coluna "Verificado" da tabela. O processo deverá ser repetido para os restantes relés térmicos que o equipamento tiver.



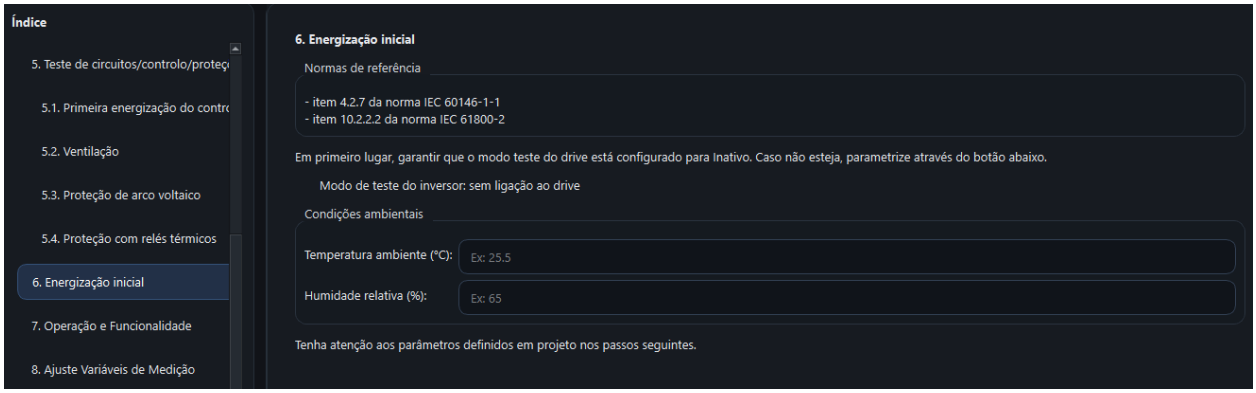
Quando pressiona "Os alarmes não ocorreram" ou "As falhas não ocorreram", aparecerá a instrução seguinte e o fluxograma será reiniciado.



6. Energização Inicial : Sistema de Pré-Carga e Realimentações de Tensão dos Barramentos CC

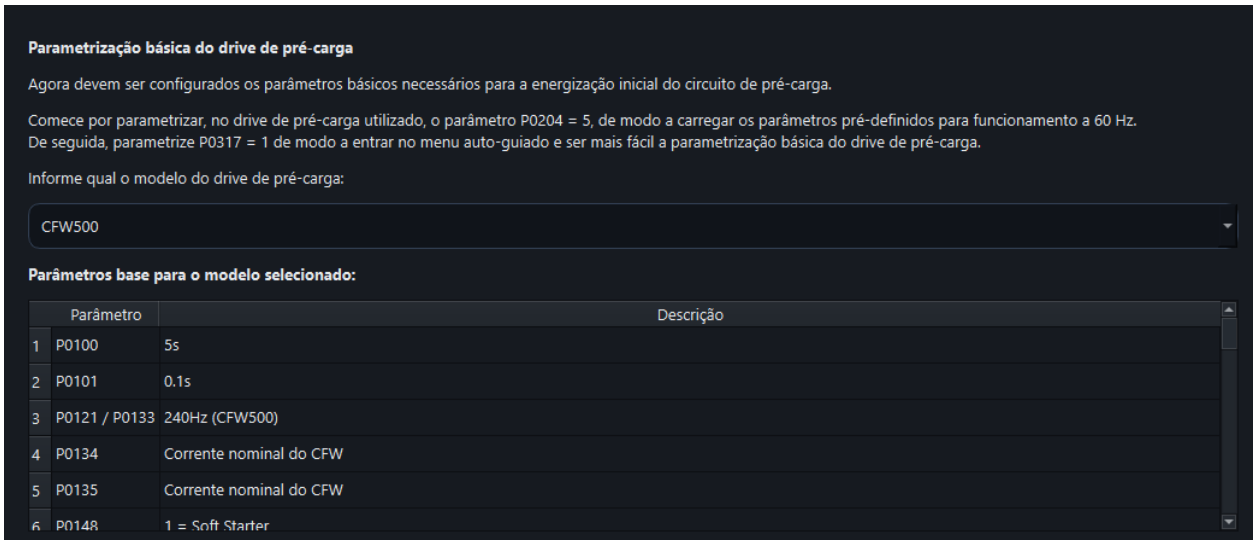
Este ensaio começa por requerer que o drive tenha o seu modo teste inativo, ou seja, que o parâmetro **C1.2.2/P00297** seja igual a 0. Caso se verifique, isto estará explícito no ecrã. No caso se isso não acontecer, aparecerá um botão para que o drive seja parametrizado corretamente.

É pedido que seja inserida a temperatura ambiente (ºC) e a humidade relativa (%).



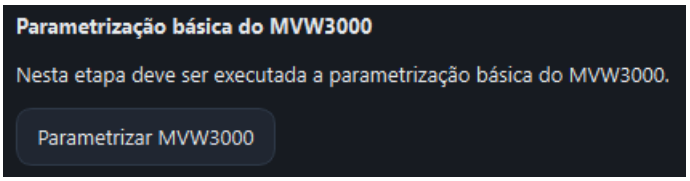
No passo seguinte, é necessária a parametrização do drive de pré-carga. Deve fazer a parametrização de **P0204 = 5** para carregar os parâmetros pré-definidos para funcionamento a 60 Hz e, de seguida, parametrizar **P0317 = 1** de modo a entrar no menu auto-guiado.

Informando a aplicação qual o drive de pré-carga instalado no MVW3000, são apresentados qual a parametrização a efetuar.

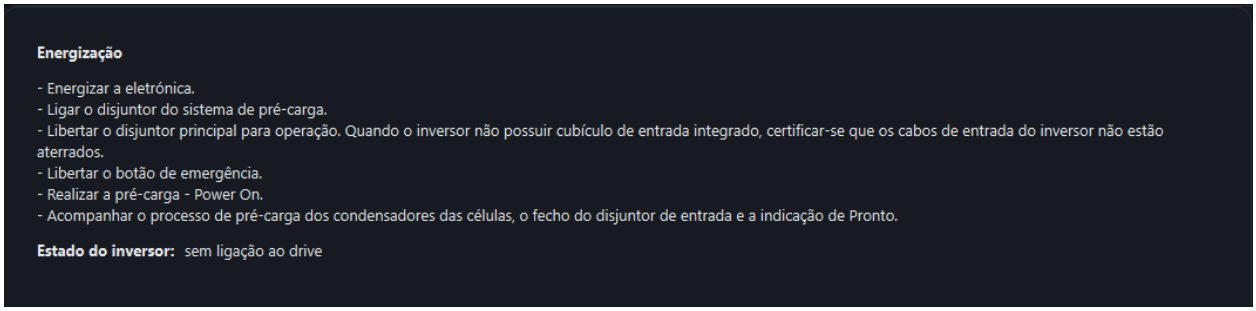


Depois da parametrização do drive de pré-carga, faz-se a parametrização básica do MVW3000 tendo em conta as suas características. Para isso, no passo seguinte à parametrização do drive de pré-carga, deve pressionar o botão "Parametrizar MVW3000".

É tido em conta o tipo de filtro do drive, ou seja, no caso de o drive ter filtro sinusoidal com contactor de saída, o parâmetro **C5.11.3.1/P00587** será automaticamente colocado a 1.



No passo seguinte, deve realizar as instruções que se encontram na página. O estado do drive deve aparecer como "Pronto". Apenas quando for esse o estado do drive será permitido o avanço.



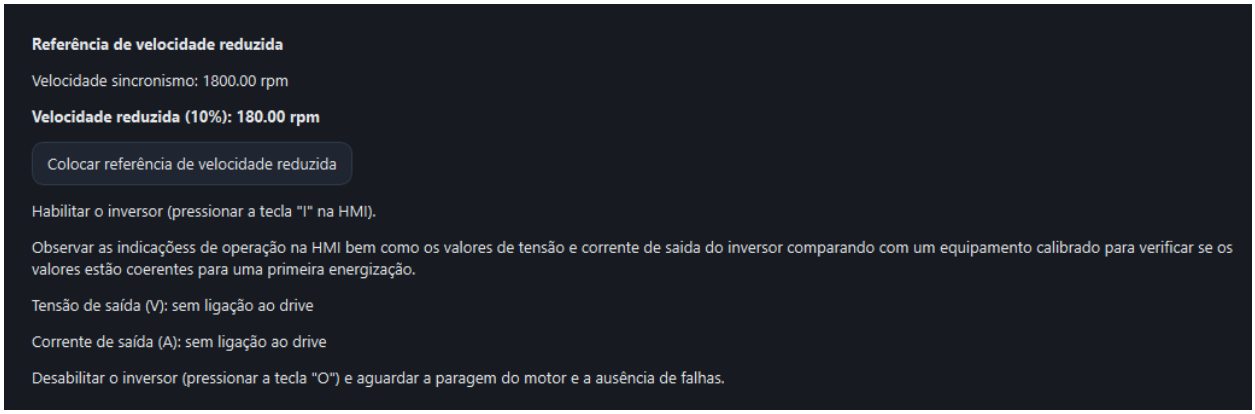
De seguida, deve inserir os valores de Vrede e Vsec/Vprim (razão entre a tensão do secundário e tensão do primário), assim como informar quantas células por fase tem o drive em ensaio. Ao informar qual é o número de células por fase, a tabela irá ajustara automaticamente as linhas.

A tensão do barramento CC das células em relação ao valor calculado e a temperatura das células em relação ao valor lido no termómetro calibrado têm uma tolerância de ± 5%. Qualquer tensão ou temperatura de qualquer célula que esteja fora do intervalo aceitável aparecerá a vermelho e impedirá o avanço para a fase seguinte do ensaio.



Como última fase do ensaio, é necessário parametrizar uma referência de velocidade reduzida. A especificação dá como exemplo uma velocidade de 200 rpm para um motor de 4 polos. Considerando uma frequência de 60 Hz, temos que 200 rpm é aproximadamente 10% da velocidade de sincronismo do motor, 1800 rpm.

