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Electrical Machines Monitoring System – an approach based on Internet of Things

Dissertação para Obtenção do Grau de Mestre em Engenharia Eletrotécnica e de Computadores

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Abstract

The fast improvement of the Internet and related technological advances, in particular with respect to the connection with physical smart objects, has opened new viewpoints and new possibilities for connection improvements that can deeply affect the general public.

This dissertation presents a system that allows the handling of all educational necessities regarding the working state of any induction machine, as it allows the students to visualize and monitor all the induction motor's working variables such as voltage, current, power, torque, frequency, as well as providing the students with real-time charts of these variables. Furthermore, all variables related to the motor's energy consumption and power used are shown, as well as the variables related to the control system and PID controller. The students can also monitor the thermal working state of the induction motor, which allows safer trials due to a more effective temperature monitor of the induction motor.

Additionally, the students can control the characteristics of the induction motor's trials, as the system allows start/stop commands of the machine through several buttons, where the user has to define the induction motor's reference speed (in Hz), or the motor speed (in rpm) and the acceleration/deceleration times (time in seconds, the machines takes from 0 to 50 Hz and from 50 Hz to 0 respectively), the user can also define the rotor's direction. A module of the DIN VDE 0530 induction motor standard was also developed, which allows the user to see the induction motor's performance in all different working duties.

Due to its versatility, this system could be a strong tool with E-learning properties. These tools include a website developed specifically for the monitoring and control of the induction motor.

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Keywords: Internet of Things, Induction Motor, DIN VDE 0530, Motor Thermal State, Continuous Duty, Short-time Duty, Intermittent Duty, E-learning

Resumo

O rápido desenvolvimento da Internet e das tecnologias associadas, nomeadamente a possibilidade de ligação a objetos físicos (inteligentes), abriu novas perspetivas e oportunidades para desenvolvimentos tecnológicos que podem ter um impacto profundo na sociedade.

Esta dissertação apresenta um sistema capaz de lidar com todas as necessidades educacionais do estado de funcionamento de qualquer máquina de indução, pois permite visualizar e monitorizar todas as variáveis de funcionamento do motor de indução, tais como tensão, corrente, potência, torque, frequência, bem como fornecer aos alunos gráficos em tempo real destas variáveis. Adicionalmente, todas as variáveis relacionadas com o consumo de energia e potência do motor são mostradas, assim como as variáveis relacionadas com o sistema de controlo e do controlador PID. Os alunos também podem monitorizar o estado de funcionamento térmico do motor de indução, permitindo ensaios do motor de indução mais seguros devido a um controle de temperatura mais eficaz do motor de indução.

Adicionalmente, os alunos podem controlar as características dos ensaios do motor de indução, pois o sistema permite comandos de start/stop do motor através de vários botões, onde o utilizador define a velocidade de referência do motor de indução (em Hz) ou a velocidade do motor (em rpm) e os tempos de aceleração/desaceleração (tempo em segundos, que o motor leva de 0 a 50 Hz e de 50 Hz a 0, respetivamente), o utilizador pode também definir o sentido de direção de rotação do rotor. Foi igualmente desenvolvido um módulo das normas dos motores de indução DIN VDE 0530, que permite ao utilizador ver o desempenho do motor de indução em todos os tipos de funcionamento.

Devido à sua versatilidade, este sistema pode ser uma ferramenta com propriedades de E-learning. Esta ferramenta inclui um site desenvolvido especificamente para a monitorização e controle do motor de indução.

Palavras-chave: Internet of Things, Motor de Indução, DIN VDE 0530, Motor Thermal State, Continuous Duty, Short-time Duty, Intermittent Duty, E-learning

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List of Acronyms

TCP/IP	Transmission Control Protocol and Internet Protocol
HTML	Hyper Text Markup Language
CSS	Cascading Style Sheets
DIN	Deutsches Institut für Normung
VDE	Verband der Elektrotechnik
CMR	Continuous Maximum Rating
D.C.	Direct Current
S1	Continuous Duty
S2	Short-time Duty
S3	Intermittent periodic Duty
S4	Intermittent periodic Duty with start
S5	Intermittent periodic Duty with start and braking
S6	Continuous Duty with intermittent periodic duty
S7	Continuous Duty with start and brake
S8	Continuous Duty with periodic speed changes
S9	Non-periodic Duty
S10	Duty with discrete constant loads

1. Introduction

This chapter is intended to provide the framework and the motivation of the work developed. The objectives of the present study are also presented and finally the structure of the document.

1.1. Motivation

The recent developments in communication technologies allows systems to no longer be monitored and controlled manually, but instead being automatically controlled by a computer or remote-controlled devices. The future age enterprises will be innovative improvements and will supplant classic systems by automatic and programmed systems, which are further developed and programmed as contrasted to existing ones. The future age enterprises will be innovative improvements and will supplant classic systems by automatic and programmed systems, which are further developed and programmed as contrasted to existing ones. This brings another phrasing of "Smart Industries" in this new time of observing and also controlling of different mechanical applications.

Here the proposed work, is an E-learning module used for monitoring and controlling an induction motor, from any wireless device such as, PC, Tablet or a Smartphone using any browser. All the possible data that describes the machine can also be presented in the wireless devices, allowing easy machine management and control for the user, such as students.

Hence, the main motivation for this work is to develop an E-learning module of an induction motor, which allows the students to see all motor's variables and respective charts at the same time with any browser, as well as enabling the machine control through the website. Furthermore, a motor temperature and possible phase input/output monitor would allow safer motor's trials. Finally, an implementation of the induction motor standard DIN VDE 0530 would allow the user to see how the motor performs in all different motor cycles.

1.2. Solution objectives

The main objective of this master thesis is to develop an E-learning tool of an induction motor, this system should allow the students to monitor remotely all the variables and respective charts related to the induction motor in real-time, as well as controlling the motor with the introduction of reference speeds and through start/stop commands. To develop this system the variable speed drive ATV 630 from Schneider was used with the Modbus protocol, and a website was developed using HTML5/CSS, allowing the students to access the induction motor working state and controlling using any browser.

This system should also allow a secure thermal monitoring of the induction motor’s working state, as well as all motor’s faults, such as Input/Output phases losses monitored using the website, thus increasing the safety of all motor’s trials.

Additionally, using appropriate instructions, it was implemented a module that allows monitoring the performance of an induction motor when working in any type of working duty, to see if an induction motor is appropriate to perform in a type of duty other than the standard (S1-Continuous Duty).

Concluding, this platform can be used for e-learning in classroom use, as it allows the students to have an easy management and control of any induction motor, showing the motor’s variables with charts in real-time thought a website. A secure thermal monitoring and secure motor’s start and stops are guaranteed.

1.3. Document structure

This dissertation is organized in 6 chapters, the organization is as follows:

In Chapter 1, the motivation, the mains goals, and contributions of the dissertation structure are presented.

Chapter 2 contains the state-of-the-art with background concepts used in the research, which come from diversified areas. These concepts are presented and discussed in this chapter.

In Chapter 3, the solution topology is presented, with an introduction to the Modbus/TCP protocol and its application to the Altivar Variable Speed Drive ATV630.

Chapter 4 describes some important characteristics of induction’s motors, such as the different types of working duties, heating/cooling curves, thermal monitoring and electrical D.C. braking.

In chapter 5, the working duties of induction motors are tested using C# code with variables introduced by the user, with the objective of testing the performance of an induction motor working in all types of duties.

At the end, the conclusions and the future work is presented.

2. State-of-the-Art

In this chapter, a brief description of the concept Internet of things (IoT) is presented, with some IoT devices examples and practical applications.

2.1. Internet of Things

The Internet of Things (IoT) has become a common paradigm of modern Information and Communication Technologies (ICT) [1]. The development of personal computers, World Wide Web (WWW) and recently mobile phones changed the way that society works and communicates. The Internet of Things (IoT) can reform businesses and everyday life because of the huge extent of applicability. The potential application zones incorporate intelligent hardware, medical field, businesses, car, smart cities and everything from easy to complex that can be associated with the web, giving new openness and approaches to utilize. Figure 2-1 demonstrates a portion of these segments.

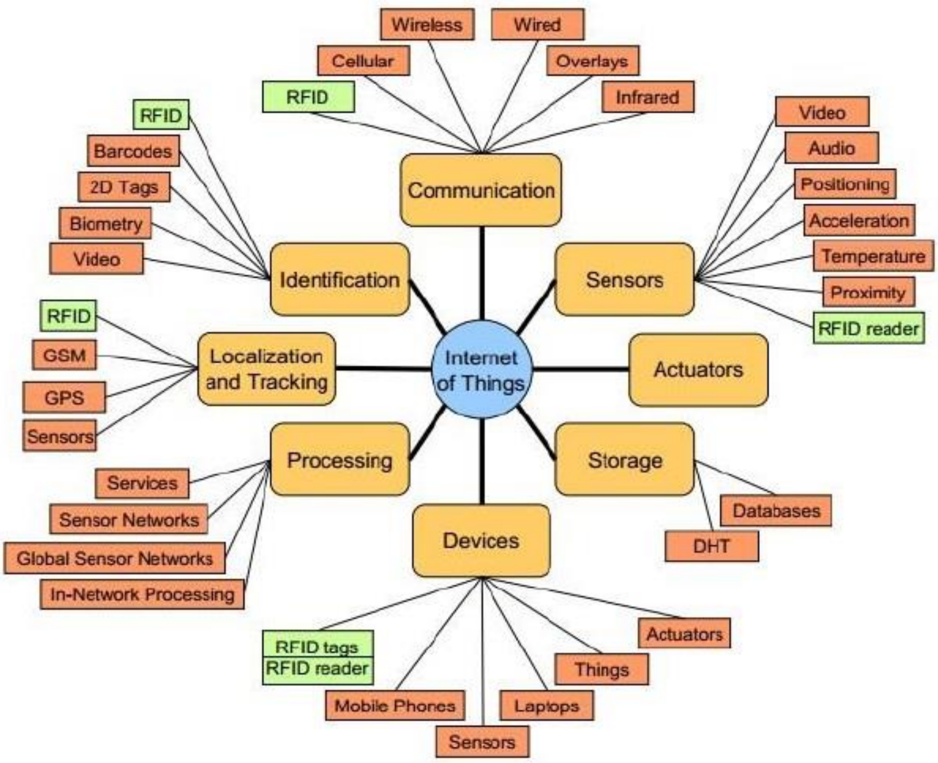


Figure 2-1 Possible segments in IoT Systems [3].

The Internet of Things (IoT) can be defined [2] as an idea and a worldview that thinks about the presence of things/objects/devices, which through remote and wired associations and unique addressing schemes, can collaborate with one another and coordinate with different things/objects/devices to make new applications/administrations and achieve shared objectives. The Internet of Things (IoT) is likewise considered by a few writers as a characteristic development of the Internet [3], being the following stage of an innovation that somehow or another is as of now stagnated and in need to react to new needs, this advancement spoken to by IoT is required and occurs normally.

There are several possible definitions for the concept of The Internet of Things (IoT), some examples are:

“The Internet of Things (IoT) is a computing concept that describes a future where every day physical objects will be connected to the internet and will be able to identify themselves to other devices. The term is closely identified with RFID as the method of communication, although it could also include other sensor technologies, wireless technologies, QR codes, etc” [4] .

“The basic idea of the Internet of Things (IoT) is that virtually every physical thing in this world can also become a computer that is connected to the internet (ITU, 2005). To be more accurate, things do not turn into computers, but they can feature tiny computers. When they do so, they are often called smart things, because they can act smarter than things that have not been tagged” [5].

2.1.1. The “Things” Concept

The definition of the concept “Things” is one of the most important key elements in the Internet of Things (IoT), so this clarification is necessary. In the Internet of Things (IoT), the concept “Things” will be used in a daily basis, from smaller systems to larger integrated systems.

There are several definitions for the concept “Things” in the Internet of Things (IoT), one example is:

“Regarding the "Internet of Things" a "Thing" could be characterized as a genuine/physical or advanced/virtual element that exists and moves in existence and is fit for being recognized. Things are normally distinguished either by assigned identification numbers, names, or potentially location addresses” [6].

The concept “Object” can be also considered as a synonymous of “Things”, can be defined as:

“Objects are linked through both wired and wireless network to the Internet. When objects in the IoT can sense the environment, interpret the data, communicate with each other, they become tools for understanding complexity and for responding to evens and irregularities swiftly” [7].

2.1.2. Industrial Internet

As indicated by the idea of the Internet of Things (IoT), the thought of mechanical web can be clarified as a specific case which by associating individuals, information and machines (especially electric machines) adds to the optimization of modern procedures. This can incorporate the remote control and the executives of a few kinds the activity of electric machines.

The Industrial Internet can be supported by several features suggested by various researches [8]:

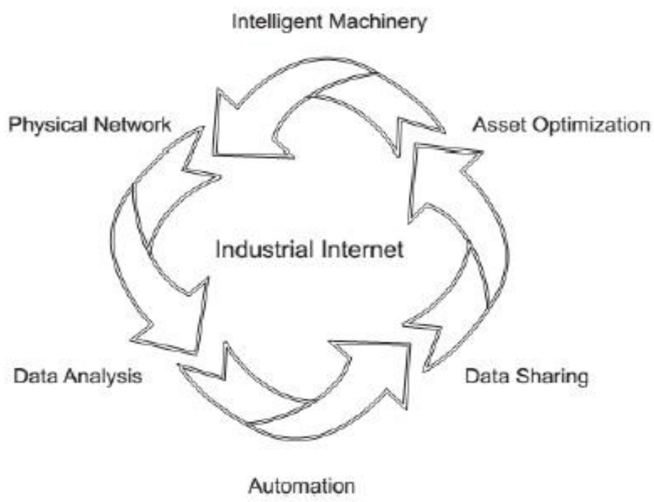


Figure 2-2 Several features supported by the Industrial Internet [8].

The use of the Industrial Internet allows [9]:

“The Industrial Internet is enabling this change to me more productive by making the physical world of industry more intelligent. By connecting process is gained. These machines become part of an intelligent network that can automate information and action to optimize plant floor performance”

The increase level of intelligence in industrial systems establishes a connection between industrial machinery and the computational world,

“The crucial feature of the Industrial Internet is that it installs intelligence above the level of individual machines – enabling remote control, optimization at the level of the entire system, and sophisticated machine-learning algorithms that can work extremely accurately because they take into account vast quantities of data generated by large systems of machines as well as the external context of every individual machine” [10].

The Industrial Internet is permitting the optimization of modern procedures thought availability and with an expansion in knowledge empowering the self-sufficiency all things considered and giving the self-sufficiency of all apparatus associated with the system, expanding profitability and lessening costs (expanding effectiveness).

2.2. Middleware for IoT

The implementation of The Internet of Things (IoT) into the real world is only possible with the integration of several technologies, to manage these technologies a division of the concept of the IoT is proposed through a technical architecture perspective [12], dividing it into a physical layer, a middleware layer and an application layer, according to the following image:

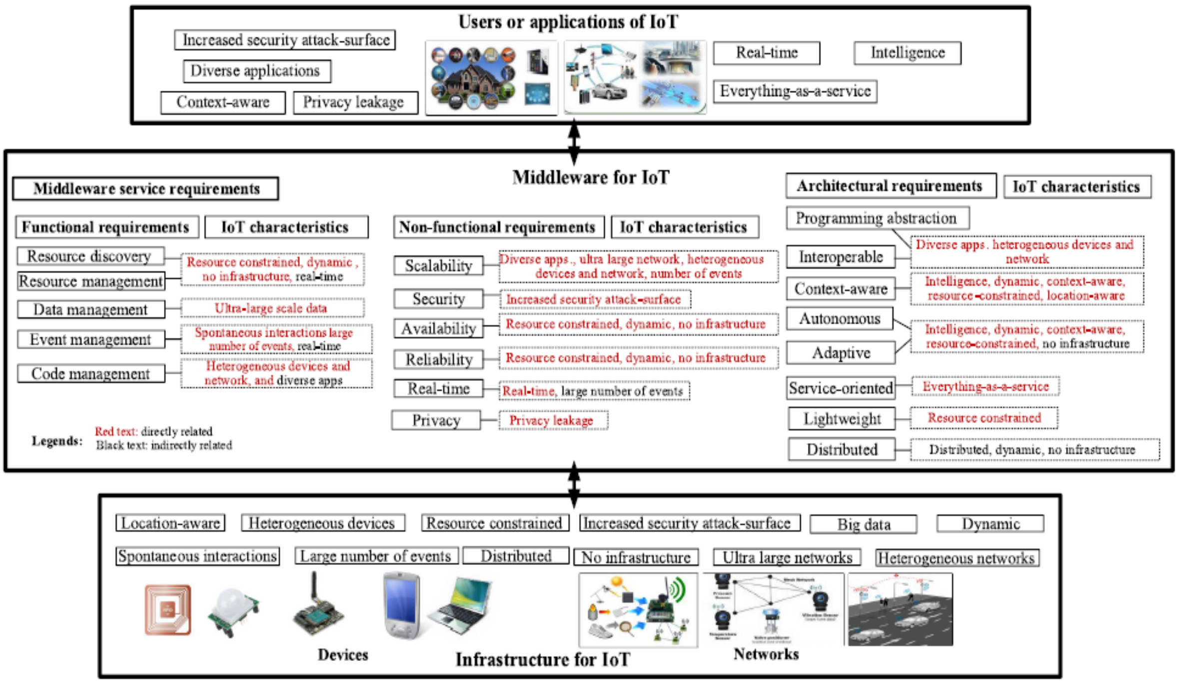


Figure 2-3 IoT Architecture proposed [12].

The three different layers proposed in this architecture are:

- **Physical/Infrastructure Layer (bottom)**: is the basic network hardware, such as sensors, actuators or computers that provide raw data and transmit to the application layer passing through the middleware layer.
- **Middleware Layer (middle):** is the software located between the technological and the application level, abstracting the complexities of the system or hardware, so enabling the developer to focus all his work into the development of the interfaces/services in the application layer.

- **Application Layer (top):** are all the interfaces and services responsible for displaying all received information from the middleware, then the user is capable of handling all user interaction with the network.

For the design of IoT middleware solutions is necessary to develop management services considering real time, availability and scalability concepts. There are several approaches to design and develop a middleware, but the most important are: embedded and cloud middleware.

2.2.1. Device-Embedded Middleware

Embedded system is an engineering artefact involving computation that is subject to physical constraints (reaction and execution constraints) arising through interactions of computational process with the physical world. The key to embedded systems design is to obtain desired functionality under both kinds of constraints. Also embedded system is characterized by running in loop specific and single functioned application; optimization of energy, code size, execution time, weight and dimensions and cost; designed to meet real time constraints; and for the interaction with external world through sensors and actuators to increase the reactivity of the system [13].

This type of embedded system (embedded middleware) allows to control equipment's such as automobiles, home appliances, communication, control and office machines due to their small size and low battery consumption. This type of component is particularity important in scenarios in which invisible embedded systems need to continuously interact with human users, in order to provide continuous sensed information and to react to service requests from the users.

Being the user the center of center of the requirement, this implies many challenges to embedded middleware and service technologies for embedded systems designed for simple, static, and non-reconfigurable processes [14], in terms of:

- **Dynamicity**: since devices are no more static and distributed system need to continuously adapt on the basis of the user context, habits etc., by adding/removing/composing on the fly basic elements.
- **Scalability:** in order to support the continuously growth of sensors/devices/appliances that the system need to support.
- **Dependability**: thrust on the system itself in order to users be dependent of it.
- **Security and Privacy**: the user is the main focus of the services, so they need to feel that their security and privacy is assured by the system.

Reading several sensors at the same time and anytime allows us to create sensor networks, where each sensor can behave as an embedded system, distributed network or one specific device being the network's coordinator (centralized network).

2.3. IoT Application Examples

IoT is capable of supporting a scope of applications almost infinite, we can find almost any type of application at present days or in the future. For example, IoT can be used to manage the remote operation of electric machines. In an industrial environment, the IoT module can be used for the following operations:

2.3.1. Industrial Machineries and Processes

Monitoring systems malfunctions or making processes faster and mobile are IoT application's examples in industry. For instance, overheating and errors could be avoided and unraveled. Some of these improvements are shown in the following list:

- **System Health/Condition Monitoring -** Electric motors have been reinvented by adding wireless sensors on devices to ease the acquisition of an electric motor's vibration data. The smart communication network in these systems is more helpful and it is very difficult to establish in the larger plants. If an electric motor overheats in the plant, that motor sensor reads the real-time data and sends the information to the application through the cloud. Manufacturers can use this data to send warnings or alerts to the maintenance team to regulate the voltage and that will shorten maintenance intervals.
- **Save Money and Time -** Preventing unexpected failures are becoming more important in industrial environments. Vibration is one of the most common harmful condition for an electric motor, it results in an electrical imbalance and effects to reduce operational life, bearing failures and mechanical failures. The Monitoring system can give early warnings of Electric motor vibration problems. Vibration monitoring saves money by analyzing the vibration data to prevent the motor failures. Condition monitoring saves time from unplanned production outages and the unnecessary stress of carrying out urgent repairs. The Monitoring data analysis allows for simple and clear reporting. This minimizes the time while interpreting the data.
- **Energy Savings -** Every Electrical motor is an energy conversion device, it converts electrical energy into rotational energy and some heat. When electric motor overloads, energy consumption

is increased, and electric motor speed will be decreased. Monitoring system allows you to find the electric motors which are consuming the most energy in your plant.

- **Electric Motor Operating Efficiency -** An electric motor's efficiency negatively impacts the heat that is generated by the motor. One solution is to reduce the motor's weight and size. Sometimes electrical motors may be oversized or undersized due to changes to a connected machine. Oversized motors have a higher cost initially and also are costlier to repair. Undersized motors have poor performance and suffer from higher losses compared to properly sized electric motors. It forces the motors to fail much sooner. Improperly sized electric motors are less efficient and costlier to operate.

Monitoring the power usage of electric motors reduce a plant's overall operational cost by providing sufficient information and allowing qualified technicians to repair or replace the proper electric motors. Technicians must have a complete picture of the data to analyze an electric motor's health. That main data includes, power condition, motor condition, performance, load assessment and operating efficiency.

2.4. Related Work

In 2017, there was a paper related with the application of an IoT module to an induction motor, proposed by [23]. The system consisted of a Wi-Fi enabled microcontroller (in this case, a Raspberry Pi-3), temperature sensor, vibration sensor, moisture sensor, infra-red sensor, current and voltage measurement circuits and an AC induction motor. The monitoring and controlling of the induction motor were developed thought a webpage or android application. The block diagram of this work is presented as:

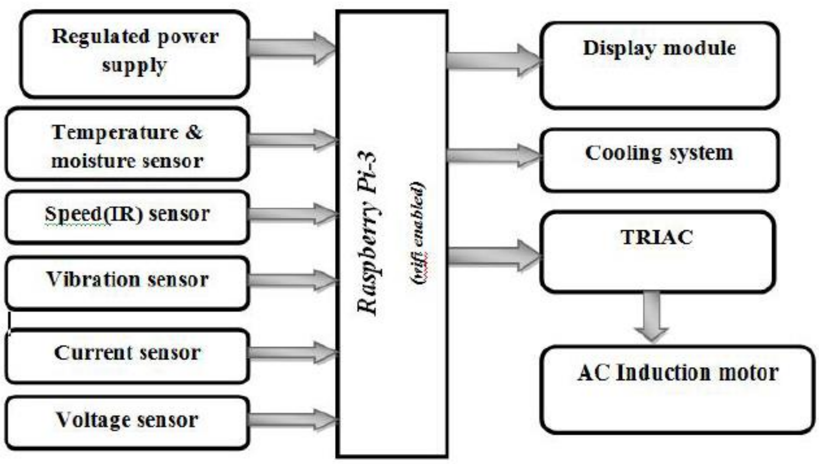


Figure 2-4 - Proposed system block diagram [23].

This system is capable of detecting Electrical, Mechanical or Environmental-related faults by the readings from the sensors, the motor control is implemented using electronics (TRIAC), and the processing unit consists of a Raspberry Pi-3, which will analyse and display the parameters, the processing unit will also communicate with the gateway module to send the motor's information to the cloud database for remote monitoring.

Although this system's complexity is considerable, as it uses electronics for motor control and sensors for variable reading, the results yielded seem to have low resolution, hence describing poorly the motor's working variables and the motor behaviour. The programmed interface has also few user control possibilities, and the working variables read from the sensors don't feature torque or any mechanical variables.

In 2017, a paper with the title Monitoring and Control of Three Phase Induction Motor using IoT base concept was published by [24]. In this system, the Variable Frequency Drive controls the speed of the machine to maintain its constant speed characteristics. This operation is monitored and controlled by the Programmable Logic Controller (PLC) and Supervisory Control and Data Acquisition (SCADA), which are two ways to deal with control a Variable Frequency Drive (VFD), whose yield is encouraged to an enlistment engine. The important guidelines are modified as stepping stool rationale programming to the PLC through the mode of a (PC). The SCADA programming introduced in the PC thusly allows the human administrator to control the whole task far from the plant and just by utilizing the virtual data sources assigned on his PC screen. The user interface provided by this project is:

Figure 2-5 - User interface provided for the IoT of an induction motor [24].

The SCADA animation of the system control and monitoring allows only the control of the motor's frequency, speed, voltage and current. The motor's torque behaviour is not possible to observe as well as the thermal monitoring. Similarly, there is no description of the variable's behaviour using charts, hence allowing only to see the motor's variables in a specified time moment.

In 2017, a paper was published by [25] entitled IoT-Based Wireless Induction Motor monitoring. In this paper, a processing plant containing induction motors was observed with remote TCP/IP protocol to distinguish and anticipate deviations from ordinary working parameters previously int the event of motor failure. Hence, the creation procedure isn't hindered, and the required support or supplanting can be performed with the slightest conceivable disturbance. In this investigation, the engine cycle, the current drawn by the engine and the engine voltage were perused by the Hall-impact current sensor and the required power utilization was determined. With this point, the planned design read the acknowledged parameters of the engine and announced them to the focal administration programming. The focal administration programming working continuously was then ready to gather these parameters and shape predictive maintenance models. The overall structure of the system hardware is described in the following image:

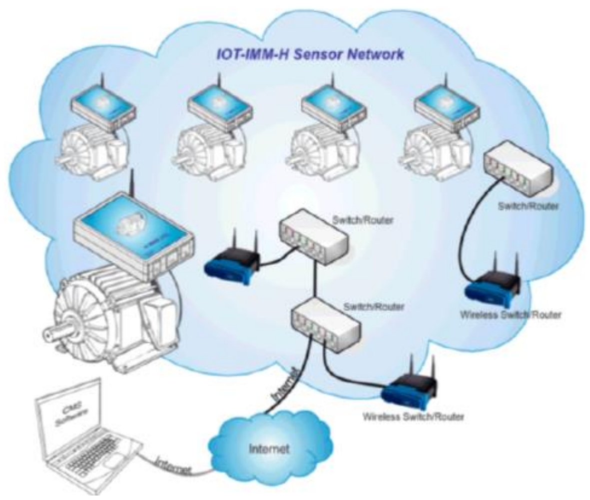


Figure 2-6 - Proposed IoT module for an induction motor monitoring [25].

The main focus of this system is to detect any motor failures and predict any errors, allowing fast maintenance or replacement without disruption. Although the system complexity is great (uses hall-effect sensors to measure voltage), the main purpose of this system is not to provide the user with motor monitoring (no real time charts are available) but to inform the user about motor malfunctions. Hence this system is not capable of reading all the motor's variables (such as the motor's torque) or to control remotely the induction motor.