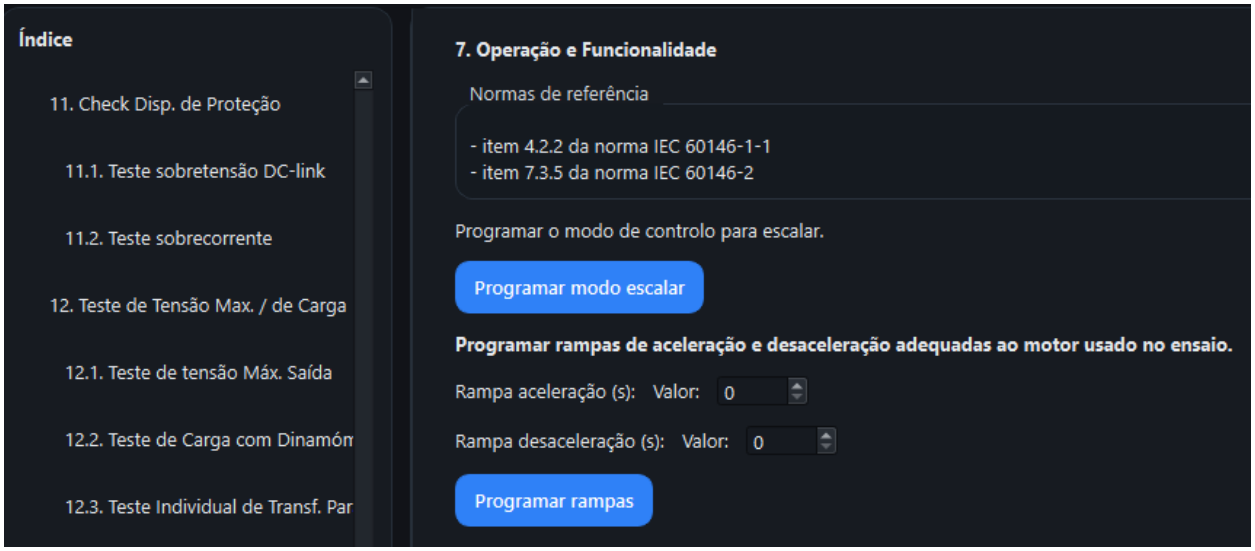
Nesse sentido, e de modo a agilizar o ensaio, a aplicação indicará para parametrização da referência de velocidade reduzida 10% da velocidade de sincronismo do motor utilizado no ensaio do MVW3000.



De seguida, devem ser seguidas as restantes instruções e avaliadas a tensão e corrente de saída do drive em teste.

7. Operação, Carga Leve, Realimentações de Corrente e Funcionalidade

Começa-se por programar o modo escalar V/f através do botão. De seguida, programam-se as rampas de aceleração e desaceleração, conforme o valor inserido nos campos – salientando que devem ser valores adequados ao motor utilizado no ensaio.

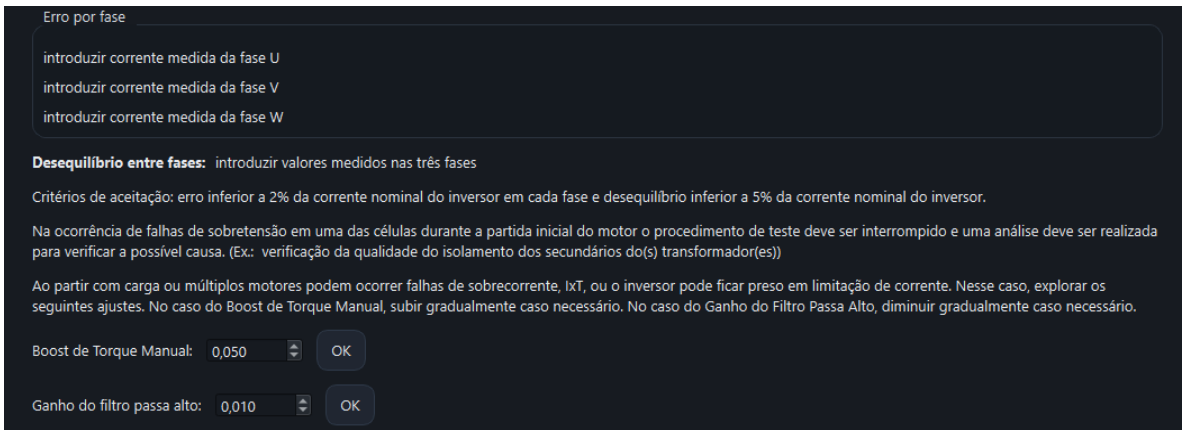


De seguida, são dadas instruções conforme a especificação. A referência de velocidade nominal é parametrizada através do botão. Deverá ser indicada a corrente lida nas 3 fases do motor (U, V e W). Os cálculos dos erros são feitos

automaticamente pela aplicação e o seu resultado condiciona a finalização do ensaio.

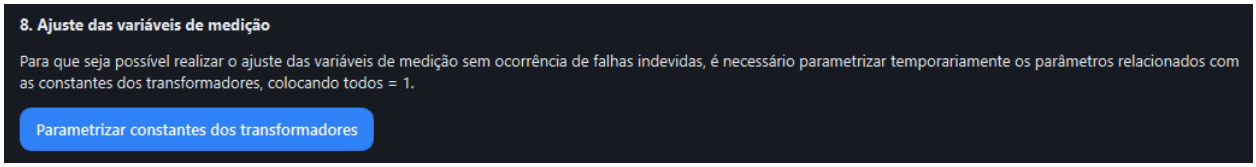


Conforme referido na especificação, o boost de torque manual e o ganho do filtro passa alto podem ser modificados no caso de ocorrência de falha de sobrecorrente, IxT ou o inversor ficar preso em limitação de corrente. Esses ajustes podem ser feitos diretamente na aplicação.



8. Ajuste das Variáveis de Medição

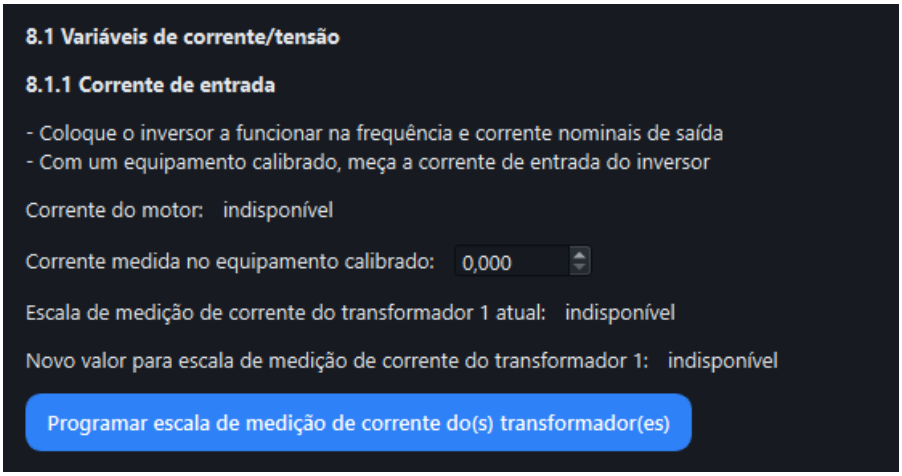
Para parametrizar as constantes dos transformadores = 1 deve usar o botão disponível para o efeito, parametrizando automaticamente e dinamicamente dependendo da quantidade de transformadores.



8.1. Ajuste das Escalas de Corrente e Tensão

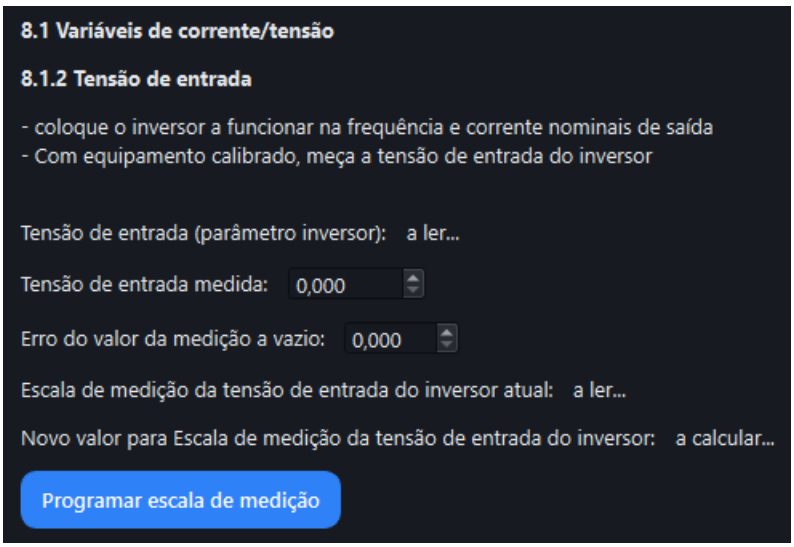
São dadas instruções e é lida a corrente do motor (ou seja, a corrente de saída do drive) através do parâmetro S2.6.4/P00032. Essa corrente também deve ser lida por um equipamento calibrado e indicada na aplicação. No caso de existir erro, é calculado automaticamente o novo valor para a escala de medição de corrente no transformador 1.

No caso de existirem mais do que um transformador, o valor da nova escala de medição será aplicada a todos de forma dinâmica. Assim sendo, apenas é necessário pressionar o botão uma vez.

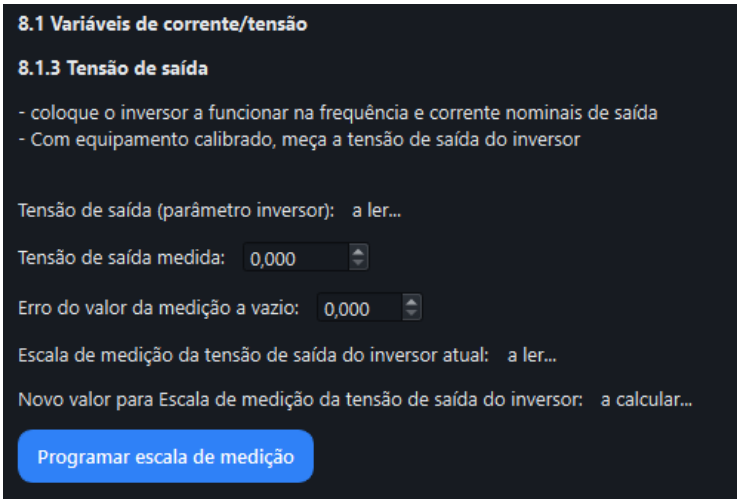


No caso de o valor estar fora do intervalo 0,9-1,1 é dado um alerta.