In the year 2017 a conference paper entitled IoT-Based Traction Motor Drive Condition Monitoring in Electric Vehicles was published by [26]. This paper presents an implementation of a Wireless Internet of Things (IoT) framework connected to the footing engine drive condition monitoring in electric vehicles (EVs). The structure and testing of the model utilizing an ESP8266 microcontroller module to get motor's vibration, current and temperature data for the motor condition monitoring application is exhibited. This IoT framework has been structured and created from the beginning utilizing financially off-the-rack parts and open-source programming stage for quick, solid information acquisitions, low power utilization, and information accumulate by the IoT framework get answered to the cloud server continuously. The test results uncover that the IoT framework is equipped for catching and detailing imperative engine's parameters to cloud server and a programmed notice is sent to administrators when engine's anomaly is identified progressively. On account of IoT innovation, the preventive upkeep of footing engine can be successfully and remotely arranged with rich information gathering and examination. With cutting edge control utilization decrease procedures, a sensor hub expends very low measure of battery control at which perfect for portable applications.

Figure 2-7 Wireless Internet of Thing traction motor drive block diagram (left) and Node-Red cloud platform (right) [26].

The proposed framework got information from sensor hubs over the web at that point gathered, oversaw and investigated information into profiles in Node-red cloud database. These profiles are then contrasted and previous ordinary task profile. Any engine's variation from the norm identification is then hailed then sent to administrator warning module which has an extraordinary adaptability because of various network modules accessible in Node-red stage. These modules give numerous standard warning devices, for example, email, SMS, GPRS.

The following table describes all motor's variables and functionalities available in each work developed, allowing a comparison between each work characteristic's and functionalities:

Table 2-1 Comparison between all variables and functionalities available in each work developed.

IoT Module for an induction motor developed	Induction Motor's Variables Monitoring	Functionalities available
V.S.D Rekha, P.V.P Siddhartha institute of Technology, Dr. K.Srinivasa Ravi, KL University. Induction Motor Condition Monitoring and Controlling Based on IoT [23].	Motor's working variables (voltage, current, rotor, speed), vibration, moisture, temperature.	Motor control using electronics (TRIAC's), Android application for remote control monitoring of an induction motor.
M. Ananda Velani, M. Aravind Raj, K. Kannadasan, D.Kirubakaran. Monitoring and Control of Three Phase Induction Motor Using IoT Based Concept [24].	Mains, Motor's working variables (voltage, current, frequency, power, motor speed, rotor speed).	Start/Stop Motor with a reference frequency/speed using VFD with SCADA.
Mehmet Şen and Basri Kul. IoT-Based Wireless Induction Motor Monitoring [25].	Motor's working variables (voltage, current, rotor, speed), AC energy measurement, true power (P), measured power (W), apparent power (S), measured voltage (VA) and reactive power (Q) with complex and real values.	Motor failure was distinguished by utilizing diverse models to investigate the stator current. These included FFT, Hilbert-change, ceaseless wavelet changes (CWT), discrete wavelet transform (DWT), the Wigner-Ville distribution (WVD) and instantaneous frequency (IF).
Jakkrit Kunthong and Mongkol Konghirun. IoT-Based Traction Motor Drive Condition Monitoring in Electric Vehicles [26].	Using an ESP8266 microcontroller module to get motor's vibration, current and temperature data.	This IoT framework allows quick and solid information acquisitions, low power utilization, and information gathered by the IoT framework to get answered to the cloud server continuously.
Work Developed.	Mains, Motor's working variables (voltage, current, frequency, power, torque, motor speed, rotor speed), Energy/Thermal (all related powers), Control Circuit, PID Controller, Thermal variables.	Start/Stop Motor with a reference frequency/speed, Input/Output Phase Lose Assign, change of motor direction, real time charts, VDE DIN 0530, thermal monitoring.

2.5. Modbus Protocol

Modbus is a communication protocol created by Modicon (now Schneider Automation) and was at first for use with their own PLC (Programmable Logic Controllers). Its originators keep up the convention detail, and since its creation it has turned into the standard communication protocol between devices in a modern domain.

The convention characterizes a message structure and organize and decides how a slave will perceive messages sent to it by the master. Institutionalization of these components implies that Modbus devices from various makes can be interconnected, without the requirement for particular programming drivers.

2.5.1. Modbus Communication

Modbus controllers communicate utilizing a master slave system, in which just a single device (the master) can start a correspondence arrangement. The sequence starts with the master issuing a demand or order on the transport (a 'query'), which is received by the slaves. The slaves react by making the correspondent answer action, providing asked for information to the master or informing the master that the required activity couldn't be completed. The master can address singular slaves or can transmit a message to be received by all slaves through a communicate message. The reaction affirms that the message was received, comprehended and acted, or it advises the master that activity asked for has not been effectively finished.

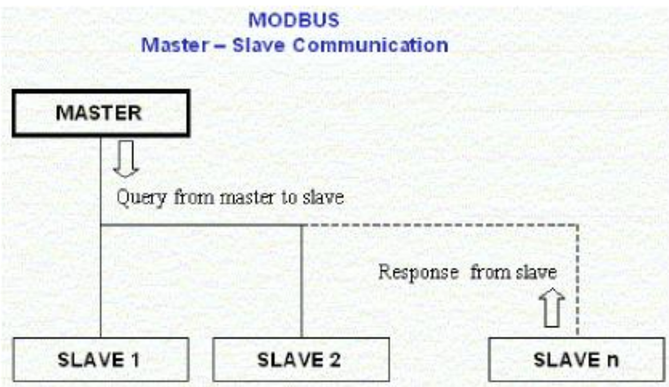


Figure 2-8 Communication topology between the master and slaves in a network using Modbus protocol [17].

2.5.2. Modbus TCP/IP

Modbus TCP/IP (or Modbus-TCP) is essentially the Modbus RTU convention with a TCP interface that runs on Ethernet. The Modbus informing structure is the application convention that characterizes the data for arranging and translating the information free of the information transmission medium. TCP/IP alludes to the Transmission Control Protocol and Internet Protocol, which gives the transmission medium to Modbus TCP/IP informing. Essentially expressed, TCP/IP enables squares of twofold information to be traded between PCs. It is additionally an overall standard that fills in as the establishment for the World Wide Web. The essential capacity of TCP is to guarantee that all parcels of information are gotten accurately, while IP ensures that messages are effectively tended to and steered. Note that the TCP/IP blend is only a vehicle convention and does not characterize what the information means or how the information is to be deciphered (this is the activity of the application convention, Modbus for this situation). So in synopsis, Modbus TCP/IP utilizes TCP/IP and Ethernet to convey the information of the Modbus message structure between perfect gadgets. That is, Modbus TCP/IP joins a physical system (Ethernet), with a systems administration standard (TCP/IP), and a standard strategy for speaking to information (Modbus as the application convention). Basically, the Modbus TCP/IP message is just a Modbus correspondence typified in an Ethernet TCP/IP wrapper. Practically speaking, Modbus TCP installs a standard Modbus information outline into a TCP outline, without the Modbus checksum, as appeared in the following figure.

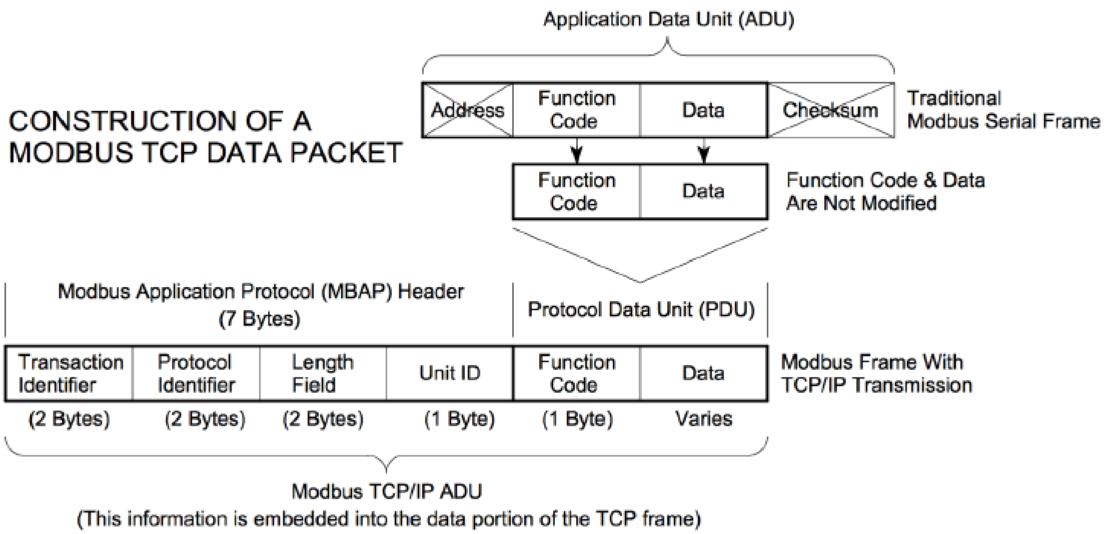


Figure 2-9 Data Message using Modbus TCP/IP [18].

The Modbus directions and client information are themselves typified into the information holder of a TCP/IP message without being adjusted in any capacity. Nonetheless, the Modbus error checking field (checksum) isn't utilized, as the standard Ethernet TCP/IP interface layer checksum strategies are rather used to insurance information trustworthiness. Further, the Modbus outline address field is replaced by the unit identifier in Modbus TCP/IP and turns out to be a piece of the Modbus Application Protocol (MBAP) header.

From Figure 2-9, we see that the capacity code and information fields are invested in their unique frame. Accordingly, a Modbus TCP/IP Application Data Unit (ADU) appears as a 7-byte header (exchange identifier + convention identifier + length field + unit identifier), and the convention information unit (work code + information). The MBAP header is 7 bytes in length and incorporates the accompanying fields: • Transaction/summon Identifier (2 Bytes): This distinguishing proof field is utilized for exchange blending when various messages are sent along a similar TCP association by a customer without sitting tight for an earlier reaction. • Protocol Identifier (2 bytes): This field is dependably 0 for Modbus administrations and different qualities are held for future expansions. • Length (2 bytes): This field is a byte tally of the rest of the fields and incorporates the unit identifier byte, work code byte, and the information fields. • Unit Identifier (1 byte): This field is utilized to recognize a remote server situated on a non-TCP/IP arrange (for sequential spanning). In a regular Modbus TCP/IP server application, the unit ID is set to 00 or FF, overlooked by the server, and essentially resounded back in the reaction. The entire Modbus TCP/IP Application Data Unit is inserted into the information field of a standard TCP casing and sent by means of TCP to surely understood framework port 502, which is explicitly held for Modbus applications. Modbus TCP/IP customers and servers tune in and get Modbus information by means of port 502. We can see that the activity of Modbus over Ethernet is about straightforward to the Modbus enroll/order structure. In this way, in the event that you are now comfortable with the activity of conventional Modbus, you are now extremely with the task of Modbus TCP/IP. IEEE 802.3 Ethernet is a long-standing office organizing convention that has increased widespread overall acknowledgment. It is additionally an open standard that is bolstered by numerous producers and its foundation is broadly accessible and to a great extent introduced. Thus, its TCP/IP suite of conventions is utilized worldwide and even fills in as the establishment for access to the World Wide Web. The same number of gadgets as of now bolster Ethernet, it is just normal to increase it for use in mechanical applications. Similarly likewise with Ethernet, Modbus is unreservedly accessible, open to anybody, and broadly bolstered by numerous makers of mechanical hardware. It is likewise straightforward and a characteristic possibility for use in building other mechanical correspondence norms. With such a great amount in like manner, the marriage of the Modbus application convention with customary IEEE 802.3 Ethernet transmission shapes an incredible modern correspondence standard in Modbus TCP/IP. Furthermore, on the grounds that Modbus TCP/IP has the equivalent physical and information connect layers of conventional IEEE 802.3 Ethernet and utilizations a similar TCP/IP suite of conventions, it remains completely good with the as of now introduced Ethernet framework of links, connectors, organize interface cards, centers, and switches.

3. Conceptual Solution

In this chapter a general conceptual solution for the E-learning platform is presented, including the problem description that lead to the development of the system, and the system´s requirements that should comply to achieve all the E-leaning tools, followed by the system’s architecture planned. All duties of induction motors in DIN VDE 0530 are described in detail, cyclic durations factors (CDF), duty cycle duration, cycles per hours, types of starts/stops, types of loads.

3.1. Problem description

The development of a system to serve as an E-learning platform for an induction motor, surpassing different limitations that the current solutions have. This system will allow students an easier motor management and monitoring compared to what the current solutions offer, for example, allowing an easier motor control defining reference variables (speed frequency and motor speed) with related start and stop commands, with respective guaranteed soft starts and stops in different configurations. Using a webpage for the E-platform allows students to monitor various motor´s variables at the same time (contrary to current solutions, which are only able to show a very limited number of variables) as well as their real time charts, thus describing the motor behavior in a real time concept.

Using the E-platform will provide an indirect connection between any browser and the induction motor, hence allowing the students to control and monitor the motor in real time, improving the previous solutions, forcing soft starts and stops allowing their configuration and a motor thermal monitoring. For the description of the motor´s variables behavior, the option to save all variables in an excel file should also be provided, allowing the students to analyze the motor’s functioning with a small-time span. As an internet browser is an easy to control and manage tool, this will develop an efficient E-learning tool.

3.2. General System Specifications

The system should allow the user, through a website, to monitor and control the working state of an induction motor. The induction motor should be connected to a variable speed drive ATV 630 from Schneider, so that all the data obtained can be stored in the IIS server through Ethernet. Once the data is obtained and stored in the server, the user can access the real time data from any browser.

As the system is intended to be used as an E-learning tool, some safety requirements should be considered, such as input phase lose, this error is shown to the user if one or more supply mains phases (phases from the mains to the speed drive) are missing, hence leading to a decrease in the induction motor performance. The output phase loss should also be considered, warning the user when one or more supply mains phases (phases from the speed drive to the induction motor) are missing, when this error is triggered the motor will freewheel stop (motor stops by his own inertia). Finally, considering situations when the motor operates with conditions that affect the machine´s life expectancy or at over-load situations, a thermal monitoring through a variable is displayed to the user, this variable measures simultaneously the instantaneous power and the winding heating, due to prolonged machine operating time, thus allowing the students to operate the machine only in guaranteed safety conditions. The fundamental feature of this E-learning tool is the control of the induction motor through simple buttons on a website, this allows the students to start and stop the motor with the introduction of the motor´s reference speed (in Hz or rpm) and the acceleration/deceleration times (time in seconds, the machine takes from 0/50 Hz to 50/Hz). The main requirement of this system is to monitor in real-time the machine´s working variables such as voltage, current, power, torque, motor thermal state etc. and the respective real-time charts, hence allowing the students to monitor the motor´s variables behavior. The students can also save all the variable´s values from all motor´s trials in an excel file, thus allowing subsequently motor study with different loads and speeds with all the variables values saved with a low span time. Additionally, different variables related to the machine´s working state such as the control circuit, PID controller and all motor´s power-related variables are displayed.

The DIN VDE 0530 is also a system specification, which allows the user to check the working behavior of an induction motor when operating in all the different working cycles, this implies different motor´s starts, different types of motor stopping (stop by ramp, electrical braking), different loads and speeds, hence allowing the user to predict how an induction motor will behave when different working conditions are applied.

3.3. System Architecture

In this implementation, the system´s communication can be described as illustrated in Figure 3-1.

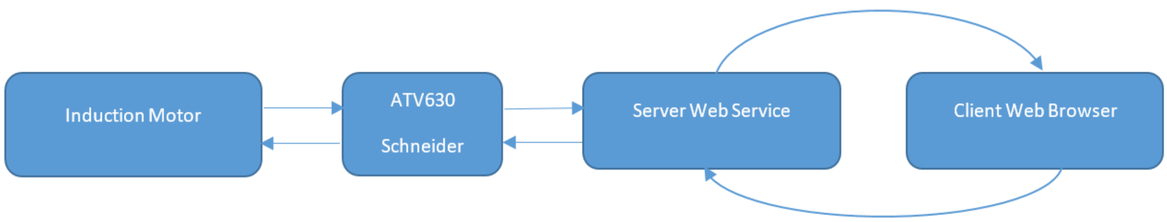


Figure 3-1 Web service implementation between the motor and the client.

As described in Figure, the induction motor receives commands directly from the variable speed drive ATV630 Schneider, which in turn is controlled by the user via remote panel. The remote-control panel has all the motor´s variables and orders displayed by the web browser; the client can connect to the service using URL. The respective orders are received by the server (IIS server) that will control the motor thought the speed drive according to the user commands.

The Web Service is designed with layers of specific protocols that provide the abstraction and all communication patterns necessary to make the services available and standard for all users. To offer this service through the internet the user is required to have:

- The server physical location.
- Web Service.
- The Port Number.
- Inputs introduced by the user related to the motor control.

As described in Figure 3-2, this Web service is accessible to any user, with minimal software/hardware requirements on the user side. After configuring the web server, the form is coded allowing it to be accessed through a web page displayed in any Internet browser. This codding is automatically generated, as well as all the layers and protocols required.

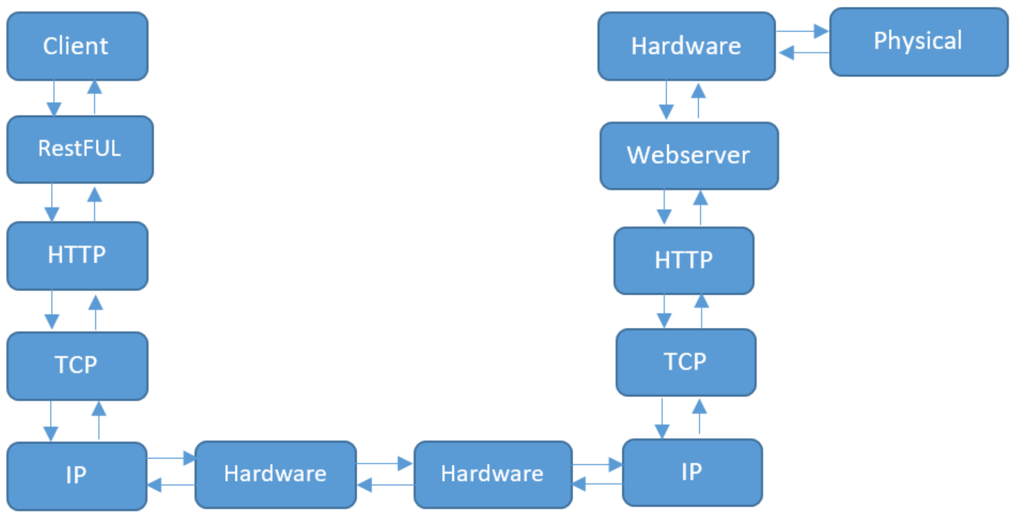


Figure 3-2 System Web Service Described.

The system architecture proposed for the development of an E-learning module for an induction motor and all operations and data changed between all modules are presented in Figure 3-3.

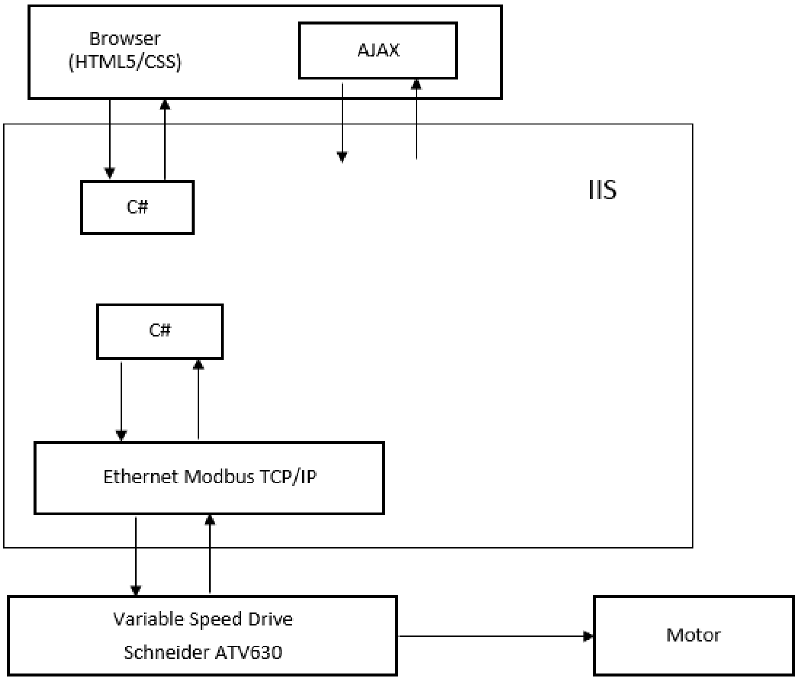


Figure 3-3 System Architecture for an IoT module of an induction motor.

The process begins with the data acquisition from the Variable Speed Drive Schneider ATV630 which is directly connected to the induction motor, this data is transferred to the IIS server through Ethernet, which in this case serves as an E-learning module as being the module responsible for the communication between the physical layer and the application layer. The data is received and stored by the IIS server using a synchronous Modbus protocol TCP/IP solution (programmed in C#), where values were retrieved with a timer.

In the application layer the data is requested by the user interface module, which is developed in the IIS server using web application languages (HTML5/CSS).

For variable real-time monitoring on the client-side, the AJAX library module was used, allowing the web application to send and retrieve data from the IIS server asynchronously with only changing partial html code (using update panels). All the induction motor variables subject to real time monitoring were showed in the client-side using this module, with different timers used as triggers (short-time span timer as trigger for the motor’s working variables (voltage, current, power, torque etc.) and long-time span timer as trigger for the other variables).

3.4. DIN VDE 0530 – Duties of Induction Motors

S_1, is the continuous maximum rating (**CMR**) and is defined as the motor rating. A hoist, a crane or a lift, as examples, are operations that don't need the motor at a constant maximum load. Most of the times the motor has to operate with varying load, on a sequence of similar operations, like start/stopping, speed control, braking and reversal. We do not need to use a CMR motor with a rating equal to the maximum load because due to idle periods, we would have an over capacity on the motor and installation. This would mean a higher cost system that can be avoided. To avoid this undesirable situation, the IEC 60034-1 have ten types of duty cycles that can be taken in consideration. When dimensioning the system, this allows a more economical sized motor to be chosen and, at the same time, to meet the variable load demand safely. The motor can than run over loaded but only for shorter periods, allowing it to run with a temperature that will not exceed the maximum permitted. They will dissipate the excess heat when in idle running or de-energized periods and reach a thermal equilibrium at the end of the load cycle.

3.4.1. Continuous Duty (CMR) (S_1)

In this duty the motor operates with constant loading of unlimited duration during which the thermal steady state of the motor is reached, possible motor duty cycle applications are blowers, compressors, pumps and fans.

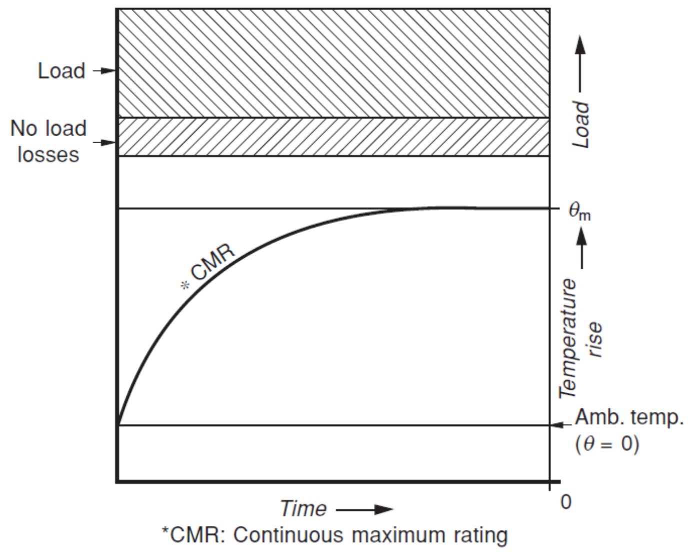
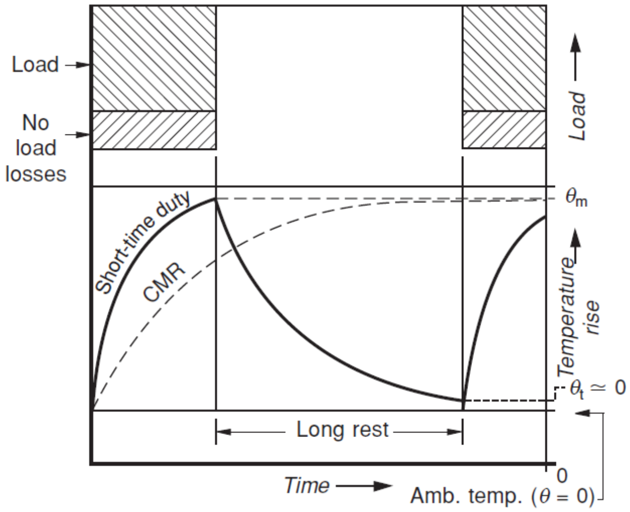


Figure 3-4 Continuous Duty [15].

3.4.2. Short-time Duty (S_2)

In this type of duty cycle the motor is at a steady load during a given time only not exactly required to achieve thermal balance, followed by a rest and de-energized period of long length to restore correspondence of motor temperature with the cooling medium (Figure 3-5). The motor ought to restart for the following cycle just when it has achieved its ambient condition. The suggested values for short-time duty are 10, 30, 60 and 90 minutes. The sort assignment for a specific rating, say for 30 minutes, will be determined as $S_2 - 30\ minutes$. Regular applications are task of bolt doors, alarms, windlasses (raising) and capstans.



Note Short-time loading is higher than the CMR and it is true for all duties S_2–S_{10}

Figure 3-5 Short-time Duty [15].

3.4.3. Intermittent-periodic Duty (S_3)

A sequence of indistinguishable duty cycles, each containing a period of activity at steady load and a rest and de-energized period. The period of energizing may accomplish the most extreme passable temperature rise (θ_m). The duty cycle is short for thermal balance to be achieved (Figure 3-6). In this duty cycle the beginning current I_{st} does not essentially influence the temperature rise. Except if generally indicated, the term of every duty cycle ought to be 10 minutes. The recommended values for the cyclic term factor CDF are 15%, 25%, 40% and 60%. A particular assignment for a specific rating, say for 40%, will be determined as $S_3 - 40\%$.

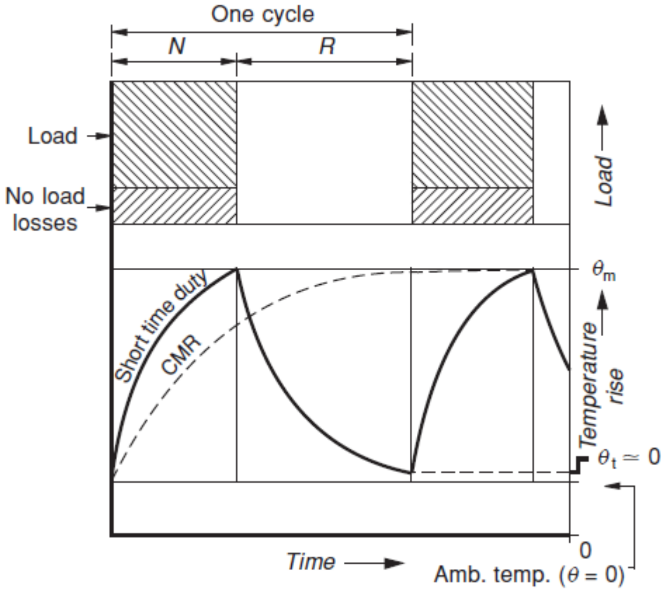


Figure 3-6 Intermittent periodic duty [15].

$$Cycle\ Duration\ Factor\ (\boldsymbol{CDF}) = \frac{N}{N+R} \tag{3-1}$$

where

N = motor operation under rated load and speed

R = motor rest and de-energized period

θ_t = temperature rise achieved during one duty cycle ($\simeq$ 0)

Usual applications are wire drawings machines and valve actuators.