No caso da tensão de entrada, a aplicação segue a mesma filosofia, mas desta vez compara o valor medido por um equipamento calibrado com o valor do parâmetro **S2.6.5/P00031**.



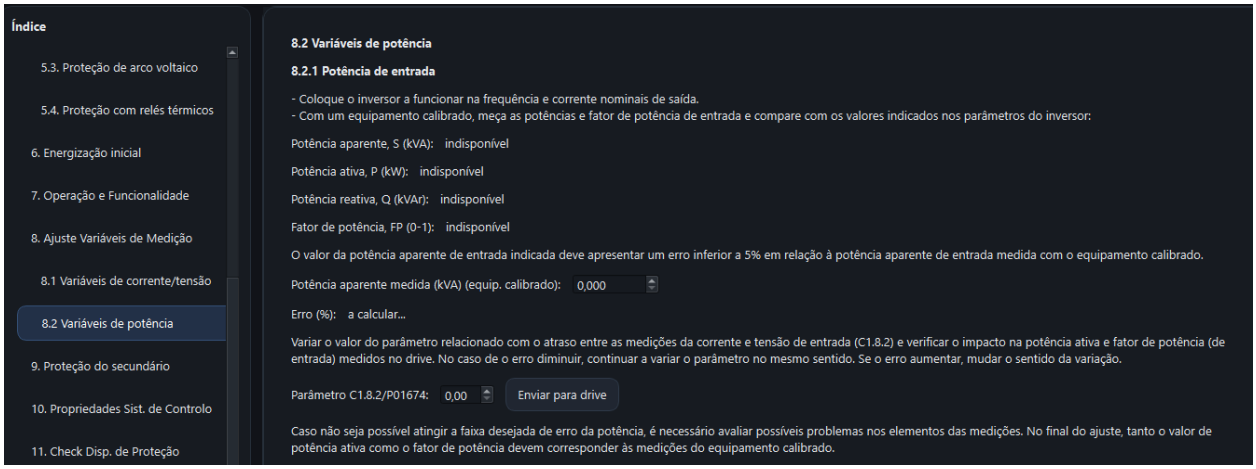
Para o caso da tensão de saída, a aplicação segue a mesma filosofia, mas desta vez compara o valor medido por equipamento calibrado com o valor do parâmetro **S2.3.5/P00007**.



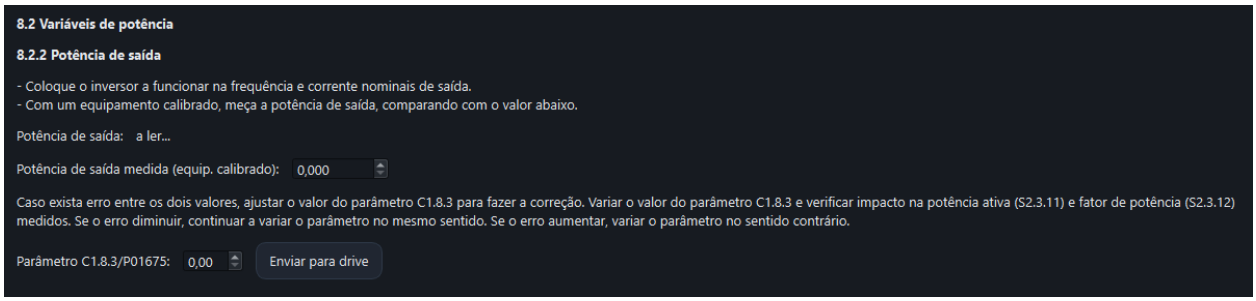
8.2. Ajuste das Medições de Potência

São mostradas as potências ativa, reativa e aparente, o fator de potência e o erro calculado automaticamente tendo em conta a potência aparente medida por um equipamento calibrado (que deve ser inserida na aplicação).

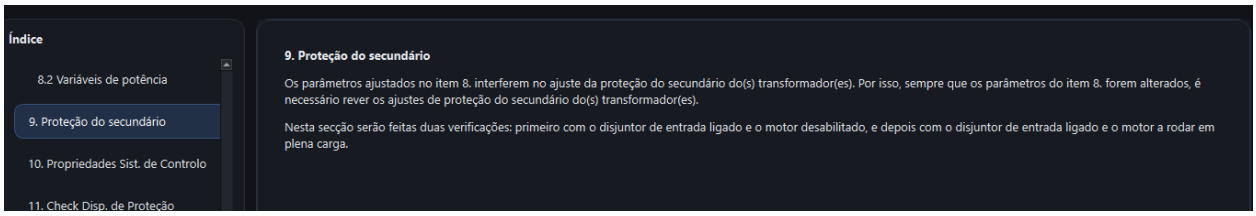
Tendo em conta o erro obtido, o parâmetro **C1.8.2/P01674** deve ser variado.



De seguida, são lidos os parâmetros **S2.3.11/P00010** (da potência de saída) e **S2.3.10/P00011** (do fator de potência). A potência de saída mostrada no parâmetro e a medida por um equipamento calibrado são comparadas e o erro é calculado automaticamente. No caso de existir erro, o valor do parâmetro **C1.8.3/P01675** é utilizado em direta ligação ao drive para fazer a correção.



9. Ajuste do Sistema de Proteção do Secundário do Transformador

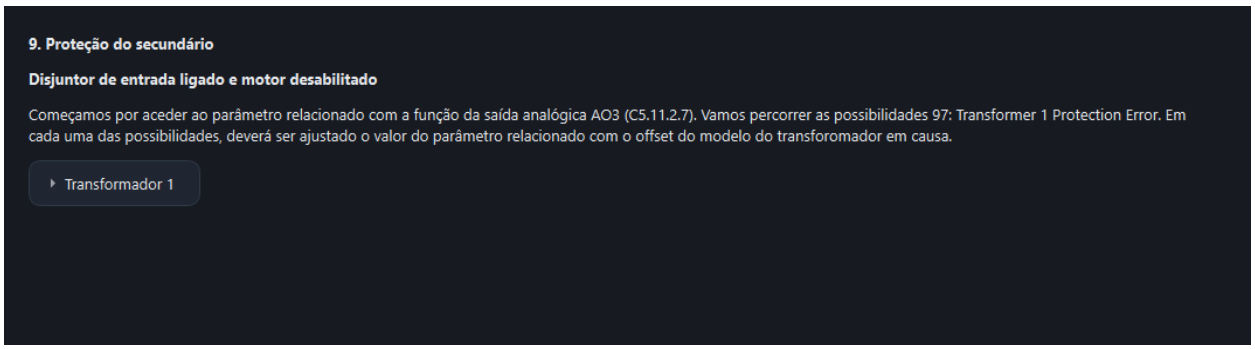


Aqui começa-se por dar informações relevantes ao utilizador no sentido da influência do ensaio anterior sobre este. Assim sendo,

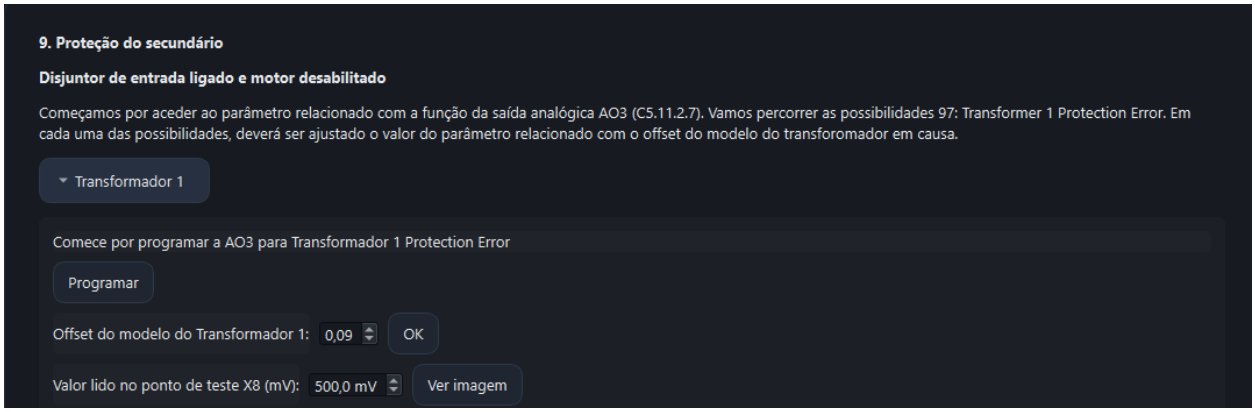
Sempre que os parâmetros forem ajustados no ensaio anterior, "Ajuste das Variáveis de Medição", é necessário rever os ajustes realizados ao sistema de proteção do secundário do(s) transformador(es). Por outras palavras, é necessário refazer este ensaio.

Este ensaio tem duas fases: uma feita com o disjuntor de entrada ligado e o motor desabilitado; outra com o disjuntor de entrada ligado e o motor a rodar em plena carga.

Tendo em conta que é um procedimento que deve ser realizado para cada transformador existente, a aplicação irá, de forma automática, criar um espaço para cada transformador.



Neste exemplo, apenas existe um transformador. Pressionando o botão "Transformador 1", aparecerá o espaço dedicado ao ajuste do seu sistema de proteção de secundário.



O procedimento descreve uma parametrização sequencial do parâmetro **C5.11.2.7/P00575** para 97 (Transformador 1), 98 (Transformador 2) e 99 (Transformador 3). Assim, no exemplo mostrado, pressionando o botão "Programar", tendo em conta que se refere ao Transformador 1, a AO3 será programada para Transformador 1 Protection Error – i.e., **C5.11.2.7/P00575 = 97**.

No caso de existirem outros transformadores, haverá o mesmo botão “Programar”, mas para **C5.11.2.7/P00575 = 98** no caso do Transformador 2 e **C5.11.2.7/P00575 = 99** no caso do Transformador 3.

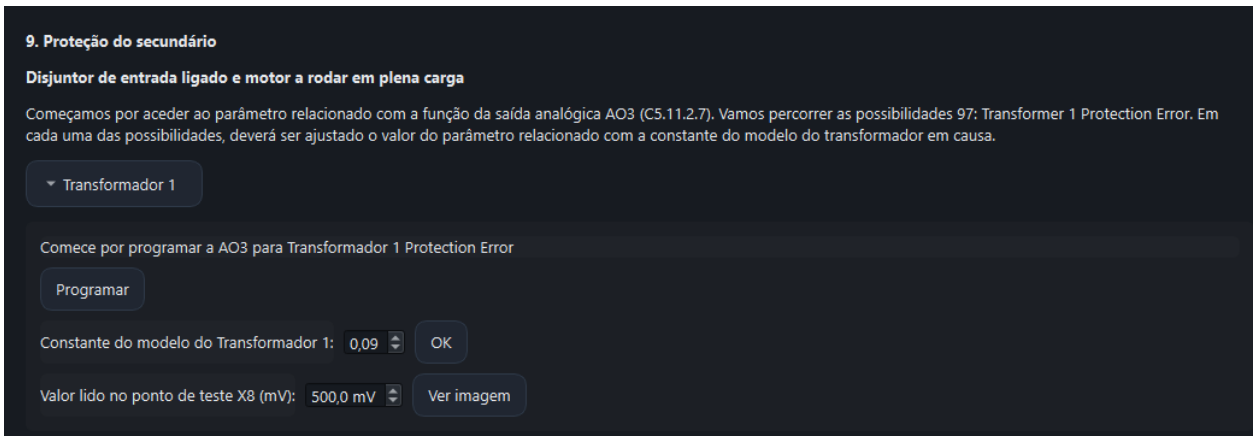
O offset do modelo do transformador pode ser ajustado pela aplicação através do campo e o valor é enviado para o drive pressionando “OK”.

No caso do **Transformador 1**, é ajustado o parâmetro **C7.13.1/P01535**.
No caso do **Transformador 2**, é ajustado o parâmetro **C7.13.2/P01536**.
No caso do **Transformador 3**, é ajustado o parâmetro **C7.13.3/P01537**.

De seguida, o valor lido no ponto de teste X8 com um multímetro deverá ser inserido no campo – que deverá estar entre 450 e 550 mV. O botão “Ver imagem” abre, em pop-up, a figura da especificação que explica onde se encontra o ponto de teste X8.

Para a fase do ensaio com o disjuntor de entrada ligado e o motor a rodar em plena carga, a aplicação segue uma filosofia semelhante. Contudo, em vez de ajustado o offset do modelo do(s) transformador(es), será alterado o(s) seu(s) modelo(s).

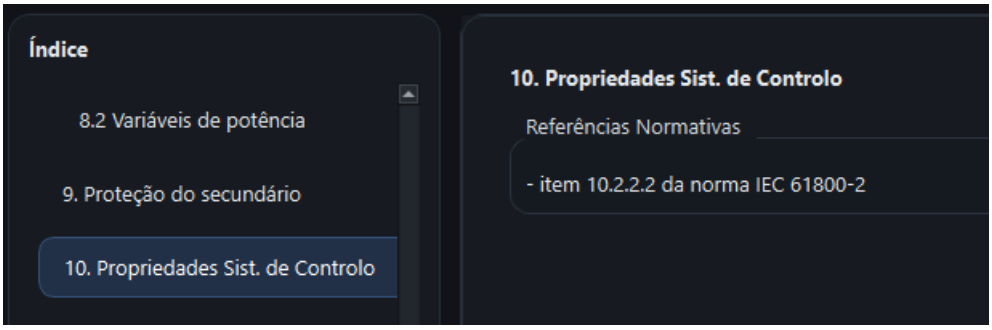
No caso do **Transformador 1**, é ajustado o parâmetro **C7.13.4/P01538**.
No caso do **Transformador 2**, é ajustado o parâmetro **C7.13.5/P01539**.
No caso do **Transformador 3**, é ajustado o parâmetro **C7.13.6/P01540**.



Neste caso, também o valor lido no ponto de teste X8 deverá ser verificado e, aliás, é verificado pela aplicação – deverá estar entre 450 e 550 mV.

10. Check das Propriedades do Sistema de Controlo

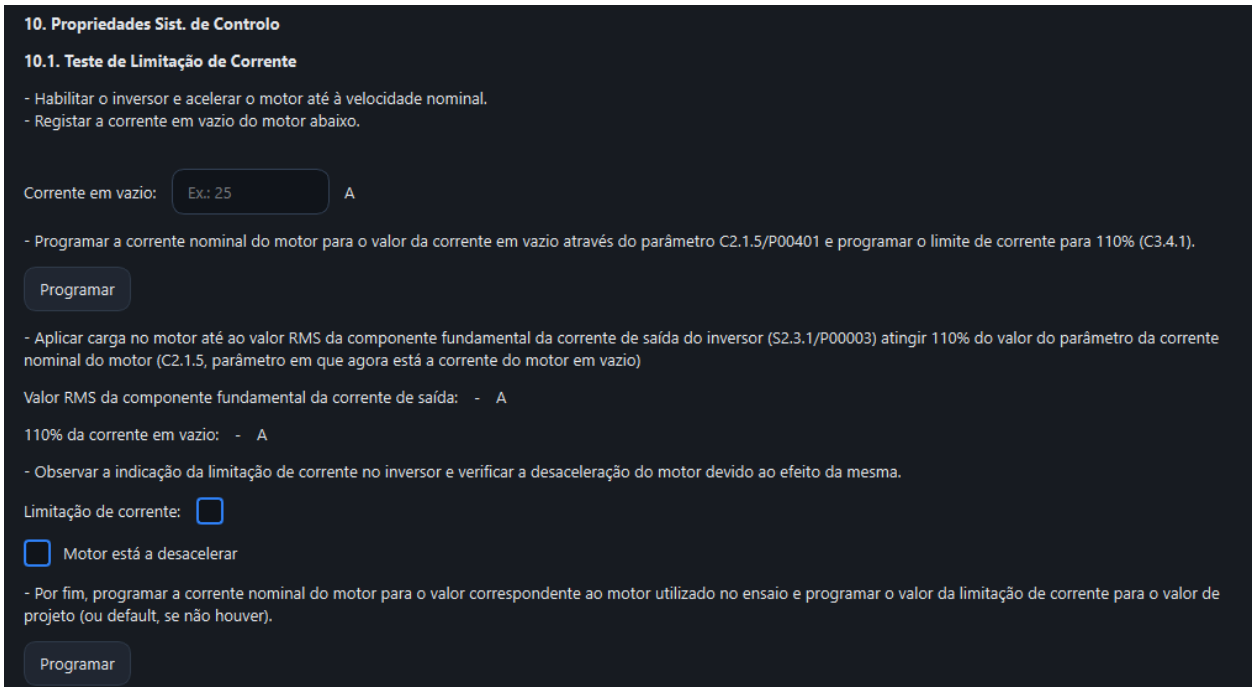
A página começa apresentando referências normativas do ensaio.



10.1. Teste de Limitação de Corrente

Passando para a página seguinte, são dadas instruções e é pedido que seja colocada a corrente em vazio do motor medida. Programar o parâmetro correspondente à corrente nominal do motor (**C2.1.5/P00401**) para o valor da corrente em vazio e programar o limite de corrente para 110% (**C3.4.1/P00135**) é feito de forma automática pressionando "Programar".

De seguida, conforme a especificação, deve ser aplicada carga no motor até ao valor RMS da componente fundamental da corrente de saída do drive (ou seja, o parâmetro **S2.3.1/P00003**) ser igual a 110% (valor em **C3.4.1/P00135**) do valor parametrizado em **C2.1.5/P00401** (corrente nominal do motor), que, neste momento, é o valor medido da corrente em vazio do motor.

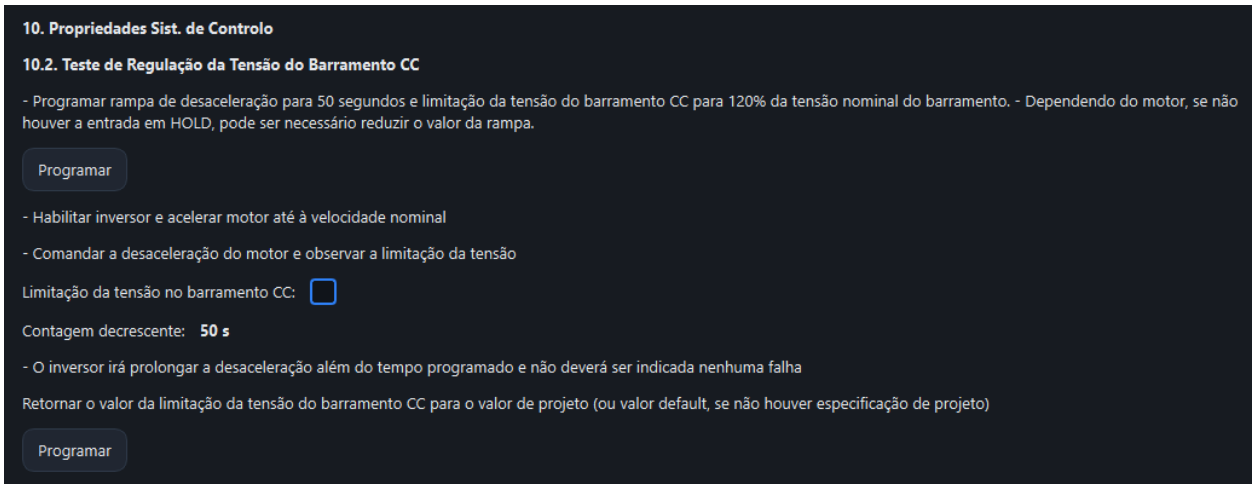


É esperado que o drive entre em limitação de corrente e seja observada a desaceleração do motor devido ao efeito da mesma. A entrada do drive em limitação de corrente é automaticamente verificada (através do bit 10 do parâmetro **S5.1.3/P00690**). No entanto, é necessária a verificação manual da desaceleração do motor.