3.4.4. Intermittent-periodic Duty with Start (S_4)

A sequence of indistinguishable duty cycles, with each duty cycle containing a relevant period of motor starting, followed by a period of motor operation at rated conditions. Before the start of the next duty cycle, there is a rest and de-energized period, hence the duty cycle is too short not allowing motor thermal equilibrium to be reached (Figure 3-7). In this induction motor duty cycle, the motor goes to rest by natural deceleration by the respective motor load, after the supple source has been disconnected, or by using mechanical braking which doesn't affect thermally the motor's load, hence not causing more heating to the windings.

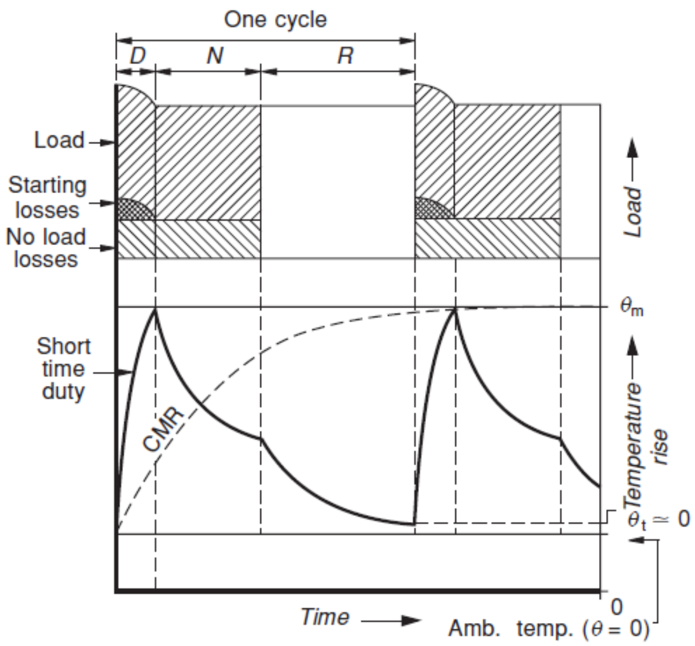


Figure 3-7 Intermittent periodic duty with start [15].

$$Cycle\ Duration\ Factor\ (\boldsymbol{CDF}) = \frac{D+N}{D+N+R} \tag{3-2}$$

where,

D = period of motor starting

N = operation under rated load and speed

R = motor rest and de-energized period

θ_t = motor temperature rise reached during one duty cycle (≃ 0)

In this duty cycle the following variables are indicated: the cyclic duration factor, the number of duty cycles per hour (c/h) and the factor of inertia (FI). Hence, for example, for a 40 % CDF with 90 operating cycles per hour and a factor of inertia of 2.5, the cycle will be represented as:

S_4 – 40 % - 90 c/h and FI – 2.5.

Usual applications for this induction motor duty cycle are lifts, cranes and hoists.

3.4.5. Intermittent-periodic Duty with Start and electrical braking (S_5)

A sequence of indistinguishable duty cycles, with each cycle containing a period of motor starting, followed by a period of motor operation at a constant load (with rated-conditions), and a period of electrical braking. Before the beginning of the next duty cycle, there is a motor de-energized rest period, hence motor thermal equilibrium is not reached (Figure 3-8).

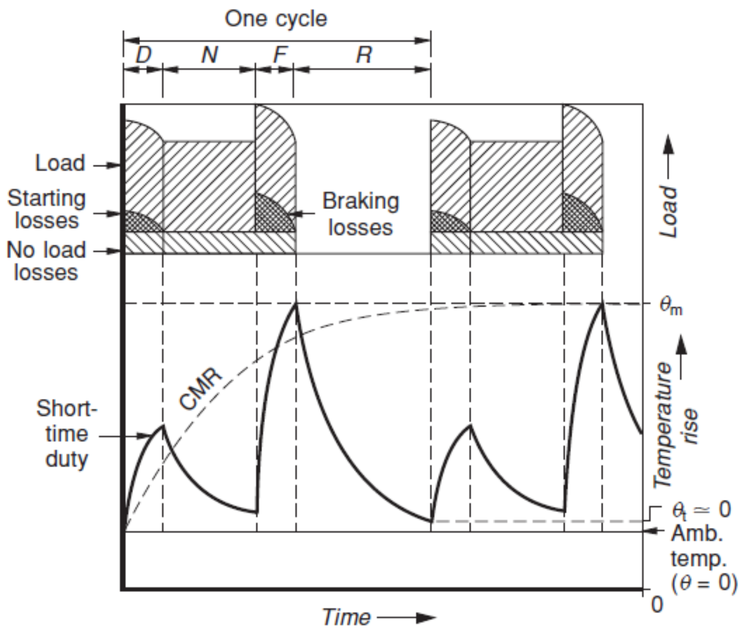


Figure 3-8 Intermittent periodic duty with start and electrical braking [15].

$$Cycle\ Duration\ Factor\ (\boldsymbol{CDF}) = \frac{D+N+F}{D+N+F+R} \tag{3-3}$$

where

D = period of motor starting

N = operation under rated load and speed

F = electrical braking

R = motor rest and de-energized period

θ_t = temperature rise reached during one duty cycle (≃ 0)

In this duty cycle, the cycle should be followed by the value indication of the following variables: cycle duration factor (CDF), the number of duty cycles per hours (c/h) and the FI e. g.

S_5 – 40 % - 90 c/h and FI – 2.5.

Usual applications for this induction motor duty cycle are cranes, rolling mills and hoists.

3.4.6. Continuous Duty with intermittent loading (S_6)

The induction motor duty cycle S_6 (continuous-operation periodic loading) is a sequence of indistinguishable motor duty cycles, with each motor duty cycle containing a period of motor operation at a constant load (N) and a period of motor operation with no-load (V) (Figure 3-9), motor thermal equilibrium is not reached during this duty cycle. The recommended values of the cycle duration factor (CDF) are: 15 %, 25 %, 40 %, and 60 %.

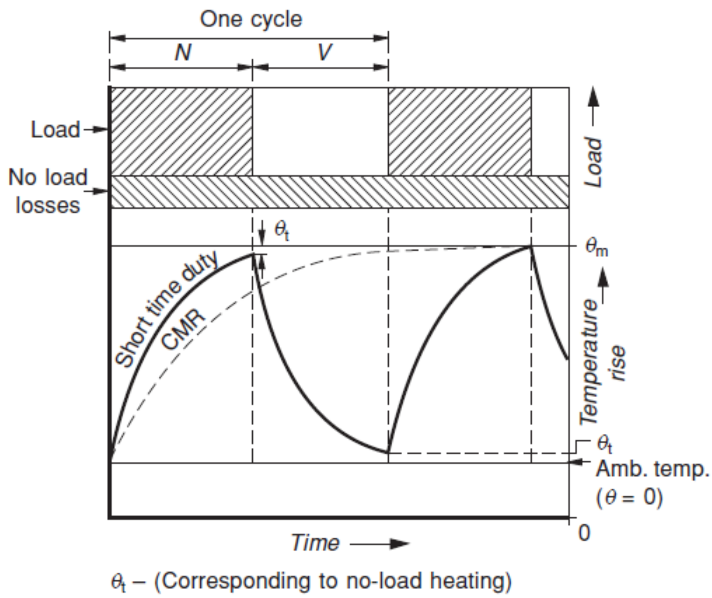


Figure 3-9 Continuous duty with intermittent periodic loading [15].

$$Cycle\ Duration\ Factor\ (\boldsymbol{CDF}) = \frac{N}{N+V} \quad (3\text{-}4)$$

where

N = motor operation under rated voltage and speed

V = motor operation with no-load

θ_t = motor temperature rise obtained during one duty cycle which corresponds to the no-load heating

The duty cycle definition will be expressed as:

$S_6 - 40$ % CDF

Usual motor applications in this duty cycle are machine tools and belts.

3.4.7. Continuous Duty with start and brake (S_7)

A sequence of indistinguishable duty cycles, each cycle containing a period of motor starting, a time of motor activity at a constant load, and a period of electrical braking, hence there is no motor rest-period. This duty cycle is too short for motor thermal equilibrium to be reached) (Figure 3-10).

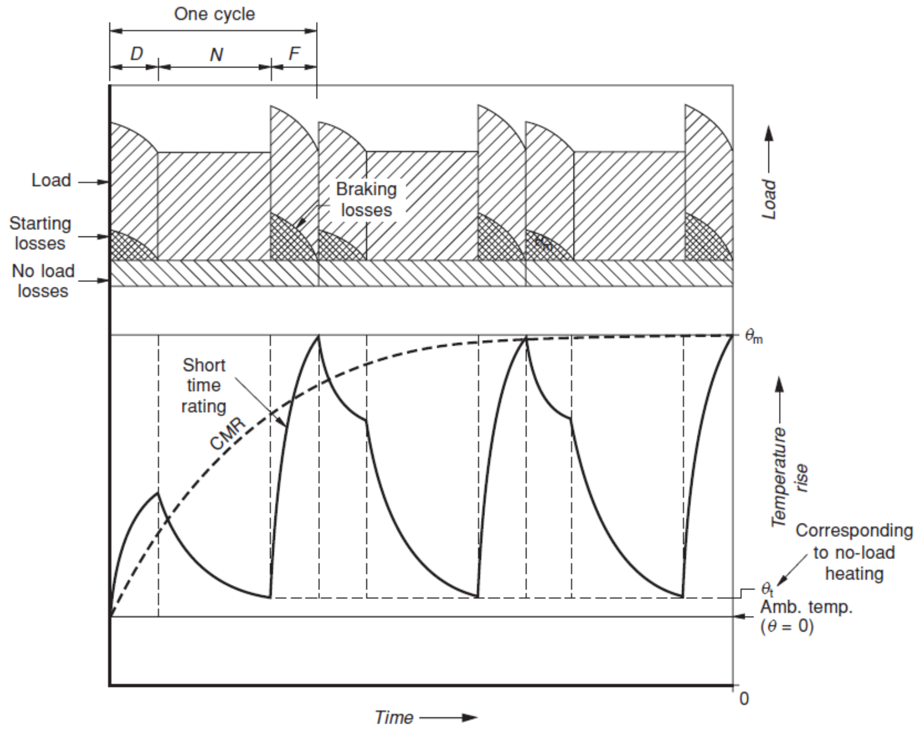


Figure 3-10 Continuous duty with start and braking [15].

The Cycle Duration Factor (CDF) is calculated as:

$$Cycle\ Duration\ Factor\ (\boldsymbol{CDF}) = \frac{D + N + F}{D + N + F} = 1 \quad (3\text{-}5)$$

where

D = period of motor starting

N = operation under rated speed and load

F = motor electrical braking

θ_t = motor temperature rise reached during one duty cycle (≃ 0)

This duty cycle definition is defined by the number of cycles per hour (c/h) and the FI, usual applications for this type of duty cycle are machine tools.

3.4.8. Continuous Duty with periodic speed changes (S_8)

A sequence of indistinguishable duty cycles, each cycle contains a starting period, a period of activity at a steady load corresponding to a pre-set motor speed, followed by one or more periods of motor operation at other constant loads and speeds, during the duty cycles there is no motor rest or de-energized periods and the motor thermal equilibrium is not reached. Usual applications are when the motor is required to run at different speeds (Figure 3-11).

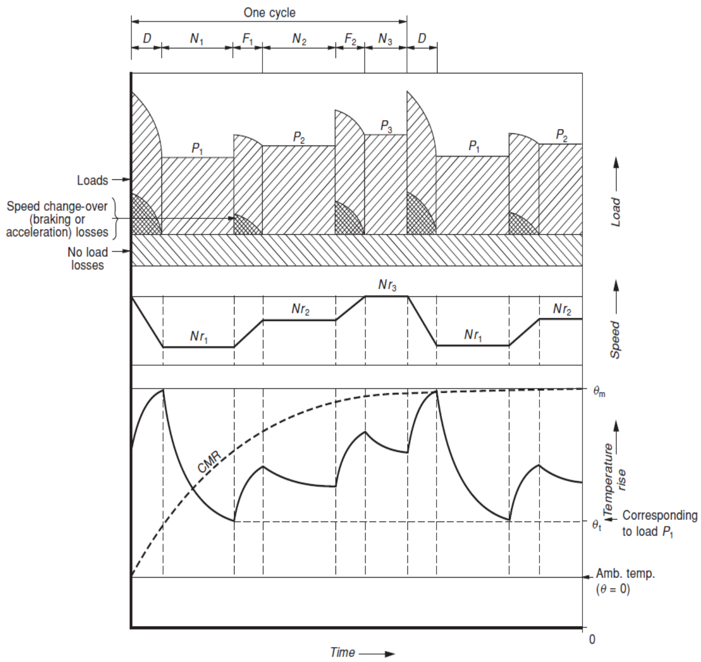


Figure 3-11 Continuous duty with periodic speed changes [15].

$$Cycle\ Duration\ Factor\ (\boldsymbol{CDF}) = \frac{D + N_1}{D + N_1 + F_1 + N_2 + F_2 + N_3} \quad (3\text{-}6)$$

with speed Nr_1 for load P_1, and

$$Cycle\ Duration\ Factor\ (\boldsymbol{CDF}) = \frac{F_1 + N_2}{D + N_1 + F_1 + N_2 + F_2 + N_3} \quad (3\text{-}7)$$

with speed Nr_2 for load P_2, and

$$Cycle\ Duration\ Factor\ (\boldsymbol{CDF}) = \frac{F_2 + N_3}{D + N_1 + F_1 + N_2 + F_2 + N_3} \quad (3\text{-}8)$$

with speed Nr_3 for load P_3. Where,

$F_1,\ F_2$= change of motor speed and acceleration

D = motor electrical braking, Nr_3 to Nr_1

$N_1,\ N_2,\ N_3$ = operation under rated speed and load

θ_t = motor temperature rise obtained during one duty cycle, which corresponds to the heating under normal rated conditions (P_1 as in Figure 3-11)

Three different speeds were considered for this duty cyle (lower Nr_1 to higher Nr_3), having three cycle duration factor's CDF's for one cycle, each corresponding to a different speed.

For this duty cycle, the variables considered are: number of duty cycles per hours (c/h), the Inertia Factor (IF) and the load at the various speeds.

An example of a CDF must be indicated for each speed, for example:

Table 3-1 Description Example of a S8 duty cycle.

c/h	FI	kW	$Speed$ (rpm)	$CDF(\%)$
20	2.5	10	1440	60
20	2.5	6	960	40
20	2.5	4	730	40

3.4.9. Non-periodic Duty (S_9)

In this duty the load and speed both differ non-intermittently, not like previous motor duty cycles. The motor in this duty cycle supplies variable load requests at different speeds and shifting over-loads, yet inside the admissible temperature rise limits. It is a duty like S_8, aside from some time period the over-loads may surpass the full load however are within the thermal withstand limit of the induction motor (Figure 3-12):

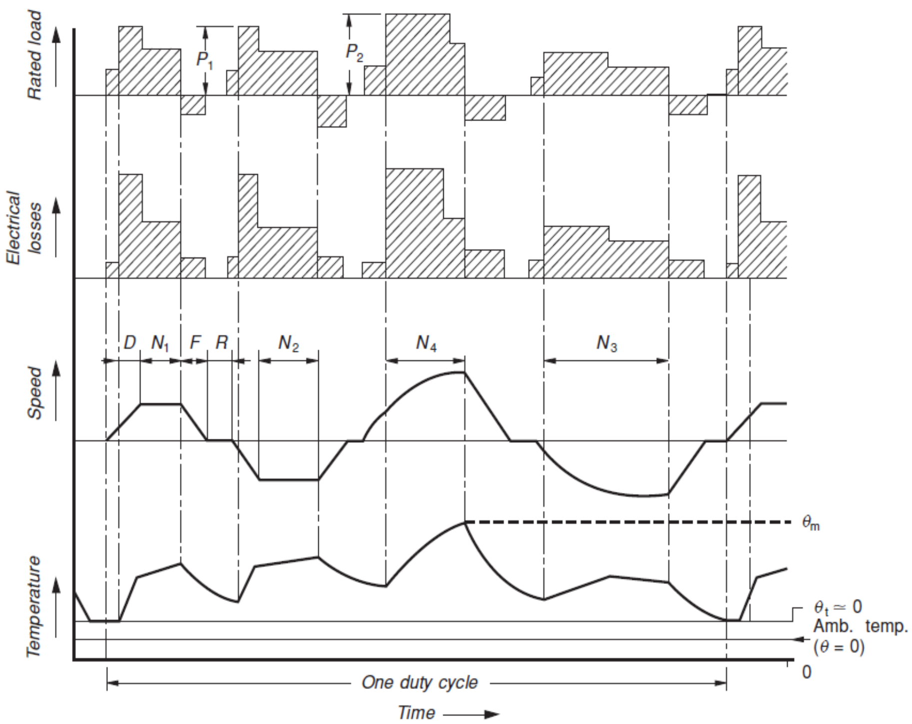


Figure 3-12 Duty with non-periodic load and speed variations [15].

D = period of motor starting

N_1, N_2, N_3 = operation within rated load at different speed (P_1)

N_4 = operation during over-load (P_2)

F = change of motor speed using electrical braking

R = motor rest and de-energized

θ_t = motor temperature rise reached during one duty cycle ($\simeq 0$)

3.4.10. Duty with discrete constant loads (S_{10})

This induction motor duty cycle contains few different loads, not more than four in each cycle. Each load is performed for adequate term to enable the machine to accomplish its thermal equilibrium (Figure 3-13). However it is permitted, that each load cycle may not be indistinguishable, given that each discrete load is performed for an adequate length to acquire thermal equilibrium. The temperature reached during each discrete load is inside permitted limits or inside such restricts that on the off chance that it surpasses as far as possible, the thermal future of the machine isn't changed. For instance, performing one discrete stacking P_2 as in Figure 3-13, the temperature came to (θ_2) may surpass the permitted temperature (θ_m) for a brief length (t_2), however the last temperature toward the finish of the cycle is still with the end goal that the following cycle can be performed. The brief time frame span abundance temperature θ_2 came to while playing out the load obligation P_2, won't contrarily influence the thermal future of the machine (Figure 3-13).

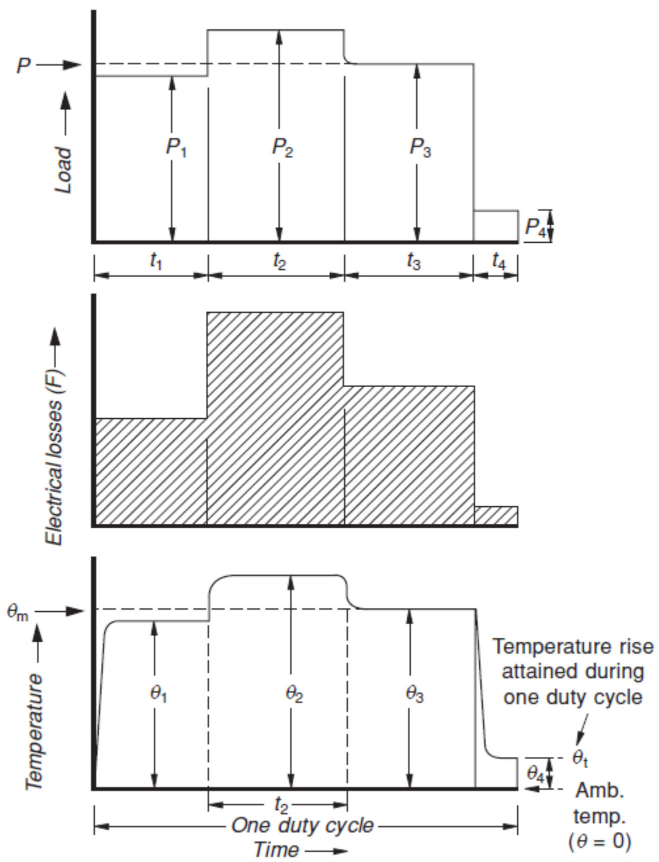


Figure 3-13 Duty with discrete constant loads [15].

t_1, t_2, t_3, t_4 = the duration of each operation during the discrete constant loads P_1, P_2, P_3, P_4

P = rated load as for continuous duty– S_1

F = electrical loses suffered by the motor

θ_m = maximum permissible motor temperature obtained for a constant load P

$\theta_1, \theta_2, \theta_3, \theta_4 =$ motor temperature reached during different discrete loads.

θ_t = motor temperature rise reached during one duty cycle.

3.5. Heating and cooling characteristics curves of Induction Motors

The heating and cooling behavior of an induction motor, up to around double the evaluated current, might be considered as exponential, as a part of the warmth generated is counterbalanced by the heat sink (for the dissipation of heat) through the windings. However, past $2I_R$ it ought to be viewed as adiabatic (straight), as the warmth created is greater and the winding protection will most likely be unable to disperse this warmth similarly immediately, when it happens for a brief time period. Since an induction motor would ordinarily work at around the evaluated current I_R aside from unusual working conditions, the exponential warming and cooling qualities are increasingly important. These qualities decide the execution of an induction motor, especially when it is required to perform discontinuous obligations, and help decide safe loadings, begins, and braking's (curves (a) and (b) of Figure 3-14). A relay can be used to monitor thermal conditions when the motor's temperature exceeds normal values.

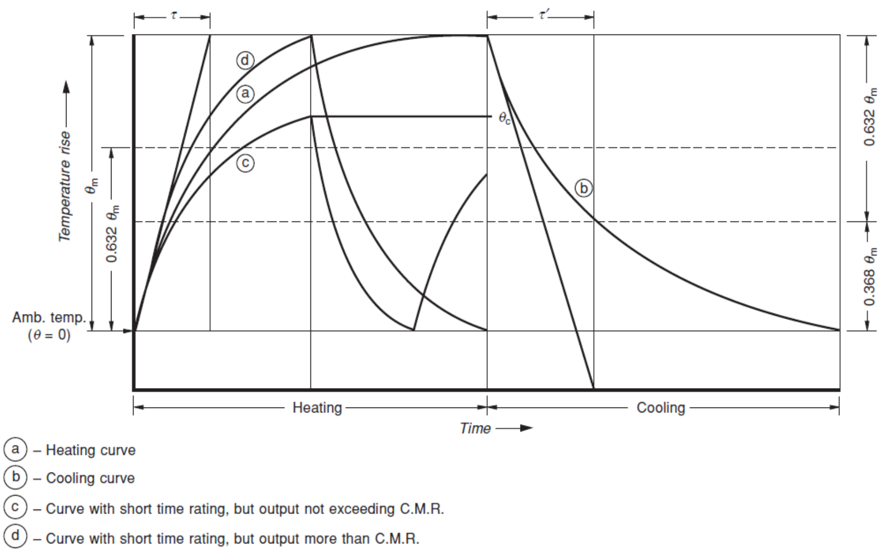


Figure 3-14 Heating/Cooling Curves of an induction motor [15].

These withstand thermal curves are given with the induction motor as a standard practice by induction motor producers. In case these curves are not accessible, a warm, IDMT or an engine insurance transfer is required to be set during commissioning, however it is fundamental to know the warming and cooling time constants of the induction motor, given by the producer.

3.5.1. Time Constants

The induction motor time constants (provided by the motor manufacturer) define the time in which the temperature rises or falls by 0.632 times its maximum value θ_m (Figure 3-14).

Meaning of thermal time constants

The short-time rating of a CMR induction motor changes with its thermal time constants and may vary starting with one manufacturer to the next, relying on the cooling configuration adjusted and its adequacy. The shorter the thermal constant, the lower will be the brief span rating CMR engine can perform.

3.5.2. Heating Curves

Exponential start on a cold start

The temperature rise of an induction motor corresponding to a near-rated current can be expressed exponentially by

$$\theta_c = \theta_m(1 - e^{-\frac{t}{\tau}}) \quad \text{(3-9)}$$

where,

θ_c = temperature rise of an induction motor after t hours (ºC) on a cold start, above the ambient temperature.

If θ_a is the ambient temperature in ºC and θ_e is the end temperature of the machine (in ºC) after time t then:

$$\theta_c = \theta_e - \theta_a \tag{3-10}$$

θ_m = induction motor temperature rise in a steady-state, or the maximum permissible temperature rise at full load in ºC of the machine under continuous temperature.

Note: For non-constant temperatures rises between θ_c and θ_m as seen in curves (c) and (d) of Figure 3-14, θ_m may be replaced by the current temperature on the heating or correspondent cooling curves.

t = time of motor heating or correspondent tripping of the relay (in hours).

τ = induction motor heating or thermal time constant (in hours). The bigger the machine, the higher this will be.

The temperature rise depends of the operating current and is a square proportion of the current. Rewriting the above equation depending on the operating current yields:

$$KI_r^2 = I_1^2(1 - e^{-\frac{t}{\tau}}) \tag{3-11}$$

where,

I_R = induction motor rated current (in A).
K = a variable depending upon the type of relay and is provided by the relay manufacturer (values between 1 to 1.2).
I_1 = actual motor current used.

Using the last equation, we can deduce that for rated current and $t = 0\ s$

$$\theta_c = \theta_e - \theta_a = I_r^2\left(1 - e^{-\frac{0}{\tau}}\right) = 0 \implies \theta_e = \theta_a \tag{3-12}$$

And for $t = \infty$

$$\theta_c = \theta_e - \theta_a = \theta_m(1 - e^{\infty}) = \theta_m \tag{3-13}$$

The temperature rise of the induction motor in a period t, after the motor current has changed from I_0 to I_1

$$\theta_c(relative) = (I_1^2 - I_0^2)(1 - e^{-\frac{t}{\tau}}) \tag{3-14}$$

Exponential start on a hot start

In a hot start the heating can be expressed as:

$$\theta_h = \theta_0 + (\theta_1 - \theta_0)(1 - e^{-\frac{t}{\tau}}) \tag{3-15}$$

or using the operating current:

$$\theta_h = I_0^2 + (I_1^2 - I_0^2)(1 - e^{-\frac{t}{\tau}}) \tag{3-16}$$

where,

$\theta_h = \theta_e - \theta_a$ temperature rise (after t hours in ºC) of the induction motor above the ambient temperature on a hot start.

To monitor the health of the induction motor, for protection it can be substituted for **K**. I_r^2 , where I_R is the equivalent maximum current at which the motor can operate continuously, can also be considered as the current setting of the relay up to which the relay must remain off.

Equation (3-16) can be rewritten as:

$$KI_r^2 = I_0^2 + (I_1^2 - I_0^2)(1 - e^{-\frac{t}{\tau}}) \tag{3-17}$$

For safety, t can now be considered as the time the induction motor is allowed to operate using a higher current I_1 before a trip occurs

$$\therefore t = tripping\ time$$

Simplifying:

$$e^{-\frac{t}{\tau}} = \frac{I_1^2 - kI_r^2}{I_1^2 - I_0^2} \qquad or \qquad e^{\frac{t}{\tau}} = \frac{I_1^2 - I_0^2}{I_1^2 - kI_r^2} \qquad (3\text{-}18)$$

and $t = \tau \, log_e \frac{I_1^2 - I_0^2}{I_1^2 - kI_r^2}$

Utilizing this condition of the thermal curve of an induction motor, a log-log diagram can be drawn for a known τ, versus I_1/I_R for various states of engine warming before a relay trip (Figure 3-15). The hand-off can be set for the most proper warm curve, subsequent to surveying the engine's real working conditions and accomplishing a genuine thermal copy protection.