No final, para programar a corrente nominal do motor (**C2.1.5/P00401**) para o valor correspondente ao motor utilizado no ensaio e programar o valor da limitação de corrente (**C3.4.1/P00135**) para o valor de projeto (ou default, se não houver) basta pressionar o botão "Programar" que se encontra no final da página e depois da respetiva instrução.

10.2. Teste de Regulação da Tensão do Barramento CC

Passando para a página seguinte, para programar a rampa de desaceleração (**C6.1.2/P00101**) para 50 segundos e o valor da limitação de tensão no barramento CC (**C3.5.2.1/P00151**) para 120%, é necessário pressionar o primeiro botão "Programar".



De seguida, são apresentadas instruções: habilitar inversor, acelerar motor até à velocidade nominal e, de seguida, comandar a desaceleração do motor, observando a limitação da tensão no barramento CC.

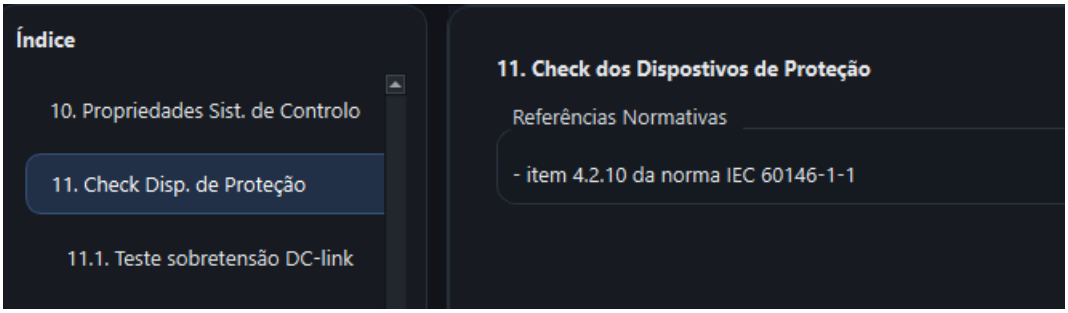
A verificação da limitação de tensão no barramento CC é feita de forma automática (através do bit 9 do parâmetro **S5.1.3/P00690**).

É iniciada uma contagem decrescente de 50 segundos para verificar que o drive irá prolongar a desaceleração além do tempo programado (no caso, os 50 segundos) e não deverá ser indicada nenhuma falha.

Para retornar o valor da limitação da tensão no barramento CC para o valor de projeto (ou default, se não houver valor de projeto) deve ser pressionado o botão "Programar" que se encontra no final da página e depois desta instrução.

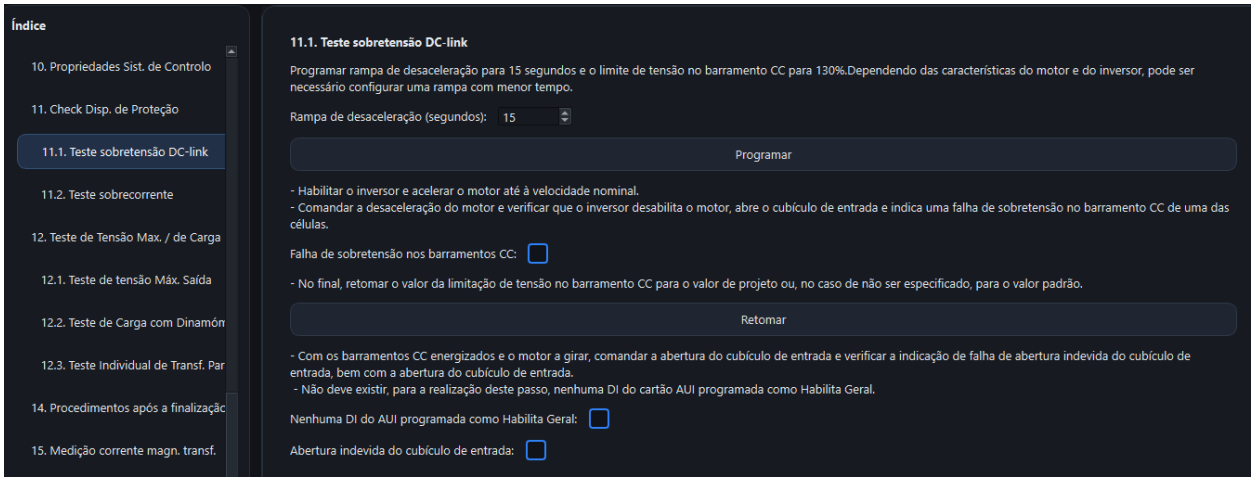
11. Check dos Dispositivos de Proteção

Na página de introdução ao ensaio, apenas é mostrada a referência normativa.



11.1. Teste de Sobretensão no Barramento CC

Para programar a rampa de desaceleração (**C6.1.2/P00101**) a 15 segundos é necessário pressionar o botão "Programar". Tendo em conta que, dependendo das características do motor e do drive, pode ser necessário configurar uma rampa com um menor tempo, essa possiblidade é oferecida na aplicação através do campo "Rampa de desaceleração (segundos): ".



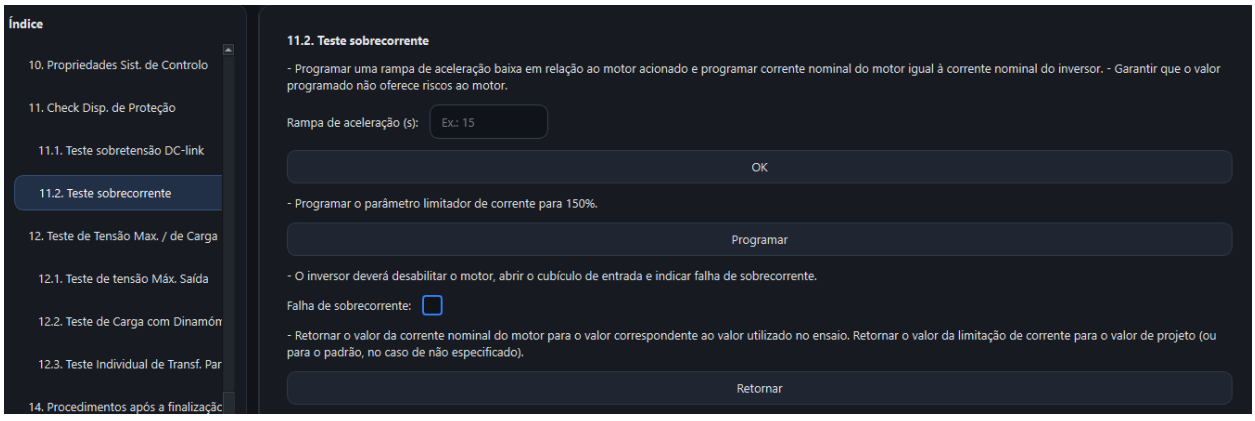
A falha de sobretensão no barramento CC de uma das células é verificada automaticamente. Para retomar o valor da limitação de tensão no barramento CC para o valor de projeto ou, no caso de não ser especificado, para o valor default, deve ser pressionado o botão “Retomar”.

Nenhuma DI do AUI estar programada como Habilita Geral é verificado automaticamente, bem como o aparecimento da falha **F027**, correspondente à abertura indevida do cubículo de entrada.

11.2. Teste de Sobrecorrente

Para programar uma rampa de aceleração baixa em relação motor, o valor da mesma deve ser indicado no campo para o efeito. Ao pressionar “OK”, será programado tanto o valor da rampa de aceleração indicada (**C6.1.1/P00100**); também será programado o parâmetro da corrente nominal do motor (**C2.1.5/P00401**) para o valor da corrente nominal do drive. No entanto, deve garantir que o valor programado para **C2.1.5/P00401** não oferece riscos ao motor.

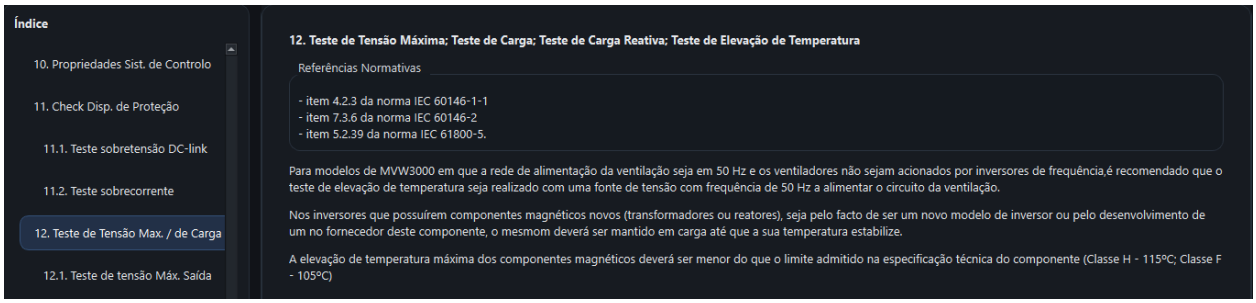
Numa fase seguinte, deve programar o limitador de corrente (**C3.4.1/P00135**) para 150% - usando, para isso, o botão “Programar”.



É esperado que o drive desabilite o motor, abrindo o cubículo de entrada e indicando a falha de sobrecorrente, que é verificada automaticamente. No final, para retornar o valor da corrente nominal do motor (**C2.1.5/P00401**) par o valor correspondente ao motor utilizado no ensaio e o valor da limitação de corrente (**C3.4.1/P00135**) para o valor de projeto (ou valor default, no caso deste não existir) é conseguido pressionando o botão “Retornar”.

12. Teste de Tensão Máxima, Teste de Carga, Teste de Carga Reativa, Teste de Elevação de Temperatura

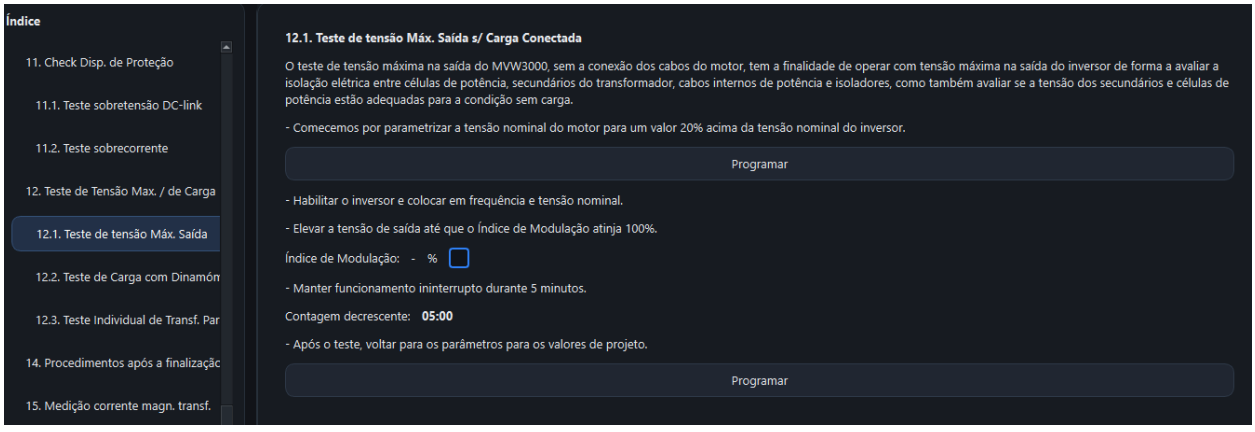
Começa-se pelas referências normativas e algumas instruções de maior importância que constam na especificação, relacionadas com a frequência da alimentação da ventilação, com componentes magnéticos novos e, ainda, com a elevação da temperatura de componentes magnéticos.



12.1. Teste de Tensão Máxima na Saída – Sem Carga Conectada

Para parametrizar a tensão nominal do motor (**C2.1.4/P00400**) para um valor acima da tensão nominal do inversor é necessário pressionar o primeiro botão "Programar".

A verificação de o Índice de Modulação atingir os 100% é efetuada automaticamente e, assim que tal acontece, inicia-se a contagem decrescente de 5 minutos para que durante esse tempo seja mantido o funcionamento ininterrupto.



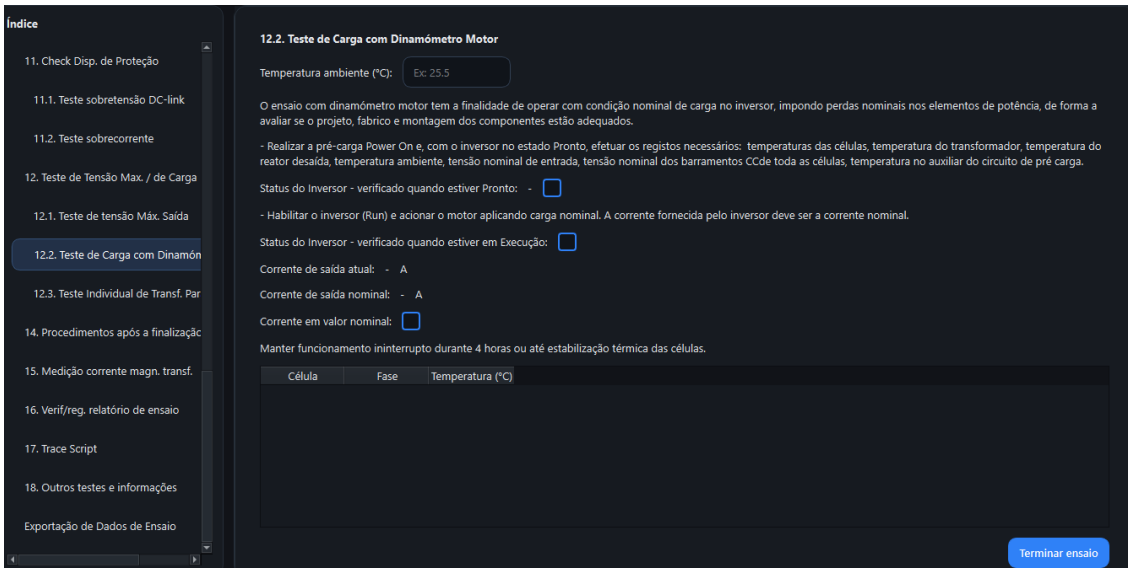
Após o teste, para voltar os parâmetros para os valores de projeto, deve ser utilizado o segundo botão "Programar".

12.2. Teste de Carga com Dinamómetro Motor

São dadas instruções conforme a especificação. O estado do drive é mostrado e verificado automaticamente – primeiro **Pronto (Ready)** e depois em **Execução (Run)**.

É feita automaticamente a verificação quando a corrente de saída atinge o valor da corrente nominal do drive.

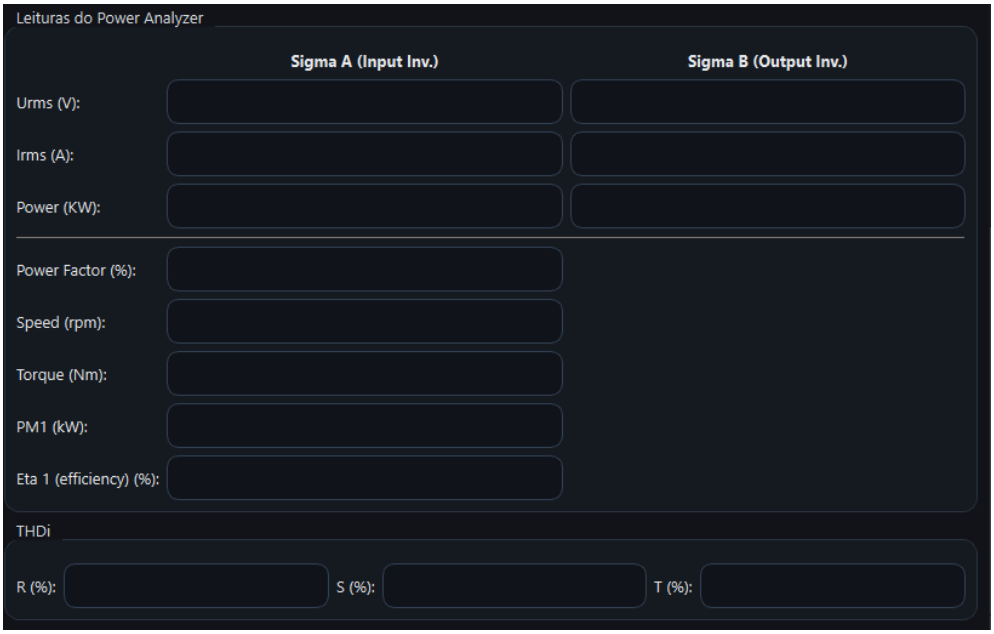
Também é feita a monitorização da temperatura das células, aguardando a sua estabilização. Quando a estabilização da temperatura das células acontece, é necessário pressionar o botão "Terminar ensaio", o que fará com que estas últimas temperaturas constem no relatório de ensaio.



Quando o ensaio é terminado, é pedido para preencher a seguinte tabela relacionada com as temperaturas medidas do(s) transformador(es). Dinamicamente, no caso de existência de mais do que um transformador, também aparecerão campos editáveis para preenchimento relativas ao mesmo.



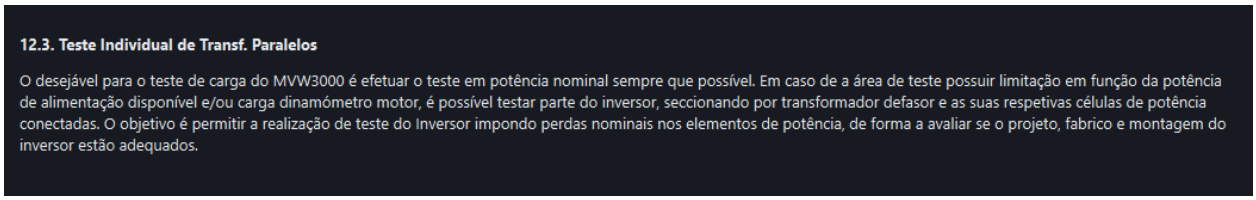
Além disso, também é pedido que sejam inseridas medições efetuadas com o Power Analyzer.



12.3. Teste Individual de Transformadores Paralelos

Em primeiro lugar, é feita uma contextualização do ensaio, que não se encontra no software como um ensaio obrigatório. É um ensaio, conforme refere a

especificação, que deve ser realizado no caso de a área de teste possuir alguma limitação ao nível da potência de alimentação disponível e/ou carga do dinamómetro – servindo este ensaio para testar parte do drive.



12.3.1. Inversor sem By-pass Automático de Células e sem Paralelismo de Células

12.3.1.1. Para Executar Carga no Transformador 1T1

Para parametrizar a tensão do motor (**C2.1.4/P00400)** para metade do seu valor original, é necessário pressionar o botão “Parametrizar”.