Equations (3-9) to (3-18) are appropriate just when the warming or cooling process is exponential, which is valid up to double the rated current as noted previously. Past this the warming can be viewed as adiabatic (direct). At higher working flows the proportion t/τ decreases, since the resistive time of the induction motor diminishes pointedly as the working current curve rises. At flows higher than $2I_R$ the equation can be changed as:

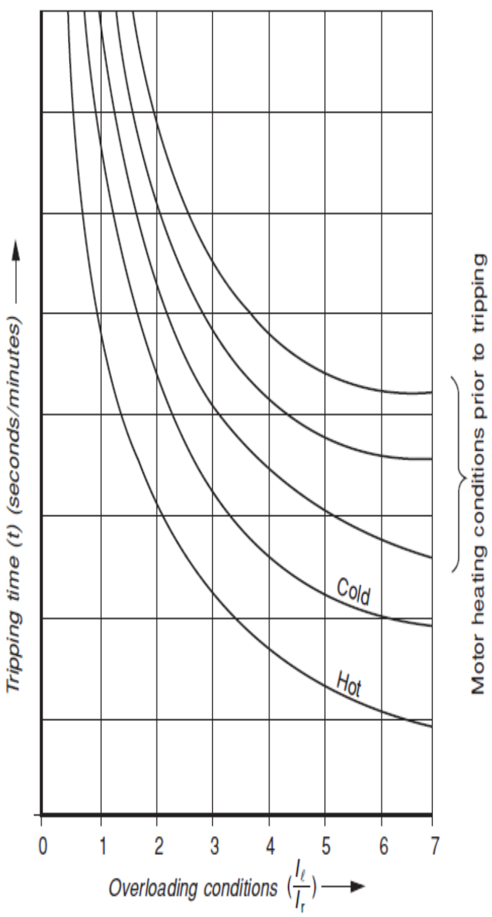


Figure 3-15 Thermal withstand curves [15].

Adiabatic heating on a cold start

$$\theta_c = \theta_e - \theta_a = I_R^2 \frac{t}{\tau} \qquad (3\text{-}19)$$

Adiabatic heating on a hot start

$$\theta_c = \theta_e - \theta_a = \theta_0 + \frac{(\theta_1 - \theta_0)t}{\tau} = I_0^2 + (I_1^2 - I_0^2)t/\tau \qquad (3\text{-}20)$$

3.5.3. Cooling Curves

The temperature decreases in time, after the motor has been turned off and current reduced to zero and can be expressed as:

$$\theta = \theta_m \cdot e^{-\frac{t}{\tau'}} \tag{3-21}$$

where,

τ' = cooling time consistent in hours being higher than the warming time steady τ. At the point when the machine stops, its cooling framework additionally stops to work with the exception of normal cooling by radiation and convection, the machines sets aside a more drawn out opportunity to cool then it does to warm (Figure 3-14).

3.6. Electrical Braking

3.6.1. D.C. Electrical Braking

Applying a D.C. voltage to the induction motor windings, a constant flux is generated since f = 0. The hypothetical synchronous speed of the engine, N_S , now decreases to zero. At the point when this consistent flux is cut by the rotor conductors, as the rotor rotates, it initiates an enduring (D.C.) e.m.f. in the rotor circuit, which delivers the required brake impact. In slip-ring engines, the braking torque can be controlled by embeddings appropriate opposition in the rotor circuit and differing the excitation voltage (Figure 3-17), not changing the excitation current. Braking in slip-ring engines by this technique is increasingly precise and less difficult. Some run curves of the mill braking bends are appeared in for a slip-ring engine (Figure 3-16). In squirrel confine engines, without outside obstruction, the stator windings can be set in several designs, for example, arrangement, parallel, star or delta, as appeared in Figure 3-17, to accomplish the changing impacts of excitation voltage. This kind of braking is valid for both squirrel confine and slip-ring engines rarely being used.

For applying the brakes, the stator is separated from the supply and a D.C. excitation voltage is connected to the windings as appeared in Figure 3-17. The windings can be implemented in any arrangement, as outlined, to acquire the required braking torque. In the event that the ampere turns in the middle of the braking are kept up as normal running, the braking torque curve will nearly take the state of the motor's typical speed– torque curve.

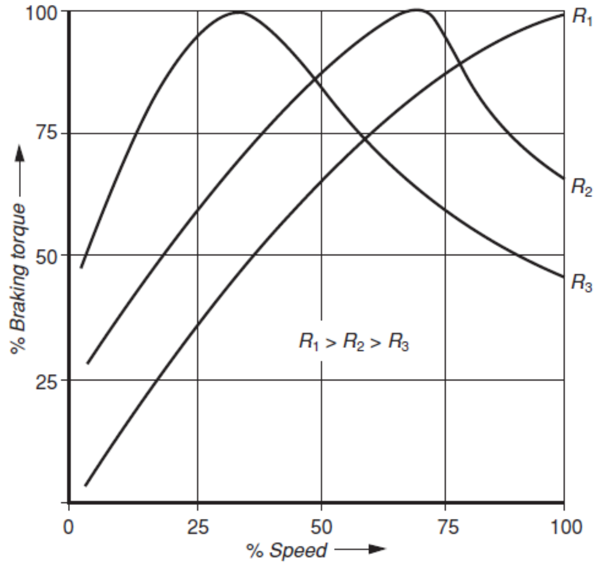


Figure 3-16 Usual braking torque curves for several external resistances using the same excitation current [15].

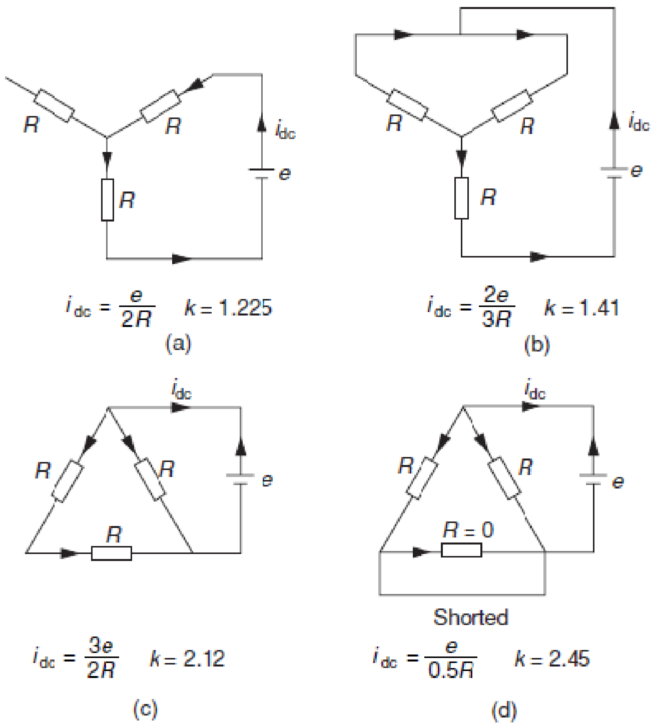


Figure 3-17 D.C. electrical braking with rotor stator connections [15].

e = excitation voltage applied to the motor

i_{dc} = braking/excitation current

R = stator resistance in each phase. In case of slip-ring, the value R varies, and external resistance can be applied.

Figure	k_i	Required dc voltage e
A	1.225	$i_{dc}2R$
B	1.41	$i_{dc}\frac{3R}{2}$
C	2.12	$i_{dc}\frac{2R}{3}$
D	2.45	$i_{dc}\frac{R}{2}$

If a D.C. independent source is not available, a transformer with a single phase and a rectifier connect as appeared in Figure 3-18 can likewise be used to get the required D.C. voltage. In spite of the fact that the prerequisite of D.C. excitation voltage isn't high, the rating of the rectifier transformer and must be comparable with the braking power required. This braking power would rely on the measure of the engine and the time of braking. On the off chance that the braking current, i_{dc} , is known, which is a proportion of the braking torque important to satisfy a specific load obligation prerequisite, the excitation voltage e can be resolved for various twisting setups, as showed in Figure 3-17. The i_{dc} can be resolved from the accompanying condition, considering a similar ampere turn with respect to a standard motor.

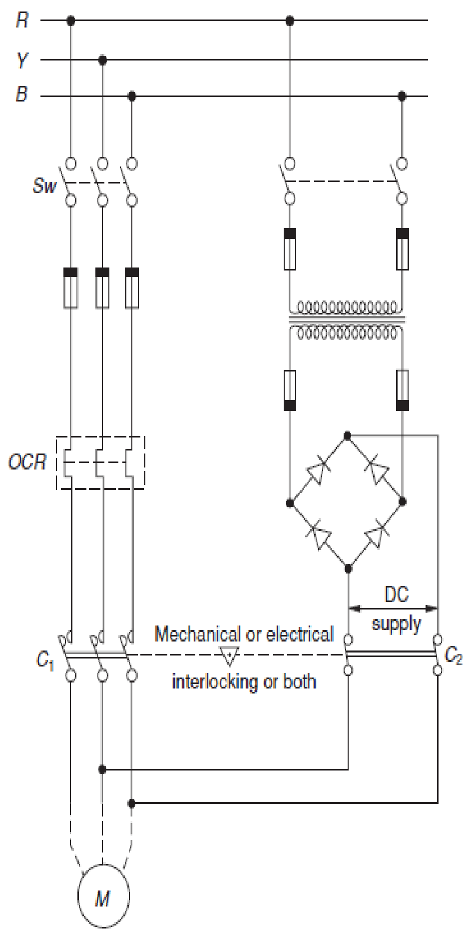


Figure 3-18 Using a bridge rectifier to obtain D.C. voltage [15].

3.7. Monitoring Induction Motor Thermal State

3.7.1. Motor Thermal Current

For thermal protection the variable speed drive Schneider ATV630 uses the following thermal curve of a machine:

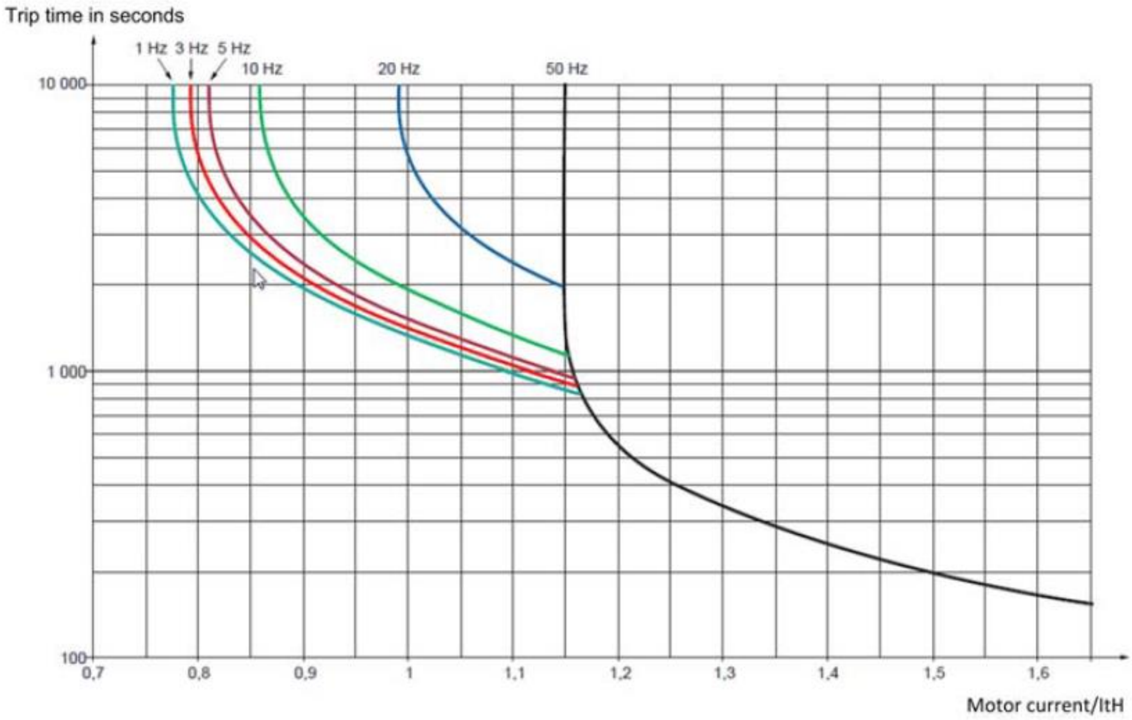


Figure 3-19 ATV630 Relay Thermal Curve [16].

where,

t = tripping time, machine operating time with a high current allowed, before a trip occurs.

$Motor\ Thermal\ Current\ [ItH]$ = Motor Thermal monitoring current as a percentage of the motor rated current.

The motor thermal current [*ItH*] can be set between the values of $0.2I_r$ and $1.1I_r$, where I_r is the motor's rated current.

3.7.2. Motor Thermal State

To monitor the motor thermal protection the variable speed drive Schneider ATV630 uses the variable Motor Thermal State [*tHr*], which represents a percentage. The motor thermal stage is represented as I^2t.

The Thermal Motor State depends of:

- Copper and iron constants as well as the type of motor ventilation.
- Current measured used by the motor.

Hence the motor thermal state is calculated with the square of the ratio of the RMS measured current over the current thermal value, so the variable Motor Thermal State does not correspond to a measured temperature but a percentage of the thermal current.

When the Motor Thermal State has the value of 100 % the motor is at a thermal steady state, if it reaches 118 % the motor enters in an overload state, which is saved by the drive between power changes.

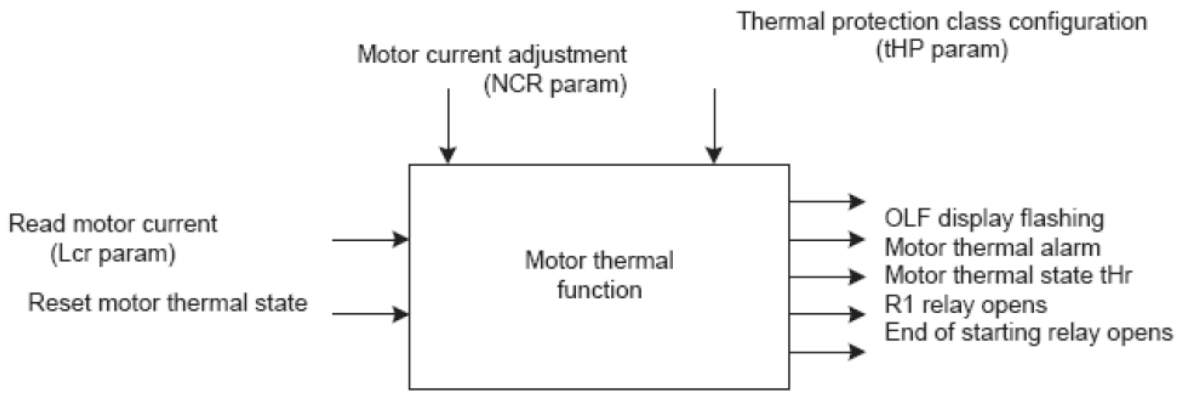


Figure 3-20 Motor Thermal Monitoring [16].

The motor thermal state is estimated:

- By calculating: (Imot/ In mot) * (Imot/ In mot).
- For a reference temperature (ambient temperature) of 40 ºC.
- For the temperature rise of the frame (iron) and the temperature rise of the winding (copper).

The motor thermal state is not calculated during braking or heating (the current measured is insignificant).

The thresholds for changing the thermal mode are: Cu (copper) thermal state > 200% or Fe (iron) thermal state > 125%.

4. Proposed Topology

In this chapter a general proposed solution for the network topology is presented with all the components included in the system developed. All the system functionalities and possible induction motor’s variables are also explained. At the end some motor instructions, such as reading motor variables or writing drive registers for motor command thought Modbus are described.

4.1. Network Topology

To implement an IoT module, the following network topology was considered:

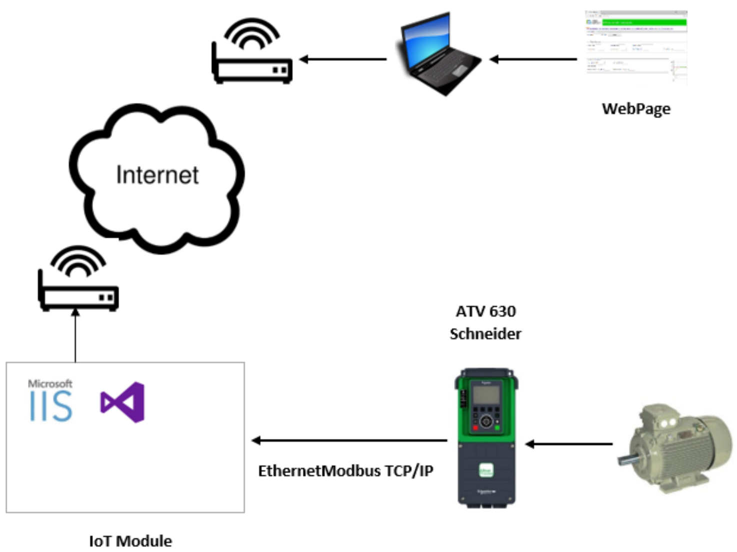


Figure 4-1 Proposed Network Topology for an induction motor module.

The IoT module was implemented in a laptop using Microsoft Visual Studio (serving as server, Microsoft IIS), here the asp.net environment was selected to develop the webform using HTML5 and CSS. Here the asp.net AJAX extension was used with all motor’s variables, using update panels. The webform application was written in a programming language which supports the Common Language Runtime. The Modbus protocol was developed in C#. The asp.net AJAX extension was used with all motor’s variables, using update panels. The extension uses a mechanism called asynchronous postback, where instead of refreshing the entire page, only the HTML inside the Update Panel on the page is sent by the server. Any control inside the page can start a postback through a trigger. A trigger is an event that will cause the Update Panel to refresh.

4.1.1. Webform Design

In this section, the website design organization chart describes the general content of the website developed, including the most important major tabs: Home/Mains Variables, Command/Controls, Motor Output Values, Motor Variables Charts, Energy/Thermal Motor values, Control Circuit and DIN VDE 0503. Additionally, the user input functionalities of each tab are presented, describing the general organization of the motor's variables monitoring and user functionalities.

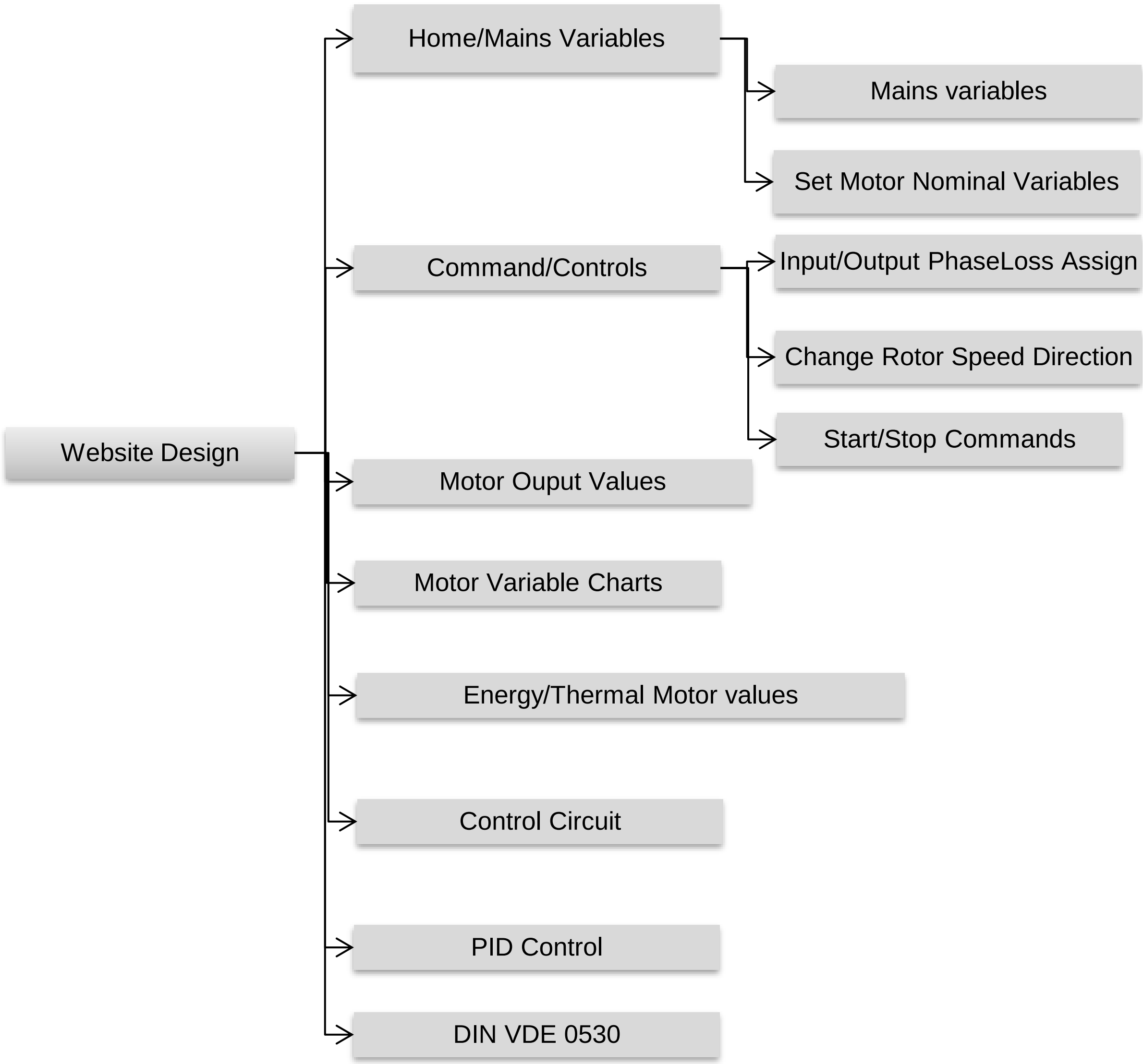


Figure 4-2 – Induction Motor IoT Module - Website Design Organization Chart.

4.2. System Description

In this chapter, all tabs contained in the website are described, with all user control possibilities indicated and the full description of all motor's variables. Using this interface allows the user to monitor the induction motor with focus on the working variables and thermal monitoring, as well as starting/stopping the motor using user pre-defined references and working variables.

4.2.1. Home Tab

In this tab, the following motor and variable speed drive ATV600 configurations are presented: embedded Ethernet configurations of the variable speed drive ATV600, all mains parameters values related to the motor, motor speed limits and ramps values and the setting of the motor's nominal variables values.

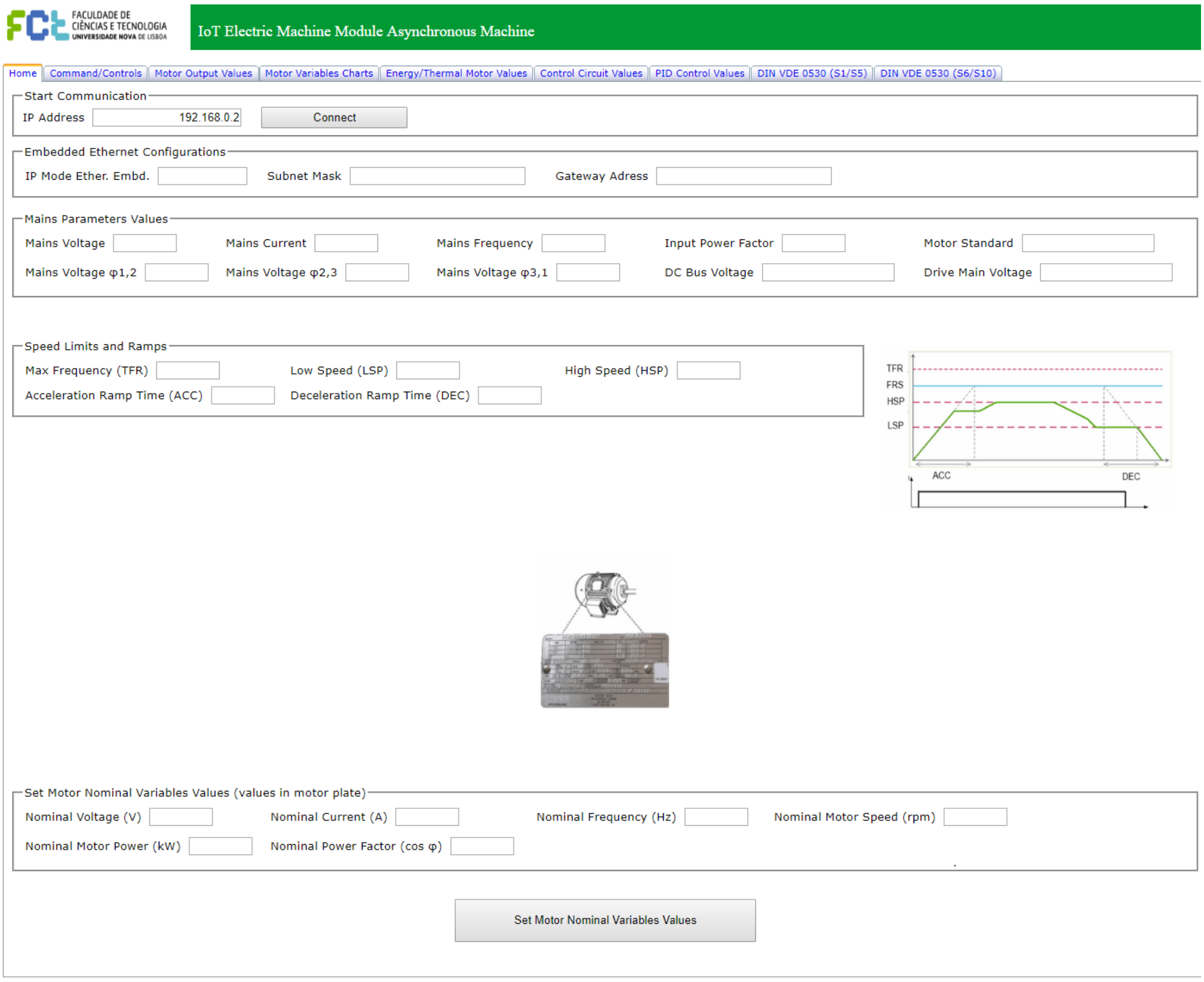


Figure 4-3 Induction Motor IoT Module - Home Tab.

In this tab, the connection to the variable speed drive ATV600 starts with the IP Address introduced and the connect button pressed, the following embedded Ethernet configurations are also presented:

- **IP Mode Ethernet Embedded**: Fixed address, Bootstrap Protocol (BOOTP), Dynamic Host Configuration Protocol (DHCP).
- **Mask**: Subnet Mask.
- **Gateway**: Gateway address.

In the Mains Parameters group values related to the motor, the following motor variables are presented in real time:

- **Mains Voltage**: Mains voltage based on AC bus measurement with motor running or stopped (Vac).
- **Mains Current**: Actual mains current (effective value of the fundamental mode) with an accuracy of 2% (related to the drive nominal current) (A).
- **Mains Frequency**: Actual mains frequency (Hz).
- **Input Power Factor**: Mains input power factor (value between 0 and 1).
- **Mains Voltage $\varphi_{1,2}$:** Mains voltage phase 1-2 measurement (Vac).
- **Mains Voltage $\varphi_{2,3}$:** Mains voltage phase 2-3 measurement (Vac).
- **Mains Voltage $\varphi_{3,1}$:** Mains voltage phase 3-1 measurement (Vac).
- **DC Bus Voltage**: DC bus voltage (Vdc).
- **Drive Main Voltage**: Rated voltage of the mains supply (Vac).

In the Speed limits and Ramps values group box, the following real-time variables are:

- **Maximum Frequency (TFR):** Maximum output frequency (normally preset at 60 Hz).
- **Low Speed (LSP):** Motor frequency at minimum reference, can be set between 0 Hz and the High Speed value (Hz).
- **High Speed (HSP):** Motor frequency at maximum reference, can be set between Low Speed and Maximum Frequency (Hz).
- **Acceleration Ramp Time (ACC):** Time required to accelerate from 0 to the Nominal Motor Frequency (seconds).