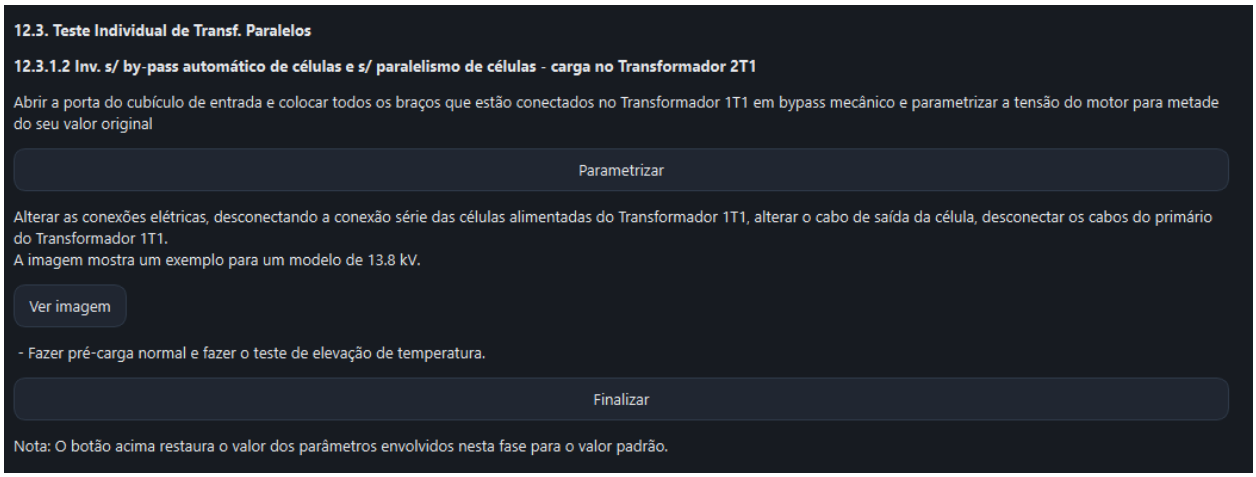
“Ver imagem” abre uma imagem exemplo das ligações em pop-up. No final, o botão “Finalizar” serve para restaurar o valor dos parâmetros previamente alterados para o valor padrão.



12.3.1.2. Para Executar Carga no Transformador 2T1

Para parametrizar a tensão do motor (**C2.1.4/P00400)** para metade do seu valor original, é necessário pressionar o botão “Parametrizar”.

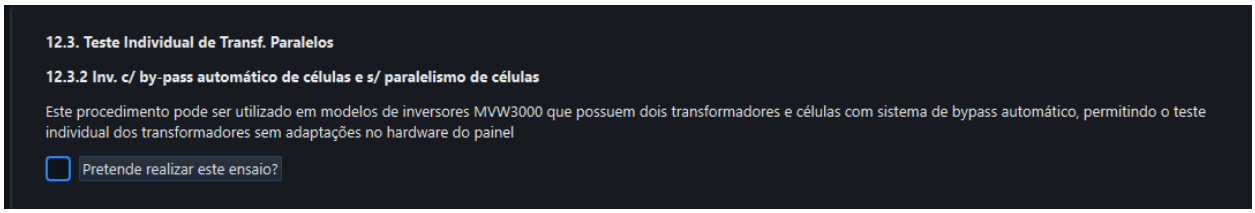
“Ver imagem” abre uma imagem exemplo das ligações em pop-up. No final, o botão “Finalizar” serve para restaurar o valor dos parâmetros previamente alterados para o valor padrão.



12.3.2. Inversor com By-pass Automático de Células e sem Paralelismo de Células

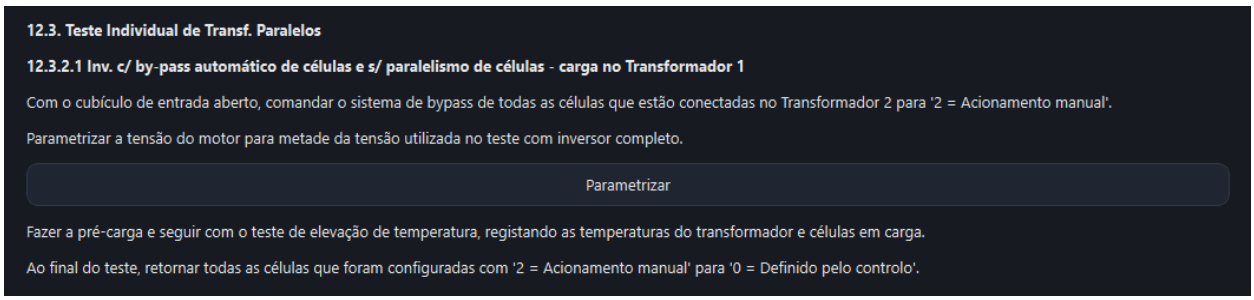
Passando para a página seguinte, é perguntado se pretendemos realizar este ensaio. Conforme refere a aplicação – e, naturalmente, a especificação – este procedimento pode ser utilizado em drives que possuam dois transformadores e células com sistema de by-pass automático, permitindo o seu teste individual sem adaptações de hardware.

Verificando que pretende realizar esse ensaio, a página seguinte será a **12.3.2.1**. Caso contrário, passará automaticamente para a **14**.



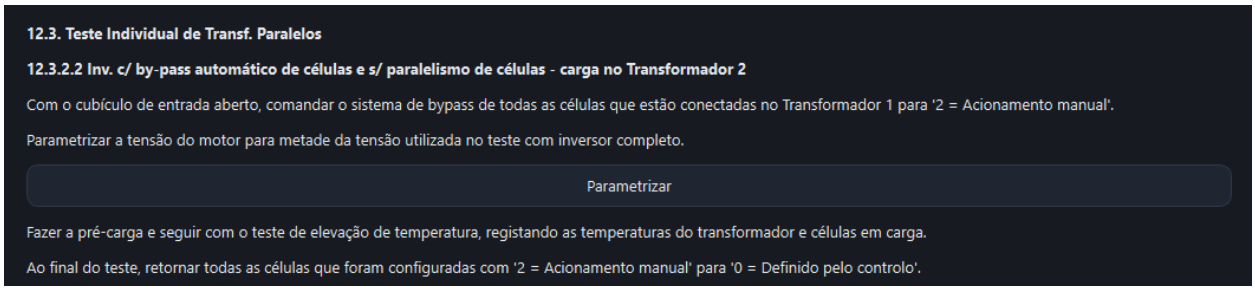
12.3.2.1. Para Executar Carga no Transformador 1

São dadas instruções conforme a especificação. A parametrização da tensão do motor (**C2.1.4/P00400**) para metade do valor utilizado no teste com o drive completo é feita através do botão “Parametrizar”.



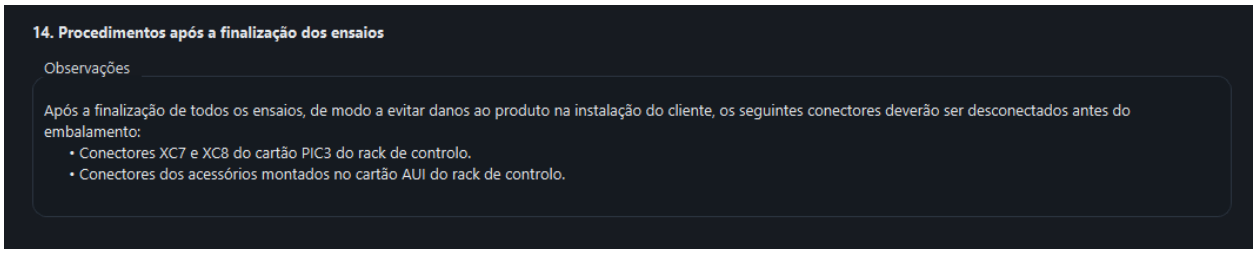
12.3.2.2. Para Executar Carga no Transformador 2

São dadas instruções conforme a especificação. A parametrização da tensão do motor (**C2.1.4/P00400**) para metade do valor utilizado no teste com o drive completo é feita através do botão “Parametrizar”.



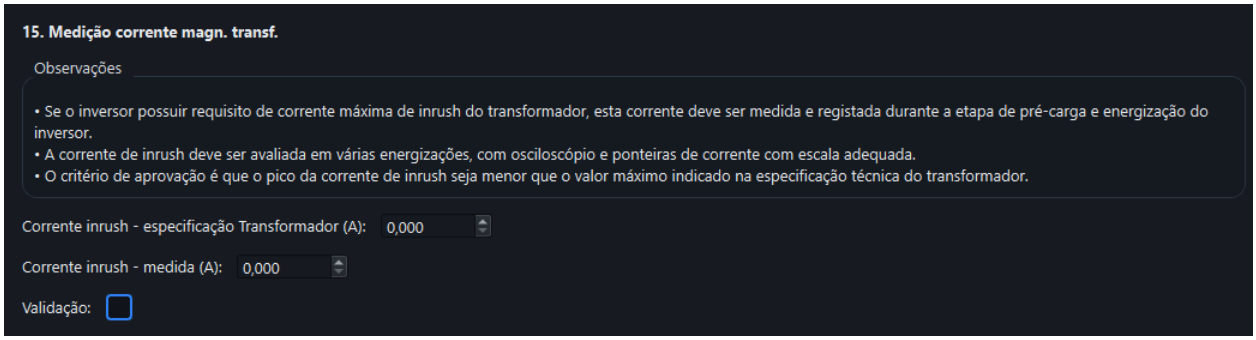
14. Procedimentos após a Finalização dos Testes

Contém apenas as instruções que constam na especificação.



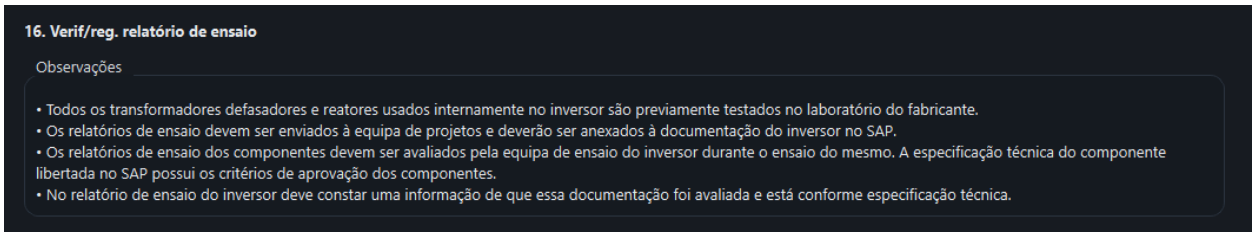
15. Medição da Corrente de Magnetização do Transformador

Contém as instruções que constam na especificação. Além disso, pede-se que seja inserida a corrente de inrush de acordo com a especificação do transformador. Além disso, pede-se que seja inserida a corrente de inrush medida. A validação, ou seja, o pico da corrente de inrush máxima ser menor que o máximo valor na especificação técnica do transformador, é verificada automaticamente.