- **Deceleration Ramp Time (DEC):** Time to decelerate from the Nominal Motor Frequency to 0 Hz (seconds).

In the last group box, the motor's nominal variables values can be introduced each time a new induction motor is connected to the variable speed drive ATV600:

- **Nominal Motor Variables**: Nominal Voltage (V), Nominal Current (A), Nominal Frequency (Hz), Nominal Motor Speed (rpm), Nominal Motor Power (kW), Nominal Power Factor (cos φ).

To change the motor's nominal variables values all fields must be introduced and the respective button pressed.

4.2.2. Command/Controls

In this section, all input/output phase losses can be monitored, allowing user to better control the induction motor in case of a phase lose. Additionally, the user can start/stop the motor by pre-defining some motor working variables as well as setting the motor rotating direction.

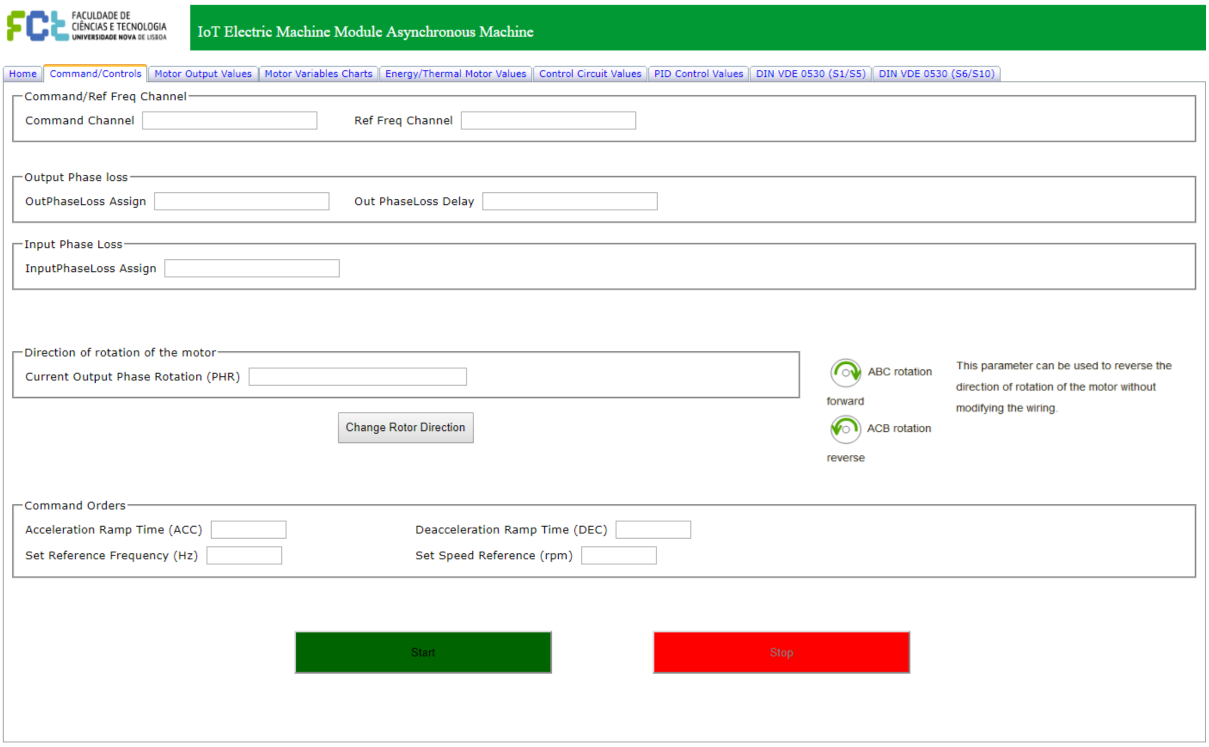


Figure 4-4 Induction Motor IoT Module - Command/Controls Tab.

In the Command/Reference Frequency Channel group box, the variables defining the channels where the variable speed drive ATV600, receives commands and the reference frequency are:

- **Command Channel/Reference Frequency Channel**: Terminals, Reference Frequency Remote Terminals/Modbus/CANopen/Embedded Ethernet.

The Input/Output Phase Loss group boxes allows monitoring of input/out phase loss error responses:

- **OutPhaseLoss Assign**: can be configurated to Function Inactive or OutputPhaseLoss (OPL) error triggered making the motor freewheel stop (motor stops by his own inertia) in case of error detection.
- **OutPhaseLoss Delay**: Output (motor) phase loss detection time (seconds).
- **InputPhaseLoss Assign**: loss of input phase error response, if one or more supply mains phases are missing and if the leads to performance decrease, the error is triggered.

The Direction of rotation of the motor group box, allows the user to define the motor's rotor rotation direction by pressing a button:

- **Current Output Phase Rotation (PHR)**: Output phase rotation, modifying this parameter operates as an inversion of 2 of the three motor phases, this results in changing the direction of rotation of the motor (ABC - standard rotation ACB - opposite rotation).

Finally, the Command Orders group box, which allows the user to start and stop the motor (pressing the respective buttons) accordingly to pre-set motor variables:

- **Acceleration Ramp Time (ACC):** Time required to accelerate from 0 to the Nominal Motor Frequency (seconds).
- **Deceleration Ramp Time (DEC):** Time to decelerate from the Nominal Motor Frequency to 0 Hz (seconds).
- **Reference Frequency:** reference frequency for the induction motor, this value can be changed without stopping and re-starting the motor (changing the value in text box and re-pressing the start button) (Hz).
- **Speed Reference:** motor rotating speed reference (rpm).

4.2.3. Motor Output Values

In this tab all the motor working variables are presented in real time, beginning with the start of the motor (pressing any start button). This allows the user to monitor the motor functioning, and thermal working state.

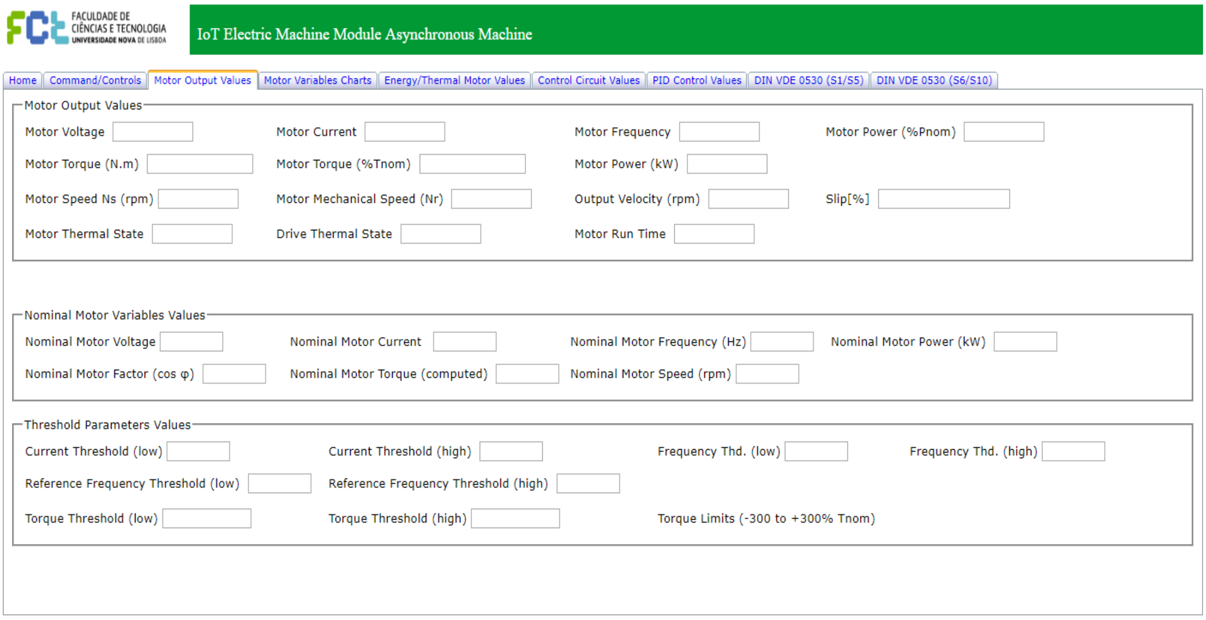


Figure 4-5 Induction Motor IoT Module - Motor Output Values.

In the Motor Output Values group box, all motor working variables are shown in real time when the motor starts:

- **Motor Working Variables**: Motor Voltage (V), Motor Current (A), Motor Frequency (Hz), Motor Power (kW), Motor Power ($\%P_{nom}$), Motor Torque (N.m), Motor Torque ($\%T_{nom}$), Motor Speed without motor slip (N_s ,rpm), Motor Mechanical Speed with motor slip (N_r, rpm), Output Velocity (rpm), Motor Slip (%).

- **Motor Run Time**: Run elapsed time display (resettable), length of time the motor has been switched on (seconds).

- **Motor Thermal Monitoring**: Motor Thermal State (%) (when this variable hits 100% the motor is working in the steady state, when the motor exceeds 118% the motor is in overload).

- **Drive Thermal State**: Drive Thermal State (%) (when this variable is greater than 118% the drive is in overheat).

The Nominal Motor Variables Values group box the last nominal variables motor values introduced by the user are shown.

- **Nominal Motor Variables Values**: Nominal Voltage (V), Nominal Current (A), Nominal Frequency (Hz), Nominal Motor Speed (rpm), Nominal Motor Power (kW), Nominal Power Factor (cos φ) and the Nominal Motor Torque (N.m) is computed using the previous variables.

Additionally, the Threshold Parameters Values group box is presented:

- **Current Threshold (Low)**: motor current low threshold (standard 0 A).
- **Current Threshold (High)**: motor current high threshold (equal to the motor nominal current).
- **Frequency Threshold (Low)**: motor frequency low threshold (standard 0 Hz).
- **Frequency Threshold (High)**: motor frequency high threshold (standard 50 Hz).
- **Reference Frequency Threshold (Low)**: motor reference frequency low threshold (standard 0 Hz).
- **Frequency Reference Threshold (High)**: motor reference frequency high threshold (standard 50 Hz).
- **Torque Threshold (low)**: motor torque low torque threshold (standard $50\%T_{nom}$).
- **Torque Threshold (high)**: motor torque high torque threshold (standard $100\%T_{nom}$).

4.2.4. Motor Variables Charts

In this tab, the user can observe in real time, the motor's working variables thought real time charts, hence describing the motor's variables behavior from motor start until stop.

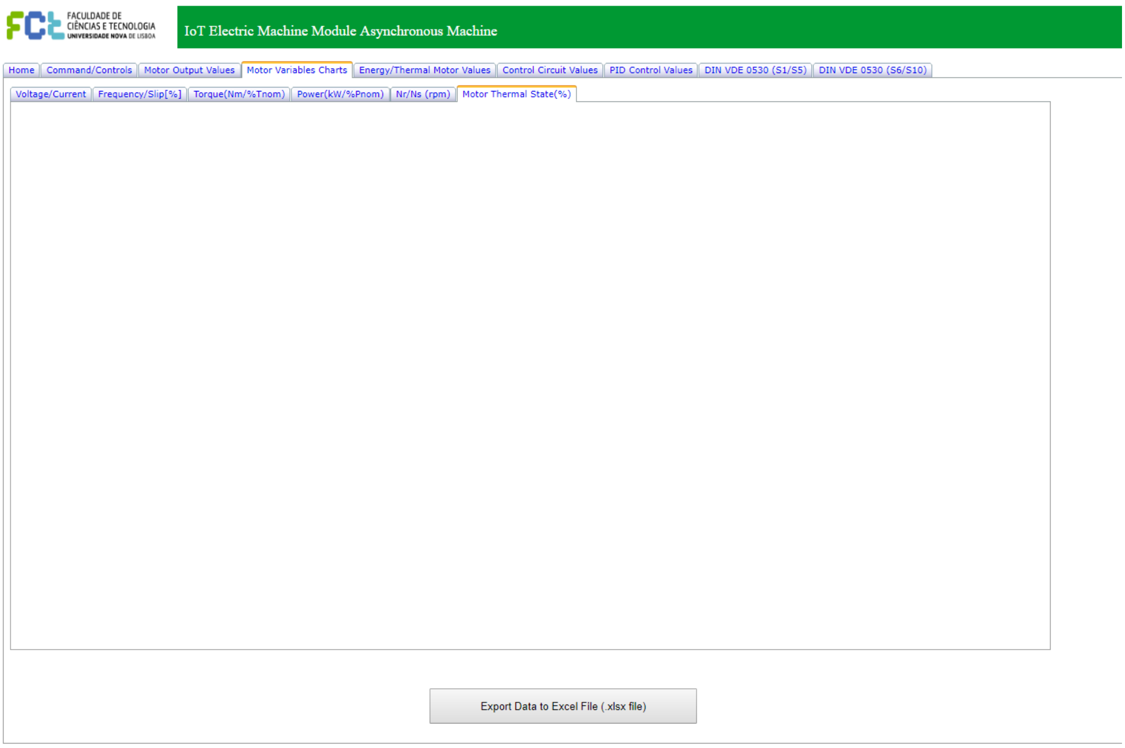


Figure 4-6 Induction Motor IoT Module - Motor Variables Charts.

Additionally, it was created a button that allows the user to export all motor's working variables in an excel file (.xlsx), on the client side.

4.2.5. Energy/Thermal Motor Values

In this section, all variables related to input energy, energy consumption, all power-related variables, thermal mode and the respective thresholds and currents are described.

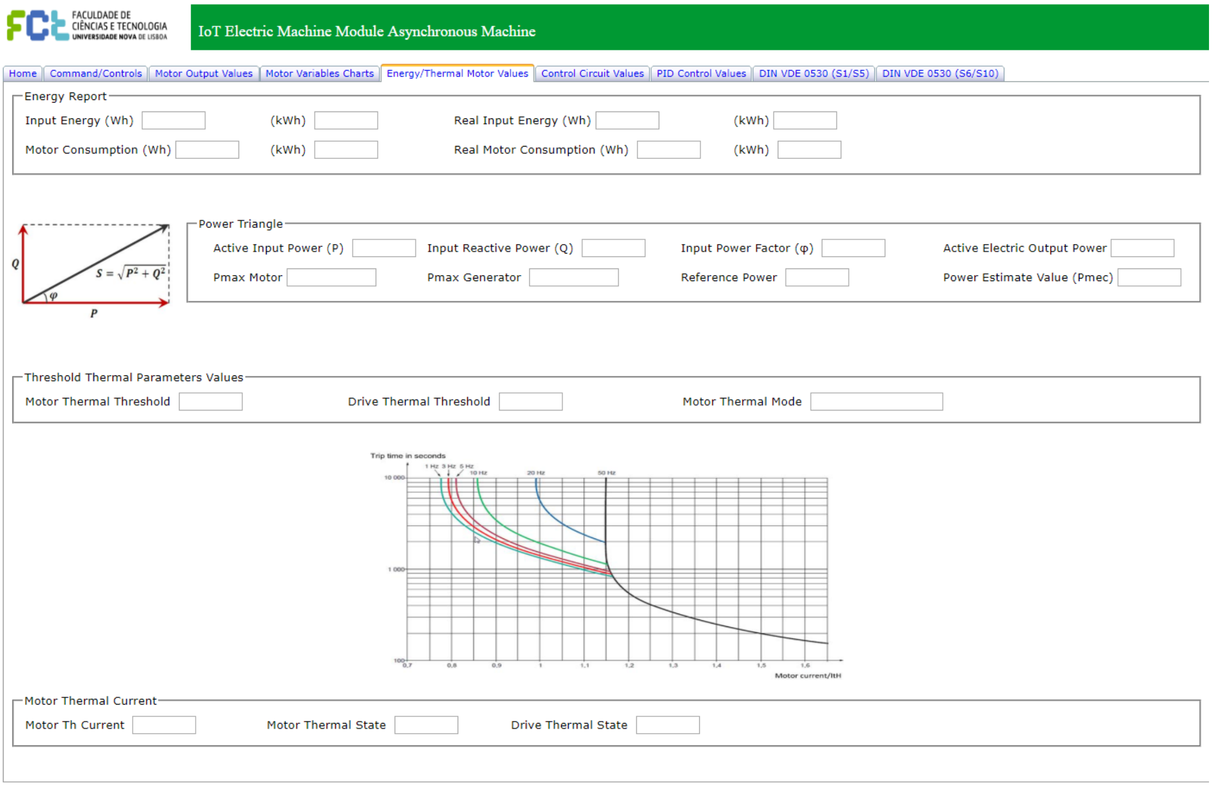


Figure 4-7 Induction Motor IoT Module – Energy/Thermal Motor Values

In the energy report group box, the following variables are shown in real time:

- **Input Energy (Wh/kWh)**: input electrical power consumed (this variable is an unsigned integer, hence no distinction between motor working as a motor or generator is considered).
- **Real Input Energy (Wh/kWh)**: input electrical power consumed (this variable is a signed integer, hence a distinction between the motor working as a motor or generator is considered).
- **Motor Consumption (Wh/kWh):** electrical energy consumed (this variable is an unsigned integer, hence no distinction between motor working as a motor or generator is considered).
- **Real Motor Consumption (Wh/kWh):** electrical energy consumed (this variable is a signed integer, hence a distinction between the motor working as a motor or generator is considered).

In the power triangle group box, all variables related to the motor power consumption and output are presented:

- **Active Input Power (P)**: active electrical input power (kW).
- **Input Reactive Power (Q)**: reactive electrical input power (VAR).
- **Input Power Factor (cos φ)**: mains input power factor (value between 0 and 1).
- **Active Electrical Input Power**: active electrical output power estimation (kW).
- P_{max} **Motor**: maximum power in motor mode ($\%P_{nom}$).
- P_{max} **Generator**: maximum power in generator mode ($\%P_{nom}$).
- **Reference Power**: reference power without drive (kW).
- **Power Estimate Value (P_{mec})**: motor shaft power estimation (kW).

In the next variable group box, all threshold thermal variables values and thermal mode are given:

- **Motor Thermal Threshold**: motor thermal threshold for the warning activation (standard value of 100%).
- **Drive Thermal Threshold**: drive thermal threshold for the warning activation (standard value of 100%).
- **Motor Thermal Mode**: motor thermal monitoring mode, which can be: no thermal monitoring, self-ventilated motor (standard), fan-cooled motor. An error is detected when the variable motor thermal state reaches 118% and motor deactivation occurs, only allowing re-starting when the motor thermal state falls below 100%.

At last, the motor thermal current group box defines the thermal current value to be controlled by the drive for motor thermal protection monitoring:

- **Motor Thermal Current**: motor thermal current to be pre-defined for the motor’s thermal protection monitoring (as a percentage of the motor’s thermal current).
- **Motor Thermal Monitoring**: Motor Thermal State (%) (when this variable hits 100% the motor is working in the steady state, when the motor exceeds 118% the motor is in overload).
- **Drive Thermal State**: Drive Thermal State (%) (when this variable is greater than 118% the drive is in overheat).

4.2.6. Control Circuit Values

This tab contains several fixed-value motor variables such as: equivalent motor electric circuit variables, rotor mechanical parameters values, transmissions values, control circuit variables and the motor stop-type configuration.

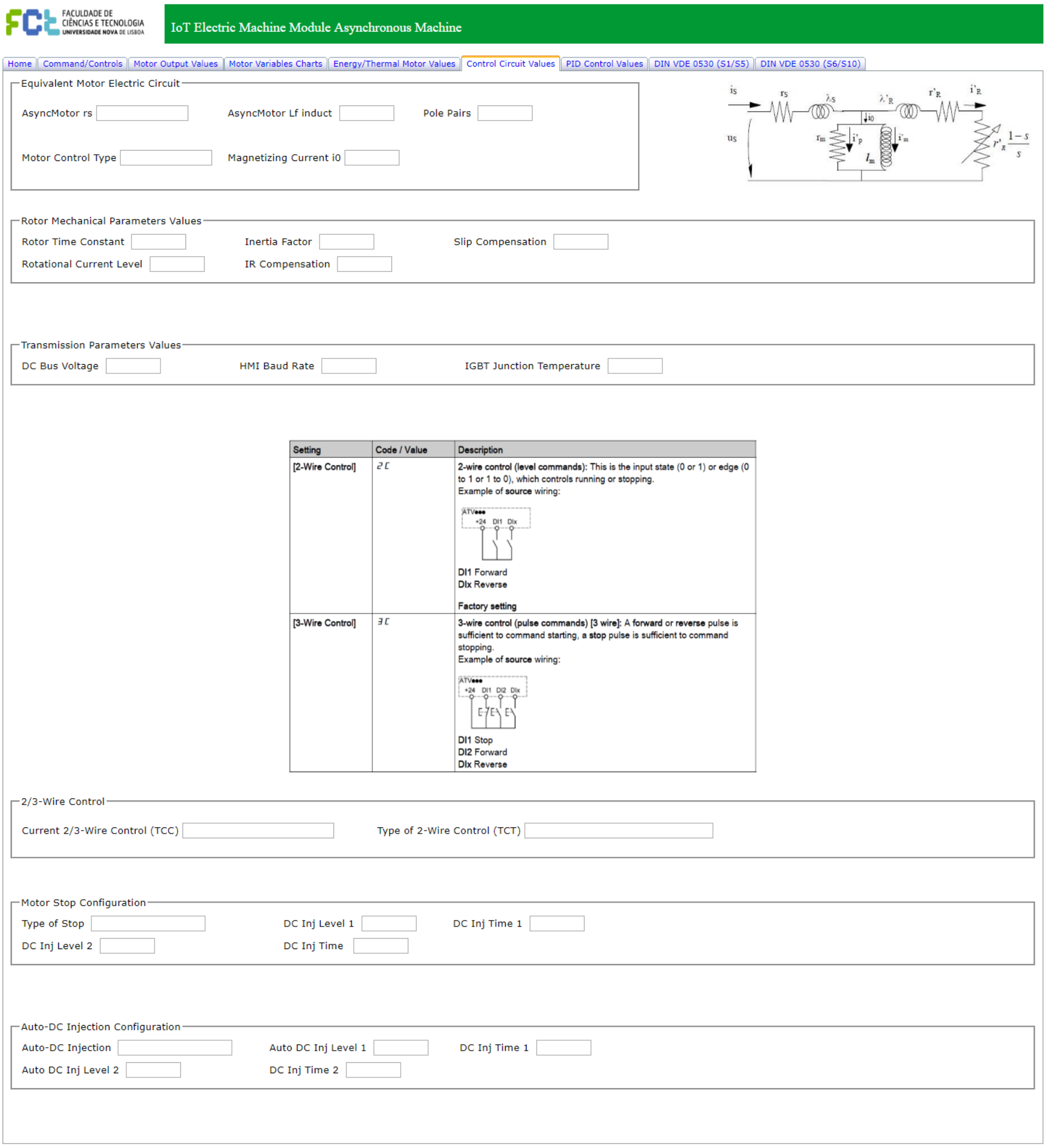


Figure 4-8 Induction Motor IoT Module - Control Circuit Values.

In the equivalent motor electric circuit group box some variables are computed:

- **Asynchronous Motor Stator Resistance r_s**: Asynchronous motor stator resistance measured in mOhm.
- **Asynchronous Motor Inductance L_f**: Asynchronous motor leakage inductance measured in mH.
- **Pole Pairs**: motor's number of pole pairs (computed).
- **Motor Control Type**: motor control type selected, in an opened-loop asynchronous motor it can be: [U/F VC Standard] U/F vector control law, [U/F 5 points] 5 points U/F vector control law, [U/F VC Quadratic] U/F vector control law for variable torque applications (pumps and fans, [U/F VC Energy Saving] U/F vector control law optimized for energy saving.
- **Magnetizing Current i_0**: magnetizing current measured in A.

The rotor mechanical parameters values group box describes the mechanical characteristics of the motor's rotor:

- **Rotor Time Constant**: rotor time constant measured in ms.
- **Inertia Factor**: rotor's inertia factor measured as a percentage (%).
- **Slip Compensation**: the motor slip is changed if the motor control type is not [U/F VC Quadratic] and if the following requirements are achieved: If the slip setting is lower than the actual slip, the motor is not rotating at the correct speed in steady state, but at a lower speed than the reference or if the slip setting is higher than the actual slip, the motor is overcompensated and the speed is unstable (expressed as %).
- **Rotational Current Level**: rotational current level, the current level should be set according to the torque required during the alignment operation (expressed as %).
- **IR Compensation**: This parameter is used to optimize torque at low speed, or to adapt to special cases (for example: for motors connected in parallel, decrease IR compensation. If there is insufficient torque at low speed, increase IR compensation. A too high value can avoid the motor to start (locking) or change the current limiting mode (expressed as %).

In the transmission parameters value the following variables are shown:

- **DC Bus Voltage**: DC bus voltage (Vdc).
- **IGBT Junction Temperature**: Estimated IGBT drive junction temperature, for a safe drive monitoring (expressed in ºC).

The next group boxes describe the type of wire control and its configurations:

- **Current 2/3 Wire Control (TCC)**: 2 or 3 wire control, 2-wire control (level commands): this is the input state (0 or 1) or edge (0 to 1 or 1 to 0), which controls running or stopping, 3-wire control (pulse commands) [3 wire]: A forward or reverse pulse is sufficient to command starting, a stop pulse is sufficient to command stopping.
- **Type of 2-Wire Control (TCT)**: [Level] State 0 or 1 is taken into account for run (1) or stop (0), [Transition] A change of state (transition or edge) is necessary to initiate operation in order to avoid accidental restarts after a break in the supply mains, [Level With Fwd Priority] State 0 or 1 is taken into account for run or stop, but the forward input takes priority over the reverse input.

The next variable group box defines the motor’s type of stop (rotor stop configuration):

- **Type of Stop**: normal stop mode, stop mode on disappearance of the run command or appearance of a stop command, the types of stop are: [On Ramp] stop on ramp, [Fast Stop] fast stop, [Freewheel] freewheel stop, [DC Injection] DC injection.
- **DC Injection Level 1**: Level of DC injection braking current activated via digital input or selected as stop mode, respectively level 1 and 2 (starting with DC electrical braking 1 and if this injection is not enough, level 2 is activated, expressed as percentage of the nominal current).
- **DC Injection Level 2**: Injection current activated by digital input or selected as stop mode once period [DC injection time 1] has elapsed, expressed as percentage of the nominal current.
- **DC Injection Time 1**: Maximum current injection time [DC inject. level 1]. After this time, the injection current becomes [DC inject. level 2] (expressed in seconds).
- **DC Injection Time 2**: Maximum injection time [DC inject. level 2] for injection, selected as stop mode only (expressed in seconds).

4.2.7. PID Control Values

In this tab, all variables related to the PID Controller included in the drive are presented:

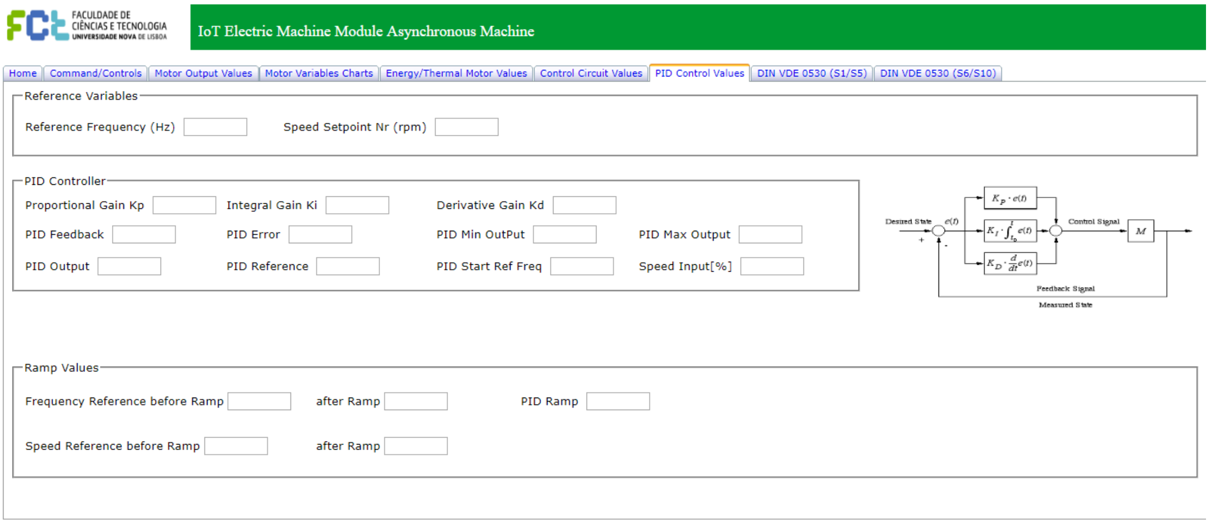


Figure 4-9 Induction Motor IoT Module - PID Control Values.

The reference variables group, states the motor's variable reference value (as a reference frequency or as a speed setpoint):

- **Reference Frequency:** reference frequency for the induction motor, this value can be changed without stopping and re-starting the motor (Hz).
- **Speed Setpoint N_r:** motor rotating speed reference (rpm).

The PID controller variables configurations values are expressed in:

- **PID Proportional Gain (K_P)**: proportional gain configures in the PID controller (value between 0.01 and 100.0 with a standard value of 1.00).
- **PID Integral Gain (K_I)**: integral gain configures in the PID controller (value between 0.01 and 100.0 with a standard value of 1.00)
- **PID Derivate Gain (K_D)**: derivate gain configures in the PID controller (value between 0.00 and 100.0 with a standard value of 0.00)
- **PID Feedback**: value for PID feedback for display only (value between 0.00 and 65,535).
- **PID Error**: PID controller detected error between –5% and +5%.
- **PID Minimum Output**: PID controller minimum output in Hz, standard 0.0 Hz.
- **PID Maximum Output**: PID controller maximum output in Hz, standard 60.0 Hz.
- **PID Output**: PID controller output between the low speed (0 Hz) and the high Speed (60 Hz).
- **PID Reference**: PID controller reference between minimum/maximum PID reference.

- **PID Start Reference Frequency**: speed reference for start-up, expressed in Hz.
- **Speed Input (%)**: PID speed input (%) reference (as a percentage of the reference frequency introduced by the user).

The last group box defines the ramp control feedback variables:

- **Frequency Reference before/after Ramp**: frequency reference value before and after the unitary ramp is applied in the PID controller (expressed in Hz).
- **Speed Reference before/after Ramp**: speed reference value before and after the unitary ramp is applied in the PID controller (expressed in rpm).
- **PID Ramp**: PID acceleration/deceleration ramp, defined to go from [Min PID reference] to [Max PID reference] (expressed in seconds with a standard of 0.0 s).

4.2.8. DIN VDE 0530

In this section, the interface developed to implement the induction machine types of working duties (DIN VDE 0530) is presented. Using this interface, allows the user to check the performance of an induction motor when working in all different duties.

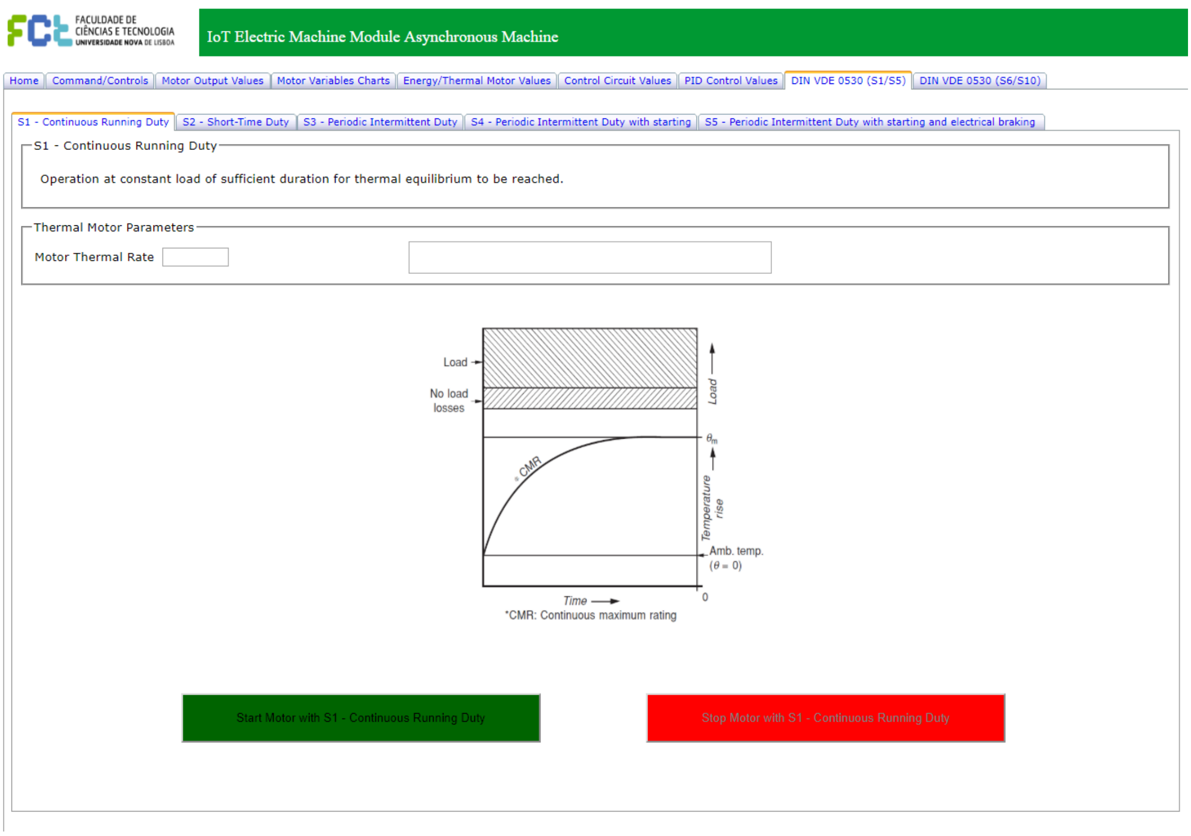


Figure 4-10 – DIN VDE0530 – User interface for S_1 – Continuous Duty.

If a motor is working in S_1 – Continuous duty, the reference frequency will be the nominal frequency (50Hz), with a load applied in near rated conditions. Using this interface, the user can see in real-time the motor’s thermal state, followed by a string that defines if the motor is working in a thermal steady state (with motor thermal state of 100%), or if the motor is reaching an overload state (corresponding to motor thermal state of 118%).

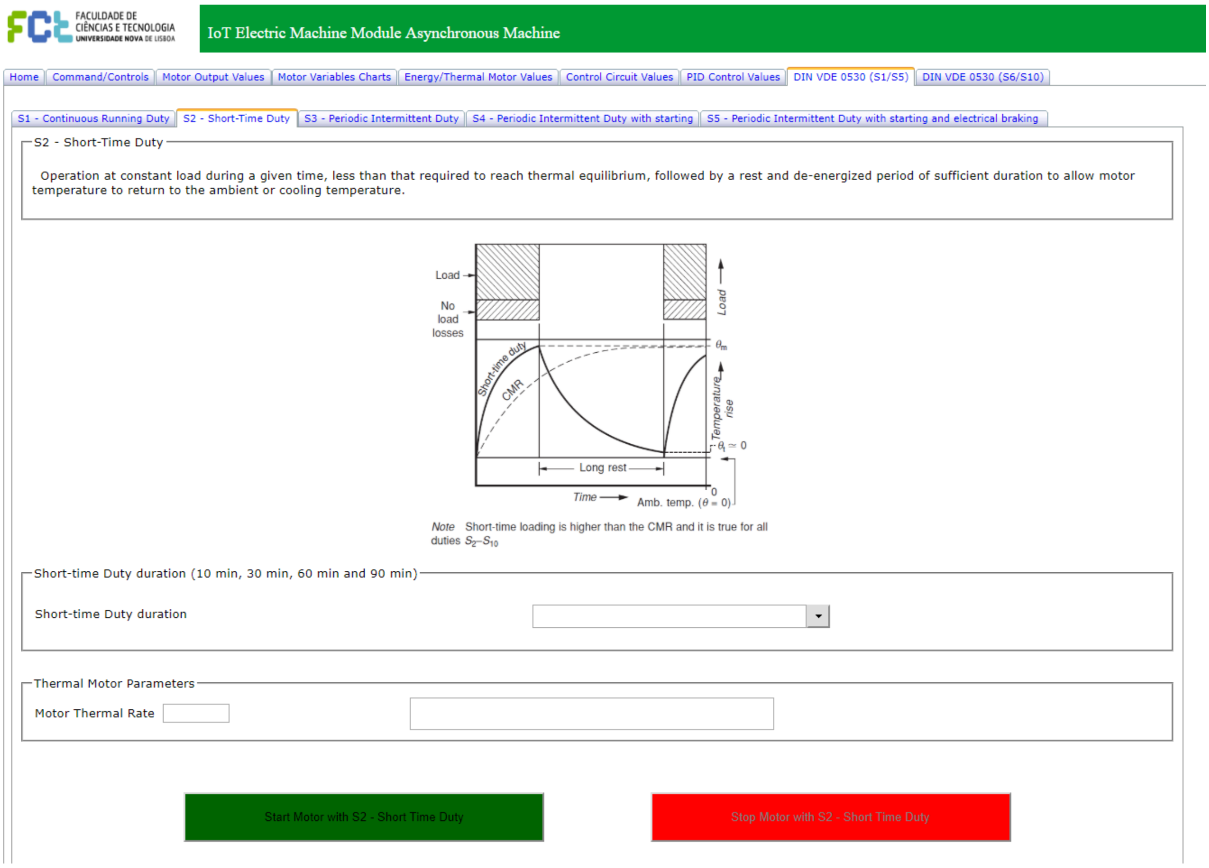


Figure 4-11 – DIN VDE0530 – User interface for S_2 – Short-time Duty.

If a motor is working in S_2 – Short-time duty, the user can define the short-time duration from a combo box (with the options of 10, 30, 60 and 90 minutes). After the option is defined, the motor starts working at the reference frequency (50 Hz) and near-rated load. The working cycle of the induction motor will be short enough so that in each duty cycle the motor can retain its original motor thermal state (implying no motor heating between cycles).

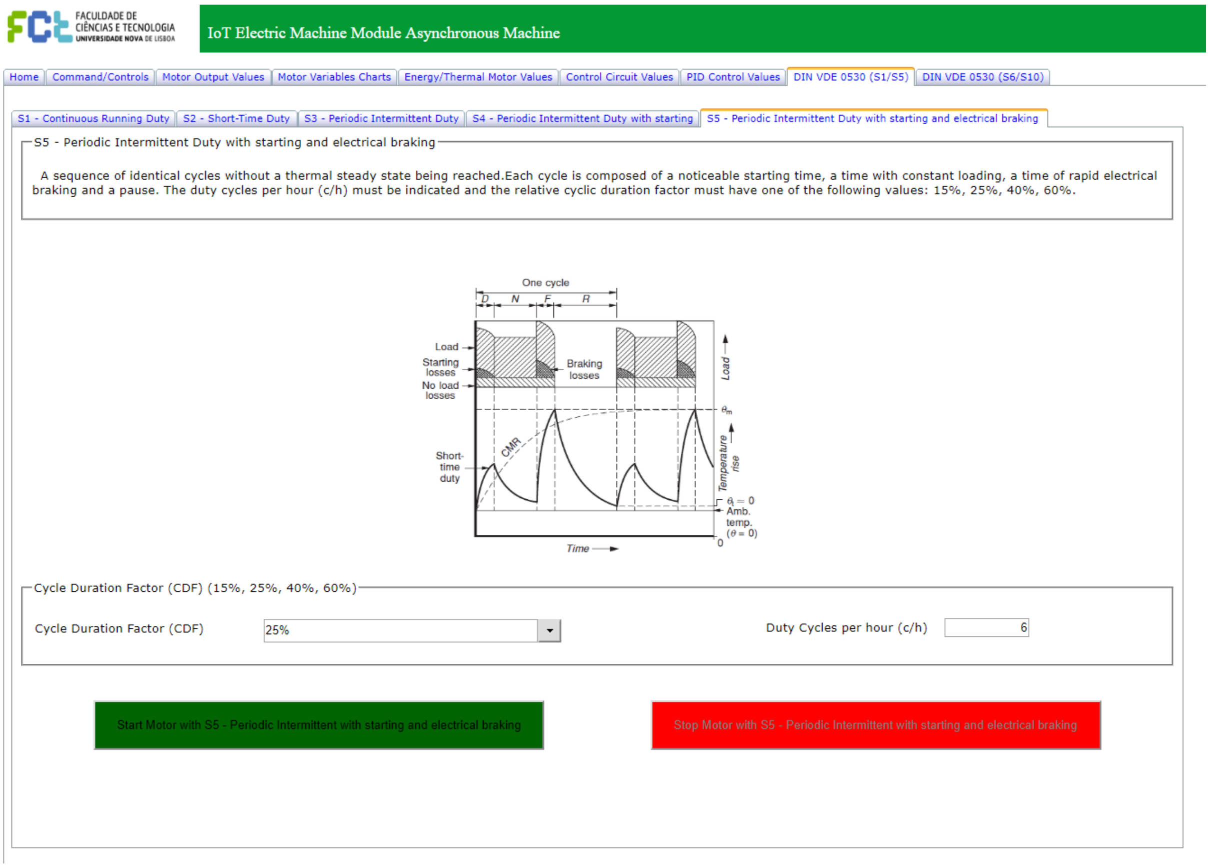


Figure 4-12 – DIN VDE0530 – User interface for S_5– Periodic Intermittent Duty with start and electrical braking.

A motor working in S_5 – Periodic Intermittent Duty with starting and electrical braking, will perform its duty cycle accordingly with the user's inputs introduced in Cyclic Duration Factor (CDF) (with the options of 15%, 25%, 40% and 60%), and the number of Duty Cycles per hour (c/h). Both these variables will define the length of working in near-rated conditions and the rest period between each duty cycle.

4.3. Altivar Process ATV600 – Modbus TCP

Modbus TCP telegrams are not only Modbus standard requests and responses encapsulated in TCP frames.

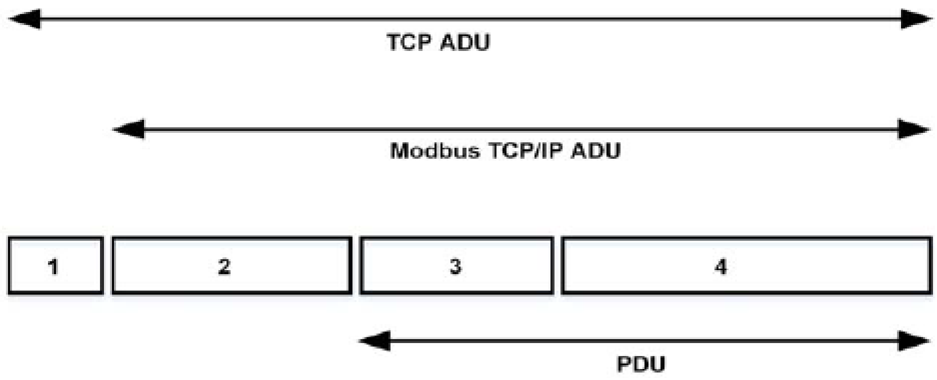


Figure 4-13 Altivar Process ATV600 Modbus TCP frame [16].

1 - TCP header
2 - MBPA: Modbus application protocol header
3 - ADU: Application data unit
4 - PDU: Protocol data unit (The Modbus message itself)

The Modbus TCP option supports the following services:

Table 4-1 Altivar Process ATV600 Modbus TCP services

Function Name	Code		Description
	Dec	Hex	
Read Holding Registers	03	03 Hex	Read N output words
Write 1 output word (Unit ID 0-248 only)	07	07 Hex	Write 1 output word
Write Multiple Registers	16	10 Hex	Write N output word
Read/write multiple registers (Unit ID 0-48 and 255)	23	17 Hex	Read/Write multiple registers

Command Register

To send command controls (start/stop motor) to the variable speed drive ATV 640 Schneider, the following bit mapping of the command control must be considered (changing bit values allows the following motor operations):

Table 4-2 Bit mapping of the command register (bit 0 to bit 7).

Bit 7	Bit 6	Bit 5	Bit 4	Bit 3	Bit 2	Bit 1	Bit 0
Fault reset	Reserved (=0)	Reserved (=0)	Reserved (=0)	Enable Operation	Quick Stop	Enable Voltage	Switch On
0 to 1 transition= Error is reset (after cause of error is no longer active)				1 = Run Command	0 = Quick stop active	Authorization to supply AC Power	Mains Contactor Control

Table 4-3 Bit mapping of the command register (bit 8 to bit 15).

Bit 15	Bit 14	Bit 13	Bit 12	Bit 11	Bit 10	Bit 9	Bit 8
Manufacturer specific assignable	Manufacturer specific assignable	Manufacturer specific assignable	Manufacturer specific assignable	Manufacturer specific	Reserved (=0)	Reserved (=0)	Halt
				0 = Forward direction asked 1 = Reverse direction asked			Halt

Table 4-4 Example of the bit mapping of the command register.

Command	State Transition	Final Operation State	Bit 7	Bit 3	Bit 2	Bit 1	Bit 0	Example Value
			Fault Reset	Enable Operation	Quick Stop	Enable Voltage	Switch On	
Shutdown	2, 6, 8	3 – Ready to switch on	X	X	1	1	0	0006 Hex
Switch On	3	4 – Switched On	X	X	1	1	1	0007 Hex
Enable Operation	4	5 – Operation Enabled	X	1	1	1	1	000F Hex
Disable Operation	5	4 – Switched On	X	0	1	1	1	0007 Hex
Disable Voltage	7, 9, 10, 12	2 – Switch on Disabled	X	X	X	0	X	0000 Hex
Quick Stop	11	6 – Quick Stop active	X	X	0	1	X	0002 Hex
	7, 10	2 – Switch on Disabled						
Fault Reset	15	2 – Switch on Disabled	0 → 1	X	X	X	X	0080 Hex

4.3.1. Motor instructions examples – Reading Motor Variables

Using the instructions described in Table 4-1 and an implementation of the Modbus protocol, the motor working variables can be read using the following code:

```
ushort ID = 3;
byte unit = 0;
ushort StartAddress = 0;
byte Length = 0;
byte[] data = new Byte[0];
int i = 0; /// valor inteiro do vector word
```

```
// motor variables
StartAddress = 3202;
Length = 30;
MBmaster.ReadHoldingRegister(ID, unit, StartAddress, Length, ref data);
i = 0;
k = HandleWord(data, Length, i);
m = HandleNegativeValues(k);
Motor.MotorFrequency[n] = (float)m / (float)(10);
i = 2;
Motor.MotorCurrent[n] = (float)HandleWord(data, Length, i) / (float)100;
i = 3;
k = HandleWord(data, Length, i);
m = HandleNegativeValues(k);
Motor.MotorTorque_perce[n] = (float)m / (float)(10);
i = 6;
Motor.MotorVoltage[n] = HandleWord(data, Length, i);
```

The Modbus instruction to read registers yields an array of bytes read in the drive, as all the motor's working variables are in sequential addresses only one instruction is needed for more efficiency (increasing the length read), as the information of each variable is contained in 2 bytes the following function was implemented (increasing the weight of the first byte to the left by 256, 2^8 +1):

```
private int HandleWord(byte[] data, byte Length, int i)
{
        int[] word = new int[1];

        if (Length < 2) return 0;
                word = new int[Length / 2];
        for (int x = 0; x < Length; x = x + 2)
        {
                word[x / 2] = data[x] * 256 + data[x + 1];
        }
        return word[i];
}
```

To handle negative numbers (when motor is working as a generator), the first bit of the 2 byte word must be considered, hence if the 2 byte word is bigger than 32767 (bigger than 2^15, the first bit is one) the value 65536 is subtracted (2^16) starting the negative number counting:

```
private int HandleNegativeValues(int n)
{
        if (n > 32767)
        {
                return (n - 65536);
        }
        return n;
}
```

4.3.2. Motor instruction examples – Writing Drive Registers

To write instructions in the drive using Modbus, the variable ID must be changed to 7 as described in Table 4-1. To set the motor's nominal variables values (introduced in the website by the user) the following code was applied (motor command register configuration must be changed to [Ethernet]):

```
//      Set Nominal Voltage

x = Int32.Parse(SetNominalVoltage.Text);
byte b0 = (byte)x;
byte b1 = (byte)(x >> 8);

ushort ID = 7;
byte unit = 0;
ushort StartAddress = 9601;
byte[] values = { b1, b0 };
byte[] result = new Byte[0];

MBmaster.WriteSingleRegister(ID, unit, StartAddress, values, ref result);
```

The Start/Stop Motor instructions were implemented with (as described in Table 4-2 and Table 4-3):

```
//      Start Motor

b0 = (byte)1;
b1 = 0;

ID = 7;
unit = 0;
StartAddress = 8501;
byte[] values = { b1, b0 };
result = new Byte[0];

MBmaster.WriteSingleRegister(ID, unit, StartAddress, values, ref result);


//      stop the motor

byte b0 = (byte)0;
byte b1 = 0;

ID = 7;
unit = 0;
StartAddress = 8501;
byte[] values = { b1, b0 };
byte[] result = new Byte[0];

MBmaster.WriteSingleRegister(ID, unit, StartAddress, values, ref result);
```

The reference frequency of the motor (introduced by the user or standard 50 Hz, the variable unit is 0.1 Hz) is:

```
//Reference Frequency 50Hz

int x = 50;

byte b0 = (byte)x;
byte b1 = (byte)(x >> 8);

ID = 7;
unit = 0;
StartAddress = 8502;
byte[] values = { b1, b0 };
byte[] result = new Byte[0];

MBmaster.WriteSingleRegister(ID, unit, StartAddress, values, ref result);
```

The acceleration ramp time (ACC) or the type of stop can be changed using the following instructions (the variable unit of ACC is 0.1 s):

```
// Acceleration time from 0 to 50 Hz

int y = 50;

byte b0 = (byte)y;
byte b1 = (byte)(y >> 8);

ushort ID = 7;
byte unit = 0;
ushort StartAddress = 9001;
byte[] values = { b1, b0 };
byte[] result = new Byte[0];

MBmaster.WriteSingleRegister(ID, unit, StartAddress, values, ref result);


// Type of Stop - DC Injection

b0 = (byte)3;
b1 = 0;

ID = 7;
unit = 0;
StartAddress = 11201;
byte[] values = { b1, b0 };
result = new Byte[0];


MBmaster.WriteSingleRegister(ID, unit, StartAddress, values, ref result);
```

5. Simulation and Experimental Results

This chapter presents the work's evaluation in two different ways, firstly the website functionalities are presented for an induction motor working in near-rated conditions, validating the remote monitoring and controlling of an induction motor through an IoT module, which can also be used as an e-learning platform. Secondly the different types of induction motor working cycles are developed using code, allowing the user to see the motor's behavior in all duty cycles.

5.1. System Validation

To test the web platform developed, an induction motor was connected to the variable speed drive Schneider 630, and the connection between the IIS server and the variable speed drive was established by introducing the variable speed drive's IP in the website. Pressing the connection button, all variables related to the ethernet configurations, speed limits and ramps and the mains parameters values can be seen in real-time:

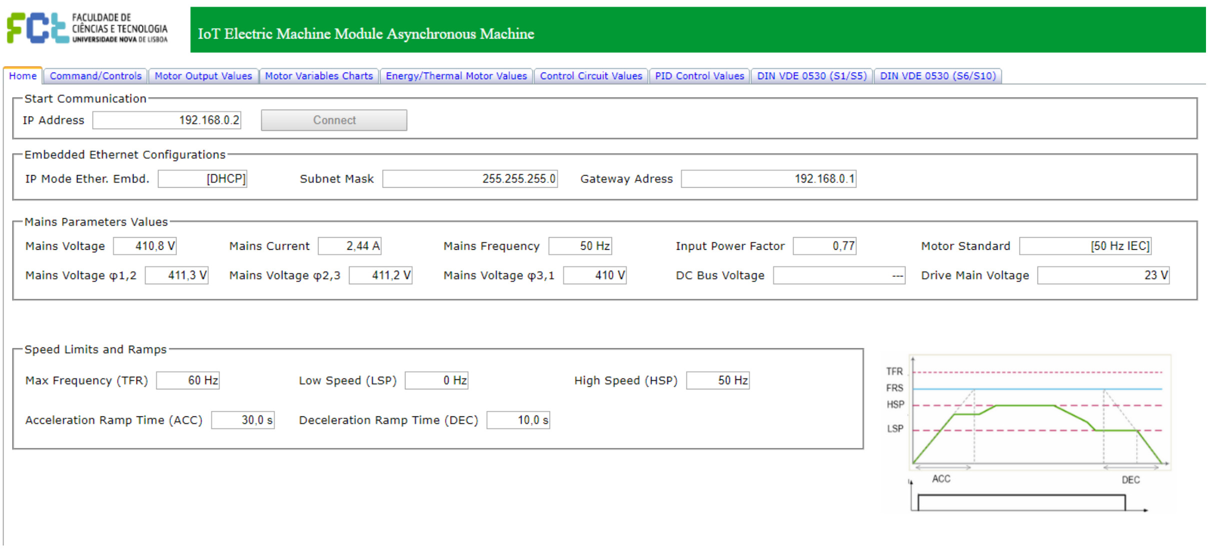


Figure 5-1 System Validation - Home Tab for an induction motor working in near-rated conditions.

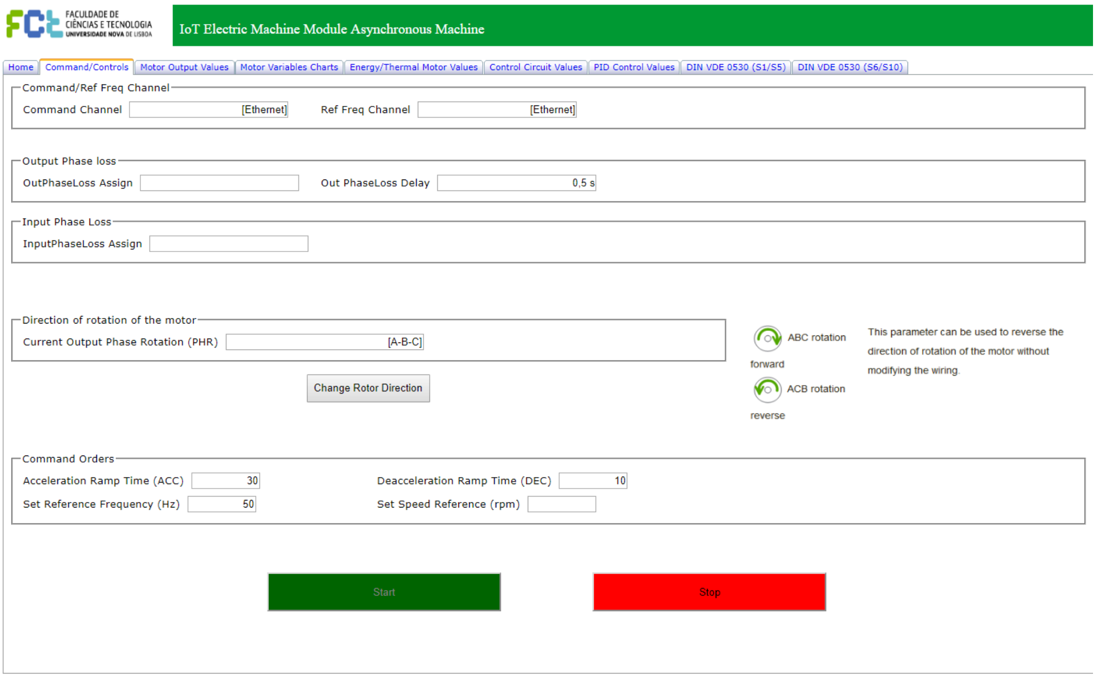


Figure 5-2 System Validation – Command Tab for an induction motor working in near-rated conditions.