16. Verificação e Registo dos Relatórios de Teste dos Transformadores e Reatores de Potência

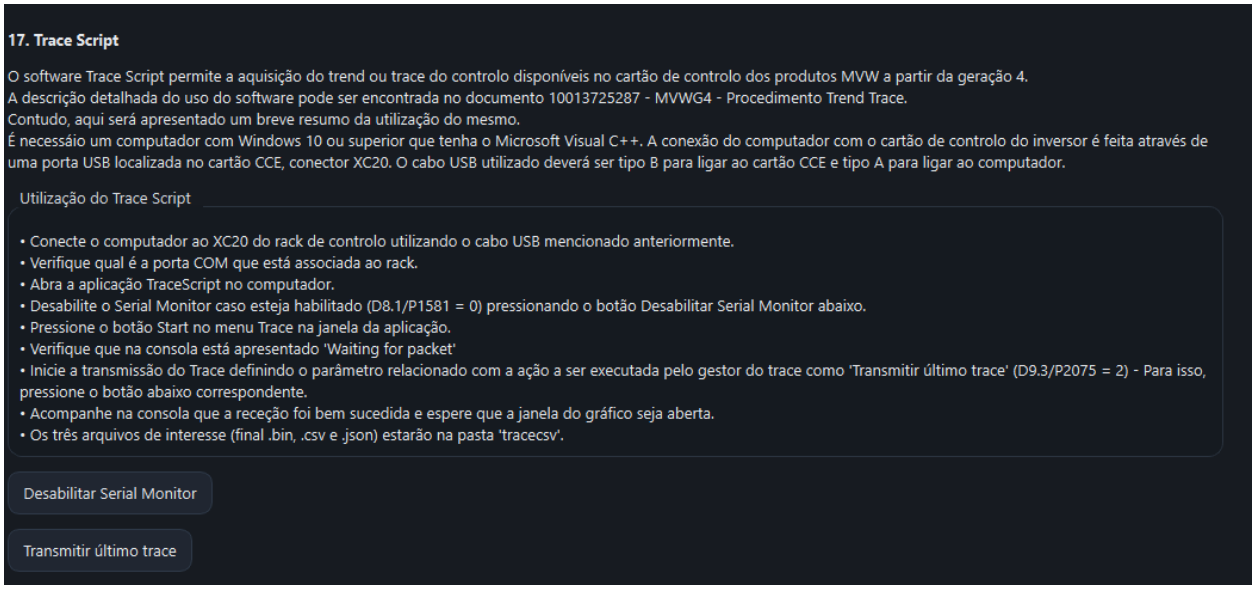
Contém apenas a informação e instruções que constam na especificação.



17. Trace Script

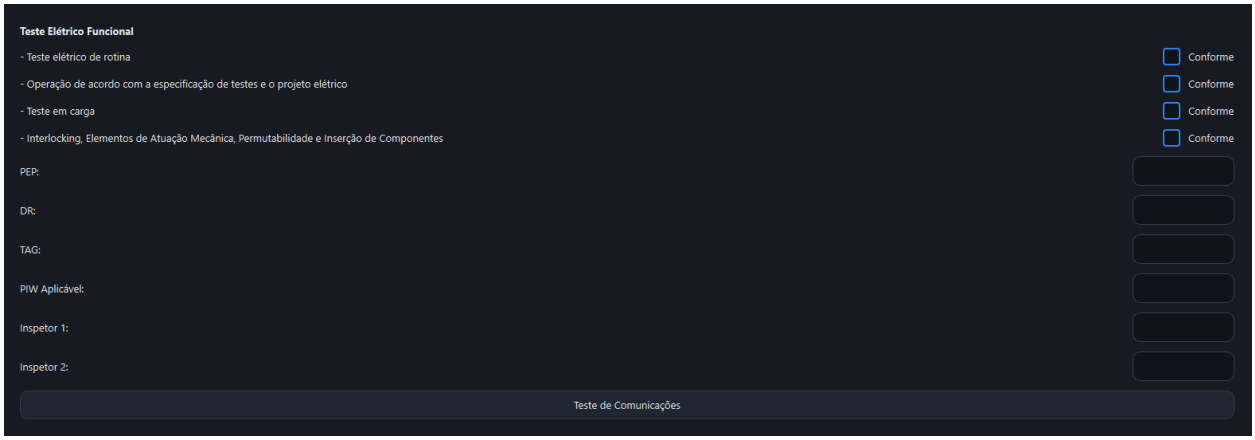
Contém as informações e instruções relativas à utilização do Trace Script.

A desabilitação do Serial Monitor, bem como a transmissão do último trace podem ser efetuadas através dos botões destinados.

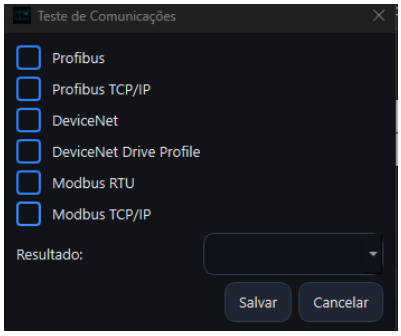


18. <u>Extra:</u> Outros Testes e Informações

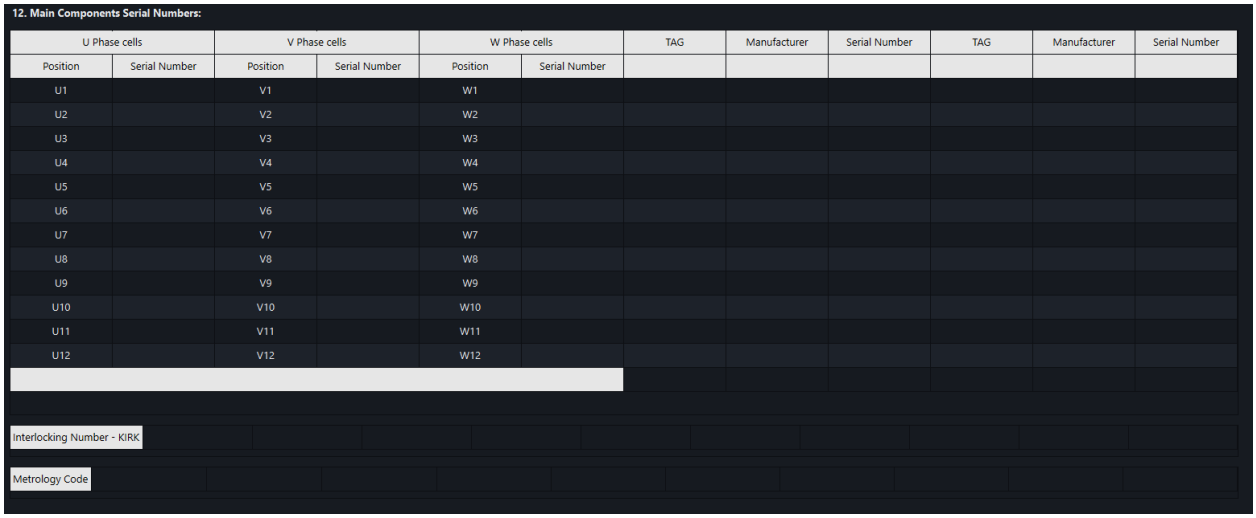
Para ajudar o preenchimento automático do relatório de ensaio, é pedido que sejam preenchidos os seguintes campos.



Ao pressionar o botão “Teste de Comunicações”, aparece uma janela em pop-up na qual se deve selecionar quais protocolos de comunicação foram testados e o resultado do teste das comunicações: **Conforme** ou **Não Conforme**.



Ainda na página referente a estas informações é pedido que sejam inseridos Serial Numbers das células de potência, assim como interlocking numbers, metrology code.

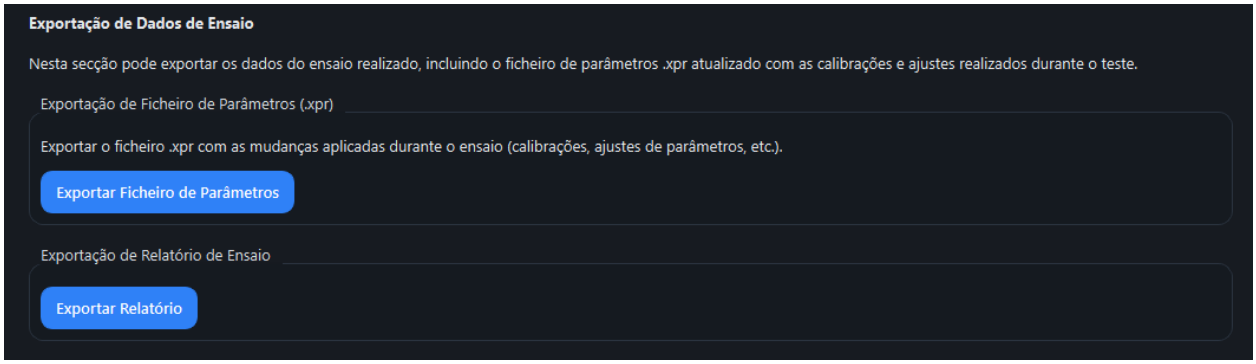


Exportação de Dados de Ensaio

Na última página do processo, é possível exportar o ficheiro de parâmetro .xpr atualizado com todas as alterações efetuadas durante o ensaio: calibrações, ajustes de parâmetros, etc.

Além disso, é possível exportar o relatório de ensaio de forma automática.

Contudo, é importante referir que o facto de o relatório ser exportado de forma automática e já preenchido não significa que sejam dispensáveis **verificações** do mesmo, **discussões** em torno de determinados valores e a sua **assinatura**.



Documentação Extra

Recomenda-se a leitura do Manual de Programação do equipamento, assim como da Especificação de Testes.