In the next tab (Command/Controls), the motor's starting instruction was defined by introducing the following variables: Acceleration Ramp time (ACC) of 30 seconds (time in seconds, in which the motor goes from the speed of 0 Hz to 50 Hz), Deacceleration Ramp time (DEC) of 10 seconds (time in seconds, in which the motor goes from the speed of 50 Hz to 0 Hz) and a reference frequency of rated value (50Hz).

The motor used in all the Simulation and Experimental Results section, had the rated values (from the motor plate):

- Nominal Voltage: 380 V
- Nominal Current: 3,2 A
- Nominal Frequency: 50 Hz
- Nominal Power: 1,5 kW
- Nominal Speed: 2880 rpm
- FP: 0,84

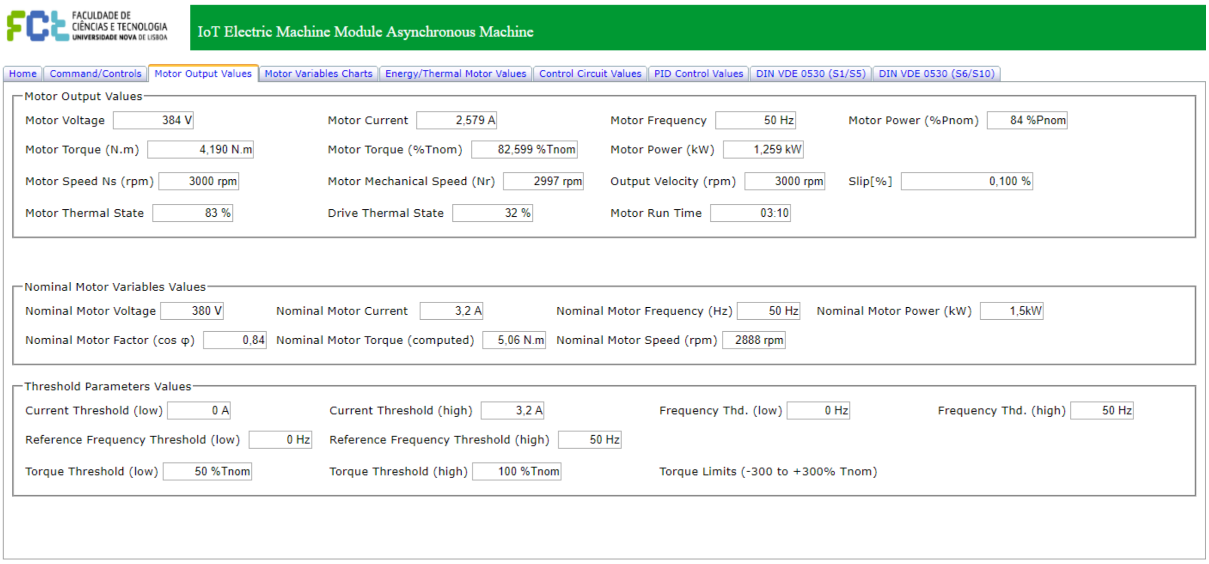


Figure 5-3 System Validation – Motor Output values Tab for an induction motor working in near-rated conditions.

After the start command was given, the motor worked for several minutes in near-rated conditions (with a near-rated load). In the Motor Output Values tab, the user can see in real-time all the motor's working variables. Since the acceleration time (time in seconds, the motor takes from the speed of 0 Hz to 50 Hz) introduced was 30 seconds, hence at 3 minutes and 10 seconds the motor was already operating at near-rated conditions (near-rated voltage, current, frequency, power, torque, rotor speed, motor speed).

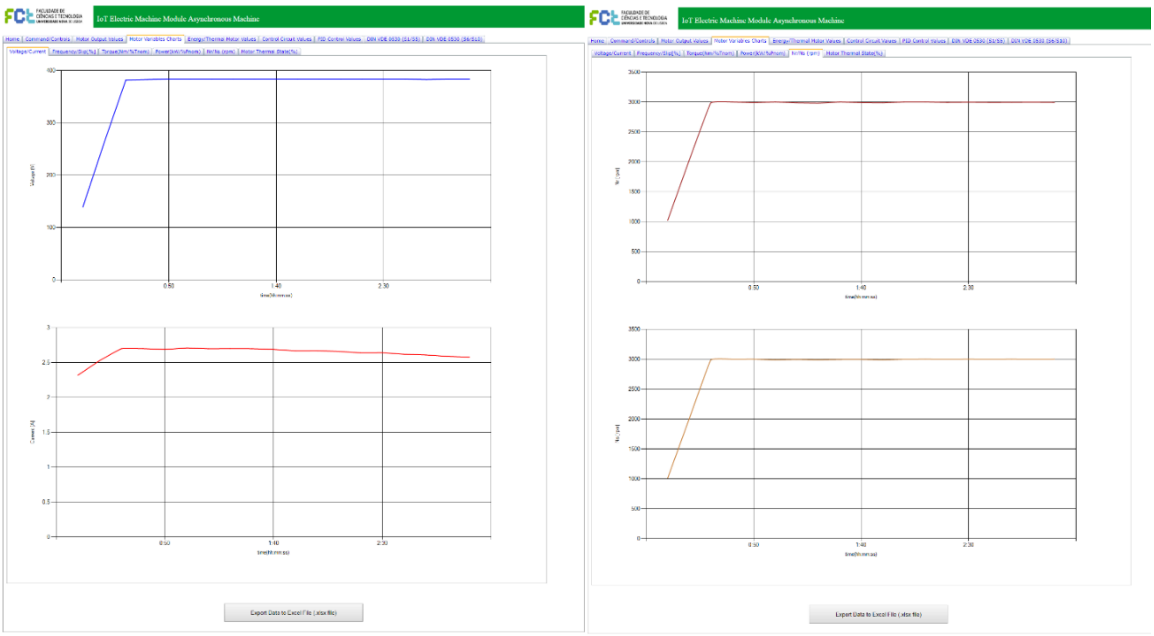


Figure 5-4 System Validation – Voltage/Current and Nr/Ns real-time motor charts.

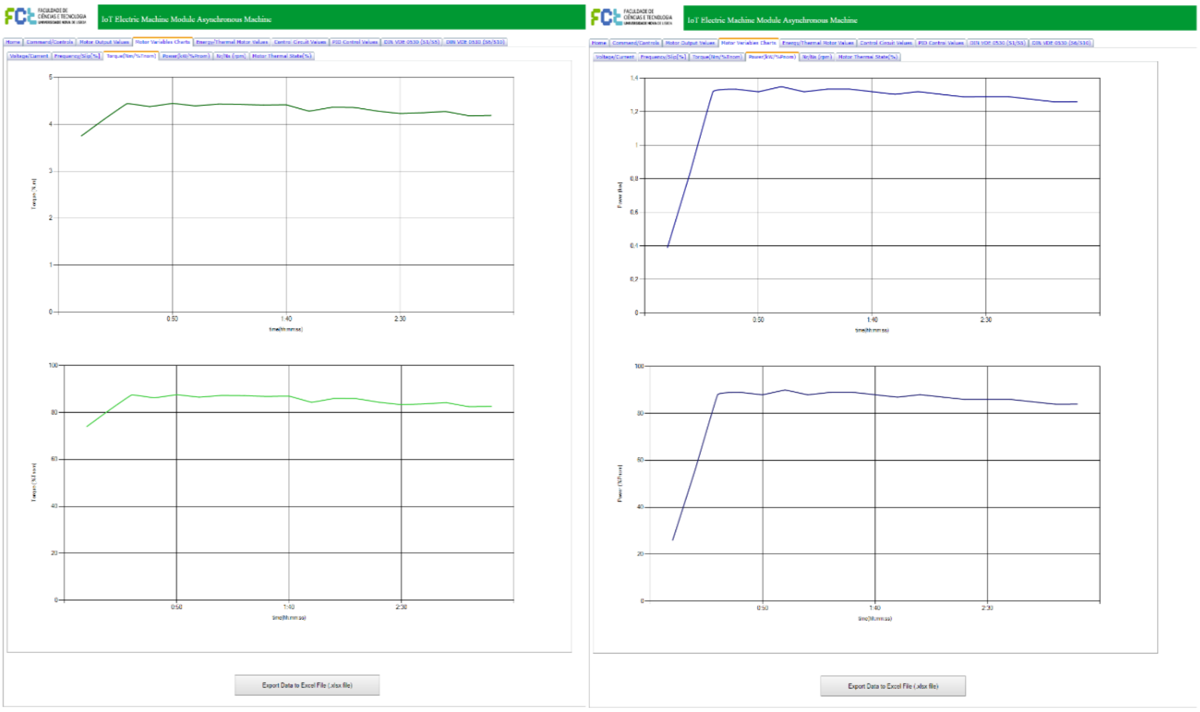


Figure 5-5 System Validation – Torque/Power real-time motor charts.

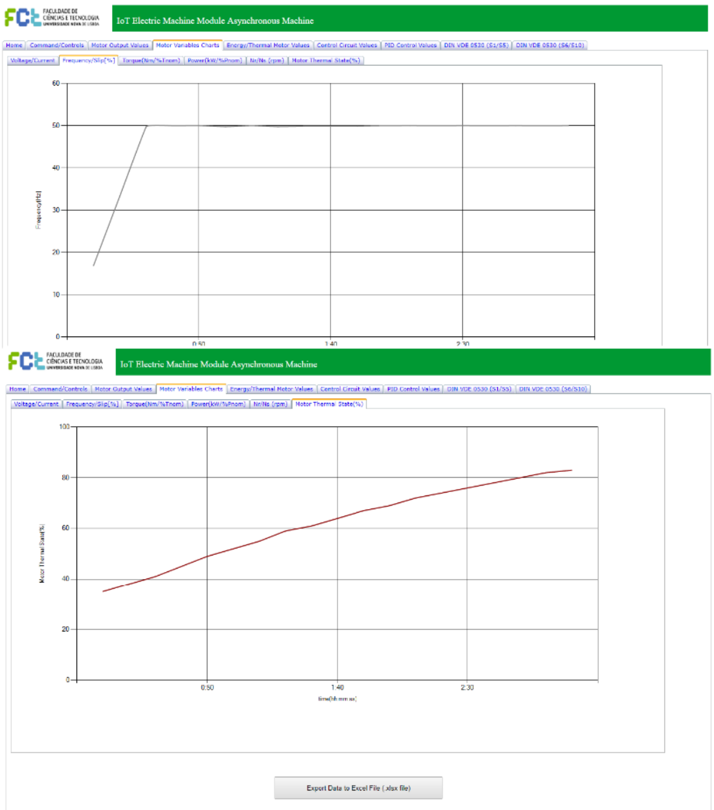


Figure 5-6 System Validation – Frequency and Motor Thermal State real-time motor charts.

In the motor's variables charts tab, the user can see in real time the motor's working variables charts (voltage, current, frequency, power, torque, Nr, Ns and the motor thermal state), allowing the user to check the variables behavior during all the motor's working cycle. In this example, the motor's variables started from zero to near-rated conditions, which are achieved after the motor is working for 30 seconds. After 30 seconds the motor's variables remain the same value (near-rated values), except for the motor thermal state which doesn't stop increasing to near 100 %, which is the motor's thermal equilibrium. This tab also allows the user to save all the motor's variables values from the beginning of the test until the end in an excel file (.xlsx file) in the client side.

5.2. DIN VDE 0530

An induction motor module was created, in which the motor can be tested running in every working duty defined in DIN VDE 0530 [22]. The motor's performance can be monitored to see if an induction motor is appropriate for a certain duty. The tab was programmed (in C#) using timers so the user can define several variables such as:

- Cycle Duration Factor (CDF)
- Duty Cycles per hour (c/h)
- Reference Frequency/Speed
- Acceleration/Deceleration Time

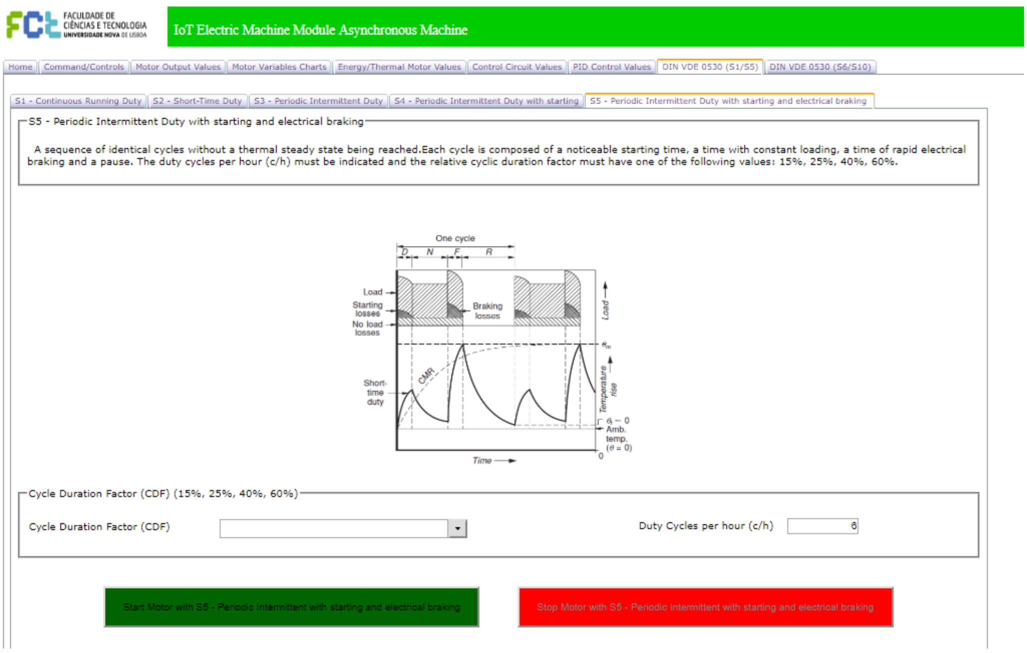


Figure 5-7 DIN VDE 0530 monitoring induction motor performance in every duty, User Interface (Webpage).

Table 5-1 DIN VDE 0530 Duties - Inputs/Outputs for the user and pre-set configurations.

Type of Duty	Inputs	Outputs	Configurations		
			ACC (acceleration ramp time)	DEC (deacceleration ramp time)	Type of Stop
S_1	-	Motor Thermal State (%) (0-99% motor thermal state not reached) (100-117% motor thermal state reached) (118%+ motor overload)	30 seconds	-	-
S_2	Short-time Duty Duration (10, 30, 60 or 90 minutes)	Motor Thermal State (%) Motor Thermal State of the cooling medium/ambient temperature	10 seconds	10 seconds	Stop on Ramp
S_3	Cyclic Duration Factor (CDF)	Motor variables Values (voltage, current, power, torque, Ns, Nr, motor thermal state)	10 seconds	10 seconds	Stop on Ramp
S_4	Cyclic Duration Factor (CDF), cycles per hours (c/h)	Motor variables Values (voltage, current, power, torque, Ns, Nr, motor thermal state)	5 seconds	10 seconds	Stop on Ramp
S_5	Cyclic Duration Factor (CDF), cycles per hours (c/h)	Motor variables Values (voltage, current, power, torque, Ns, Nr, motor thermal state)	5 seconds	-	Electrical braking
S_6	-	Motor variables Values (voltage, current, power, torque, Ns, Nr, motor thermal state)	30 seconds	-	-
S_7	CDF = 1	Motor variables Values (voltage, current, power, torque, Ns, Nr, motor thermal state)	5 seconds	-	Electrical braking
S_8	3 motor speeds with three running times (w_1, w_2, w_3)	Motor variables Values (voltage, current, power, torque, Ns, Nr, motor thermal state)	5 seconds	-	Electrical braking

5.2.1. S_1 – Continuous Duty (CMR)

In this duty, the operation of the motor is at rated-conditions and sufficient duration for motor thermal equilibrium to be attained, possible applications of this induction motor duty cycle are blowers, fans, pumps and compressors.

To simulate the motor above working in this duty the reference frequency was set to 50 Hz, as there is no need for a high speed in a short period of time the acceleration ramp time (ACC) was set to 30 seconds (amount of time from a motor speed of 0 Hz to the nominal motor speed of 50 Hz).

The motor's variables values obtained using a sampling time of 10 seconds are:

Table 5-2 S1 Continuous Duty (CMR) motor variables values.

time (mm:ss)	Voltage (V)	Current (A)	Frequency (Hz)	Nr (rpm)	Ns (rpm)	Power (kW)	Torque (N.m)	Motor Thermal State (%)
00:10	139	2,139	16,89	1026	1014	0,389	3,753	35
00:20	263	2,529	33,40	2028	2004	0,839	4,109	38
00:30	382	2,700	49,79	2988	2988	1,320	4,438	41
00:40	383	2,700	50,00	2994	3000	1,320	4,377	45
00:50	384	2,690	49,79	3003	2991	1,350	4,393	49
01:00	384	2,710	49,799	3003	2991	1,350	4,393	52
01:10	384	2,700	50,00	2991	2997	1,320	4,428	55
01:20	384	2,700	49,79	2985	2991	1,335	4,423	59
01:30	384	2,700	49,90	3003	2997	1,335	4,408	61
01:40	384	2,690	49,90	2994	2997	1,320	4,413	64
01:50	384	2,670	49,90	2991	2991	1,304	4,281	67
02:00	384	2,670	50,00	3003	3000	1,320	4,362	69
02:10	384	2,660	50,00	3003	3000	1,305	4,357	72
02:20	384	2,640	50,00	2997	3000	1,289	4,281	74
02:30	384	2,640	50,00	3000	3000	1,289	4,230	76
02:40	384	2,619	50,00	2997	3000	1,289	4,246	78
…	…	…	…	…	…	…	…	…

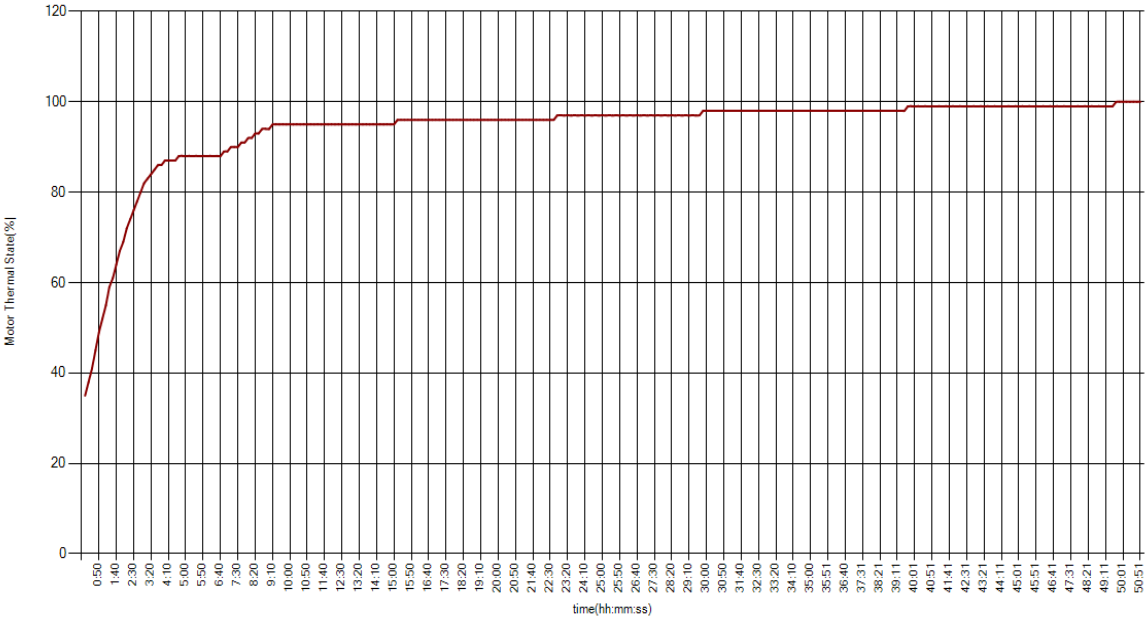


*Figure 5-8 Continuous Duty (CMR) - Motor Thermal State (%) (motor with a **hot start**).*

After rated conditions are achieved, the motor was left working for sufficient duration, so the thermal steady state of the motor is reached, this means the variable Motor Thermal State is approximately 100% (Figure 5-8). In this test, the motor had a hot start, as the motor thermal state begins with 35% (the motor thermal state corresponding to the cooling medium/ambient temperature is approximately 25%), meaning previous tests were made without giving the motor enough time to cool-down to ambient conditions.

The motor reached thermal equilibrium after approximately 50 minutes of working in near-rated conditions, as visible in the chart the variable motor thermal state is now in a stable condition, meaning it increases very slightly with time. The Duty S_1 – Continuous Duty (CMR) is the usual induction motor's working duty, meaning an induction motor must be capable of work for an unlimited period in rated conditions without the motor's thermal expectancy affected (Figure 5-8).

5.2.2. S_2 – Short-time Duty

Motor operation with a constant load during a given time, which is too short for motor thermal equilibrium to be reached, followed by a period of motor rest and de-energizing conditions of enough duration thus allowing the motor temperature to return to the ambient/cooling medium temperature. The motor duty cycle re-start should only begin when the motor has attained its ambient condition. The recommended values of short-time duty duration are 10, 30, 60 and 90 minutes, this variable (Short Time Duration) can be introduced by the user. The reference frequency was set to 50 Hz, the acceleration ramp time (ACC) was set to 10 seconds (amount of time from a motor speed of 0 Hz to the nominal motor speed of 50 Hz), and the deacceleration ramp time (DEC) was set to 10 seconds (amount of time for a motor speed of 50 Hz (nominal motor speed) to 0 Hz). In this duty, the rest/de-energized period must be long enough so the in the beginning of the next duty cycle, the motor has attained his ambient/cooling medium temperature, hence the working near-rated conditions was set to be one-third of the duty cycle duration (the rest being the rest de-energized period).

Input: Short-time Duty Duration = 10 minutes

Table 5-3 S2-Short-time Duty motor variables values.

time (mm:ss)	Voltage (V)	Current (A)	Frequency (Hz)	Nr (rpm)	Ns (rpm)	Power (kW)	Torque (N.m)	Motor Thermal State (%)
00:05	197	2,460	25,79	1590	1593	0,629	3,951	25
00:10	386	2,660	49,79	2997	2997	1,304	4,362	27
00:15	380	2,619	50,00	2997	3000	1,289	4,351	29
00:20	389	2,609	50,00	2997	3000	1,289	4,342	31
…	…	…	…	…	…	…	…	…
02:00	390	2,660	49,90	3000	3000	1,320	4,382	66
02:05	225	2,349	26,00	3006	2994	0,569	3,865	67
02:10	40	2,099	1,10	27	69	0	3,520	67
02:15	0	0	0	0	0	0	0	66
…	…	…	…	…	…	…	…	…
09:55	0	0	0	0	0	0	0	25
10:00	0	0	0	0	0	0	0	25
10:05	146	2,279	19,00	1155	1194	0,419	3,581	25
10:10	364	2,549	48,40	2919	2949	1,215	4,073	26

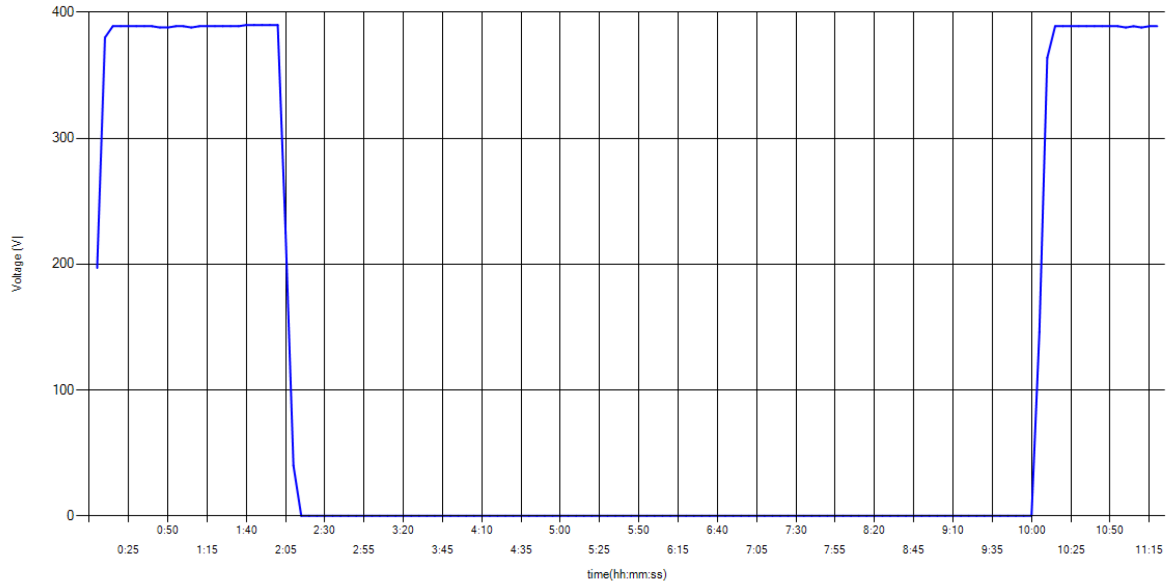


Figure 5-9 S2 Short-time Duty – Motor Voltage (V).

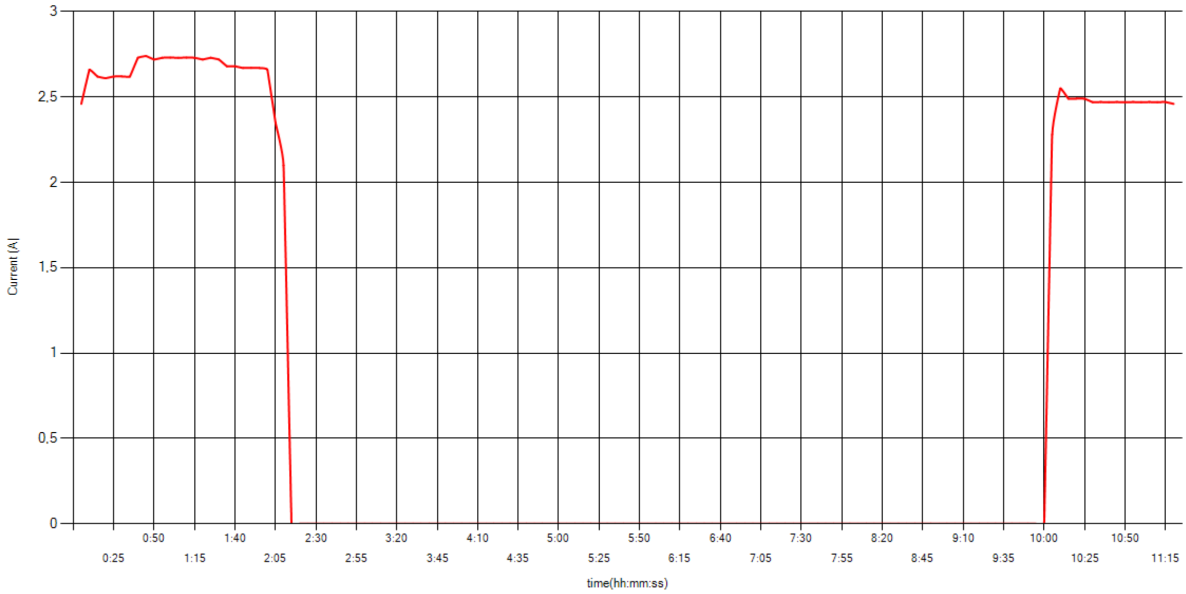


Figure 5-10 S2 Short-time Duty - Motor Current (A).

From the start until the first stop command (at 2 minutes mark), the voltage and current have near-rated values (approximal 380 V and 2,5 A). In the rest period (from 2 minutes until the start of the next duty cycle at 10 minutes) the voltage and current are zero, and then return to near-rated values in the beginning of the next duty cycle (at 10 minutes mark) (Figure 5-9 and Figure 5-10).

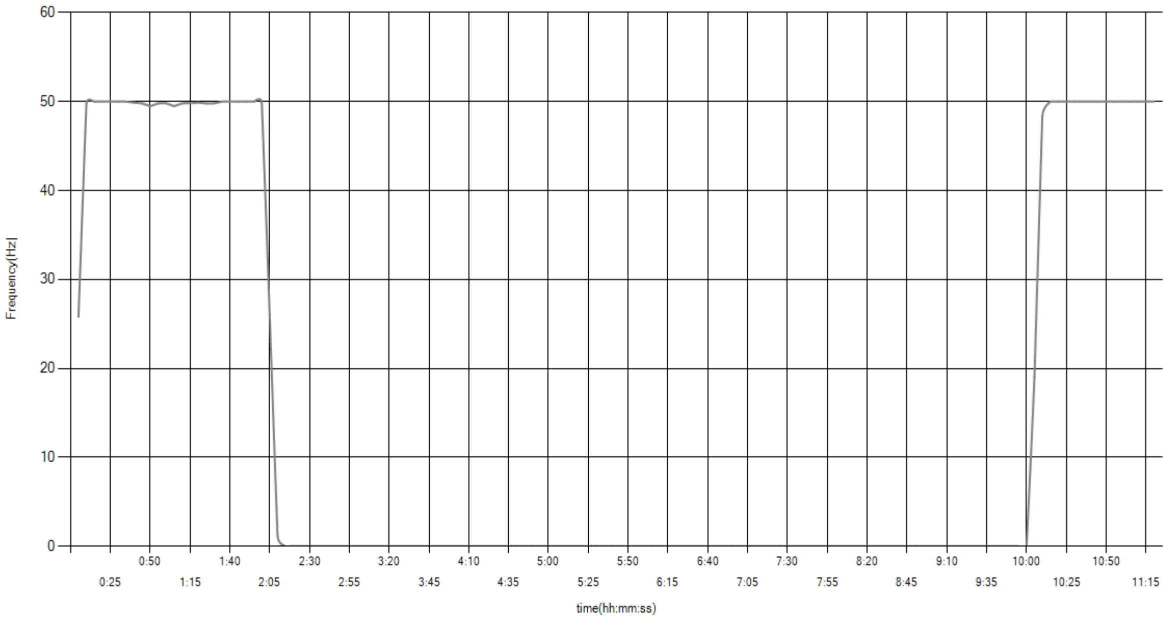


Figure 5-11 S2 Short-time Duty - Motor Frequency (Hz).

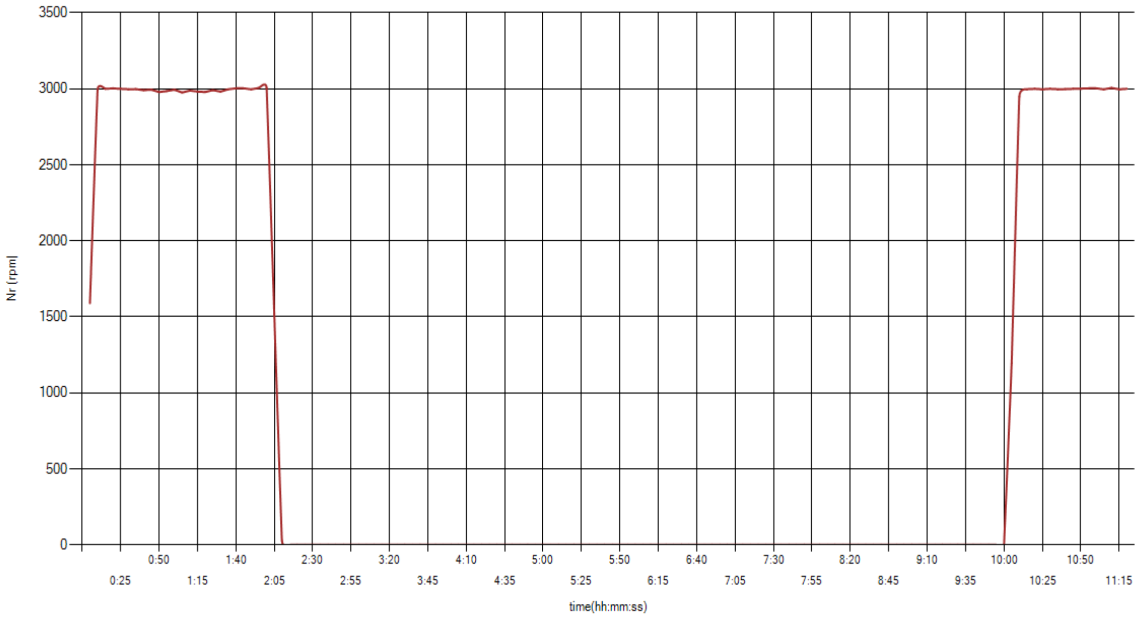


Figure 5-12 S2 Short-time Duty - Motor Rotor Speed Nr (rpm).

Similarly, to the voltage/current variables, the motor frequency and motor rotor speed have near-rated values during the first two minutes and then are zero in the rest period (from 2 minutes until the start of the next duty cycle at 10 minutes), after the rest period and in beginning of the next duty cycle, these variables return to near-rated values (Figure 5-11 and Figure 5-12).

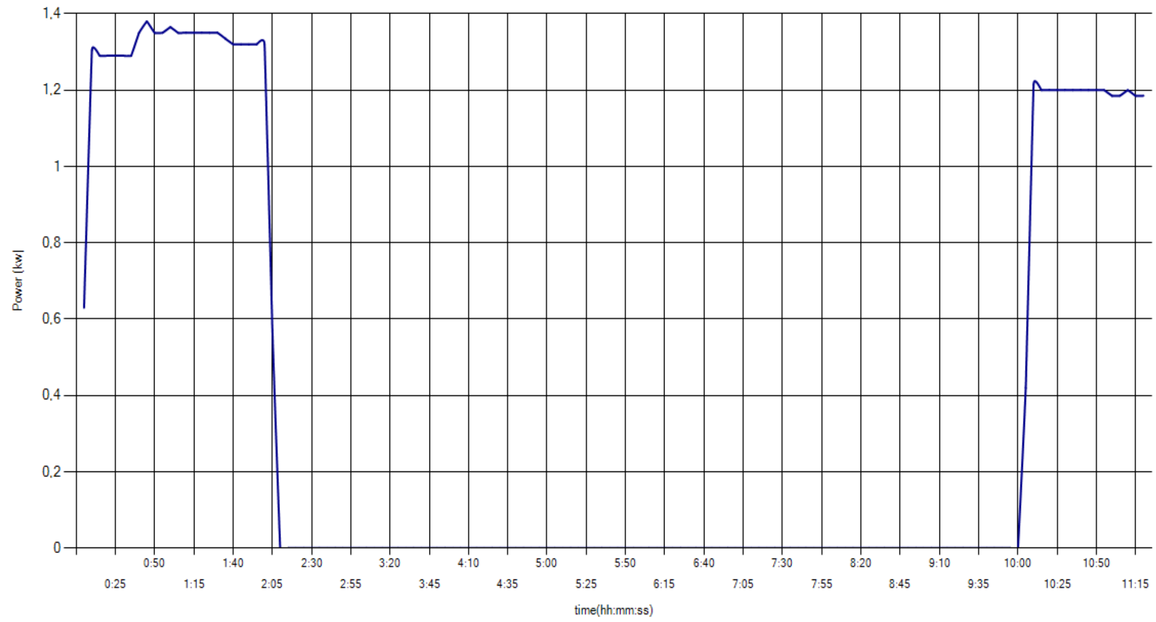


Figure 5-13 S2 Short-time Duty - Motor Power (kW).

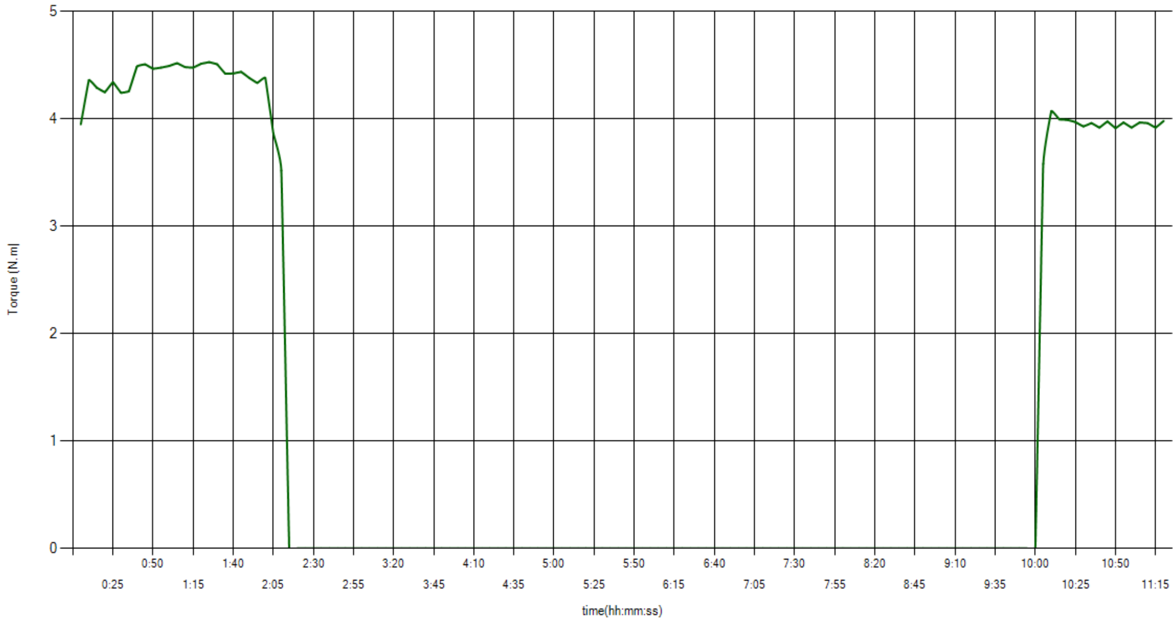


Figure 5-14 S2 Short-time Duty - Motor Torque (n.m).

The motor power and torque have also near-rated values during motor functioning (again in the first 2 minutes), going to zero in the rest period and then return to near-rated values in the next duty cycle at 10 minutes (the input of the short-time cycle duration introduced was 10 minutes). In this cycle, the motor must return to the ambient/cooling medium temperature in each new duty cycle, hence the rest period must be long enough to achieve this condition (Figure 5-13 and Figure 5-14).

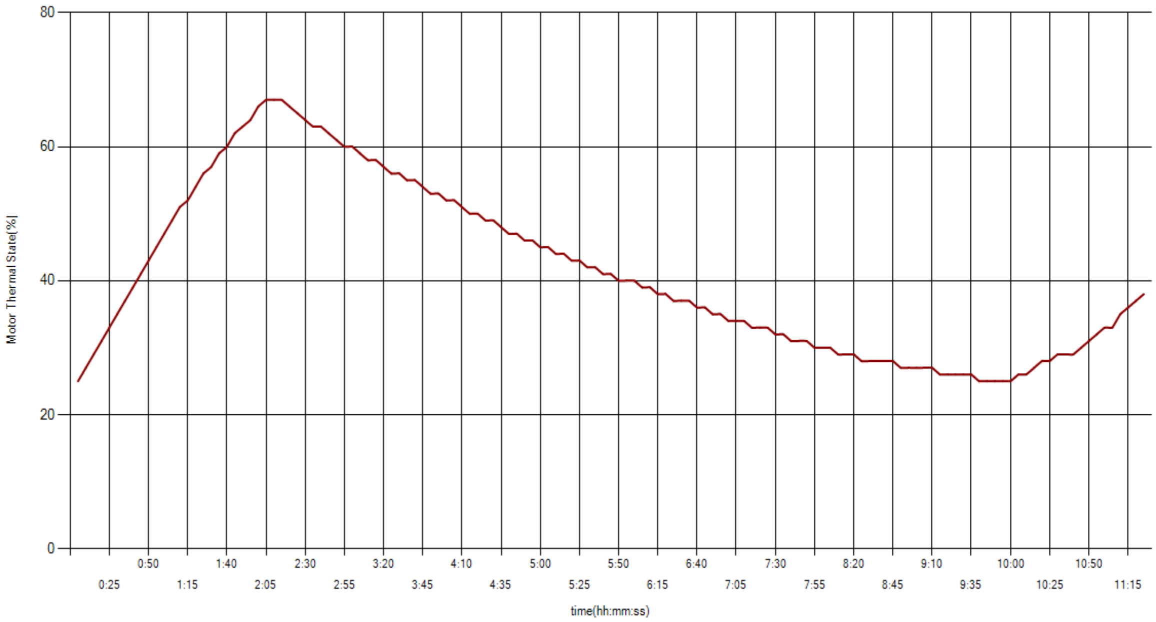


*Figure 5-15 S2 Short-time Duty - Motor Thermal State (%) (motor with a **cold start**).*

After start and working in near-rated conditions for approximately 2 minutes, the motor thermal state increased from the ambient/cooling medium temperature (corresponding to a value of 25%) to a motor thermal state of 67% at the end of the working duty cycle. From the end of the duty cycle (2 minutes mark) until the beginning of the next duty cycle (10 minutes mark) the thermal motor state decreased from 67% to 25% (corresponding to the ambient/cooling medium temperature), hence the rest/deenergized period was long enough, so initial conditions were restored. The main difference between duty cycle S_2 - short time duty and S_3 – Intermittent periodic duty, is that, in the short-time duty the rest and de-energized period must be long enough, so thermal conditions are restored in each duty cycle (there is no temperature rise in each duty cycle), hence in this case the motor had a working-period of one-fifth of the corresponding short-time duty duration (here, 2 minutes), the same was applied for other short-time duty durations (Figure 5-15).

5.2.3. S_3 – Intermittent periodic Duty

A sequence of indistinguishable duty cycles, with each motor duty cycle containing a period of operation at a constant load (rated load) with rated motor speed, followed by a motor period of rest and de-energized conditions, hence the duty cycle is too short for motor thermal equilibrium to be reached. In this induction motor duty cycle the starting current is not relevant, not affecting the motor temperature rise. Usual applications for this induction motor duty cycle are wire drawing machines and valve actuators.

Testing if a motor can perform in this particular type of duty, it was programmed so the machine stops every duty cycle duration and re-starts every 10 minutes (the duty cycle should have a duration of 10 minutes), the user was given the availability to choose from the following duty cycles: 15%, 25%, 40% and 60%.

In the following test, the duty cycle has the duration of 10 minutes and:

N = operation under rated conditions = 2 minutes and 30 seconds = 150 seconds
R= rest and de-energized period = 7 minutes and 30 seconds = 450 seconds

The cyclic duration factor (CDF) is then:

$$CDF(\%) = \frac{150}{150 + 450} \times 100 = 25\% \qquad (5\text{-}1)$$

The designation is then: $S_3 \; - 25\ \%$.

Input: Cyclic Duration Factor (CDF) = 25 %

The reference frequency was set to 50 Hz, as there is no need for a high speed in a short period of time the acceleration ramp time (ACC) was set to 30 seconds (amount of time from a motor speed of 0 Hz to the nominal motor speed of 50 Hz), and the deacceleration ramp time (DEC) was set to 10 seconds (amount of time for a motor speed of 50 Hz (nominal motor speed) to 0 Hz). A sample time of 5 seconds was considered in this duty.

Table 5-4 S3 Intermittent-periodic Duty Motor's Variables Values

time (mm:ss)	Voltage (V)	Current (A)	Frequency (Hz)	Nr (rpm)	Ns (rpm)	Power (kW)	Torque (N.m)	Motor Thermal State (%)
00:05	78	2,279	8,699	537	519	0,194	3,388	44
00:10	140	2,349	16,89	1026	1014	0,389	3,464	44
00:15	202	2,450	25,20	1533	1509	0,600	3,591	44
00:20	264	2,369	33,40	2034	2019	0,855	3,759	44
00:25	326	2,559	42,00	2532	2517	1,125	3,936	45
00:30	384	2,670	49,79	3000	2985	1,215	4,058	47
00:35	386	2,730	49,79	2979	2988	1,350	4,053	48
00:40	386	2,720	49,79	2997	2988	1,320	4,038	50
…	…	…	…	…	…	…	…	…
02:20	386	2,650	50,00	3003	3000	1,304	4,317	78
02:25	386	2,650	50,00	3006	3003	1,304	4,291	79
02:30	386	2,630	50,00	2997	3000	1,289	4,311	80
02:35	227	2,299	26,29	1545	1581	0,569	3,723	81
02:40	43	2,049	1,700	57	87	0,015	3,363	81
02:45	0	0	0	0	0	0	0	80
02:50	0	0	0	0	0	0	0	79

Here the [**Type of Stop**] selected is [**Stop on Ramp**] with the duration of 10 seconds, which gradually reduces the motor’s voltage and current.

The machine's variables values charts obtained during S_3 - Intermittent periodic loading are represented below (with a cyclic duration factor of 25% and duration of one duty cycle of 10 minutes):

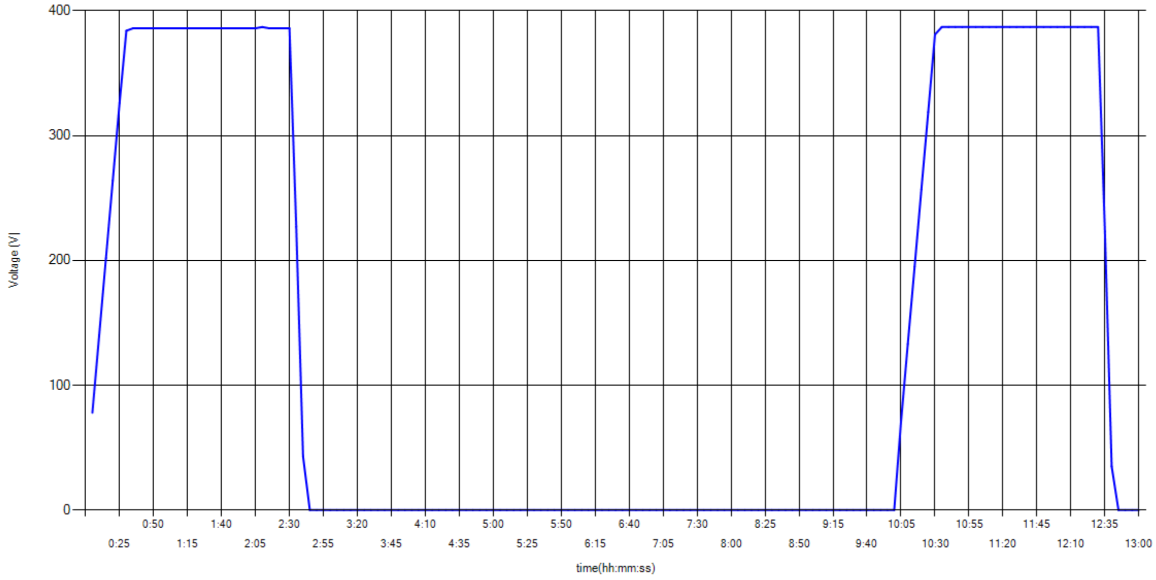


Figure 5-16 S3 Intermittent-periodic Duty Motor Voltage (V).

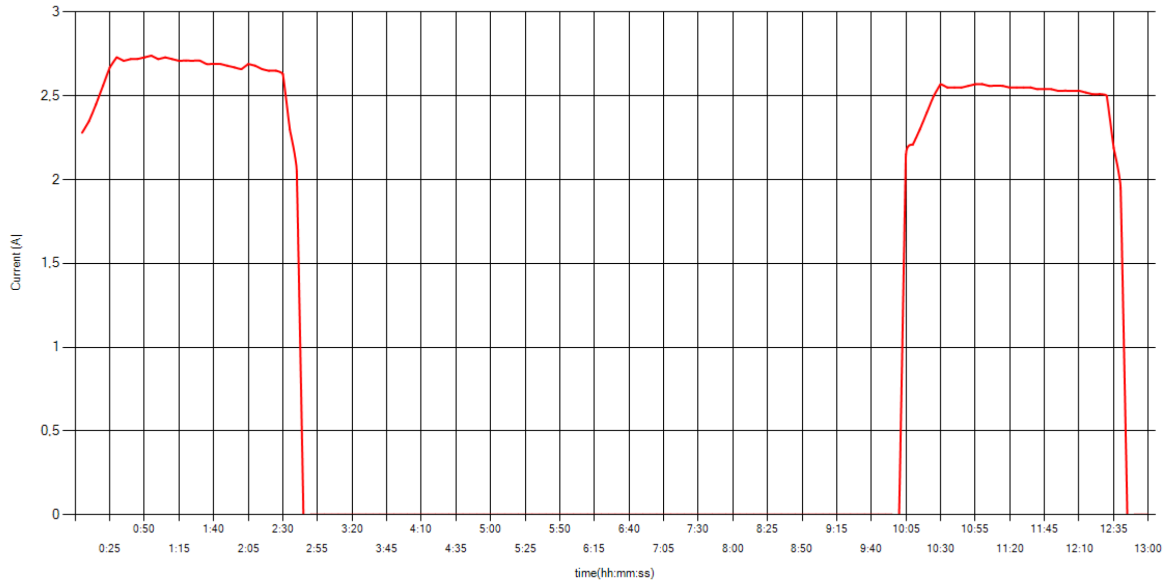


Figure 5-17 S3 Intermittent-periodic Duty Motor Current (A).

As excepted during the duty cycle duration, the voltage and current have near-rated values, when the duty cycle ends the voltage and current go to zero, beginning then, the rest and de-energized period. In the charts is visible that the voltage and current don't decrease instantly to zero when the machine's stop command is given (in 2 minutes and 30 seconds) but take approximately 10 seconds from the near-rated values to zero (Figure 5-16 and Figure 5-17).

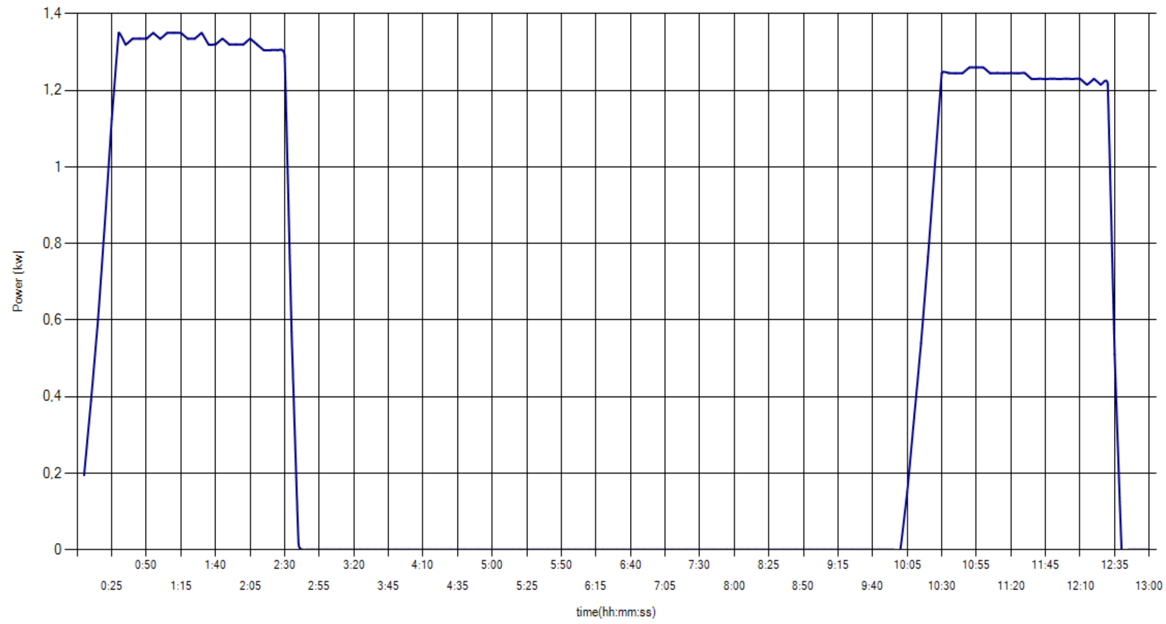


Figure 5-18 S3 Intermittent-periodic Duty Motor Power (kW).

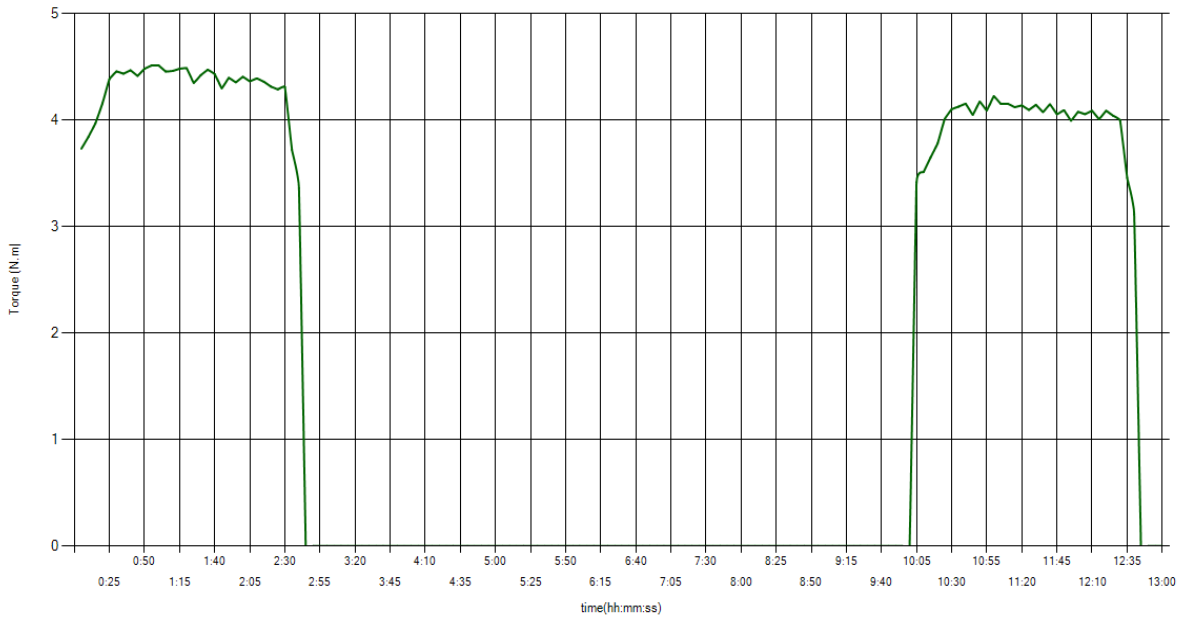


Figure 5-19 S3 Intermittent-periodic Duty Motor Torque (n.m).

Similarly, the torque and power don't decrease instantly to zero when the machine's stop command is given at 2 minutes and 30 seconds, instead these variables take around 10 seconds to go to the rest and de-energized period, we can conclude also that the torque decreases more slowly, as the rotor's inertia takes longer to stop (Figure 5-18 and Figure 5-19).

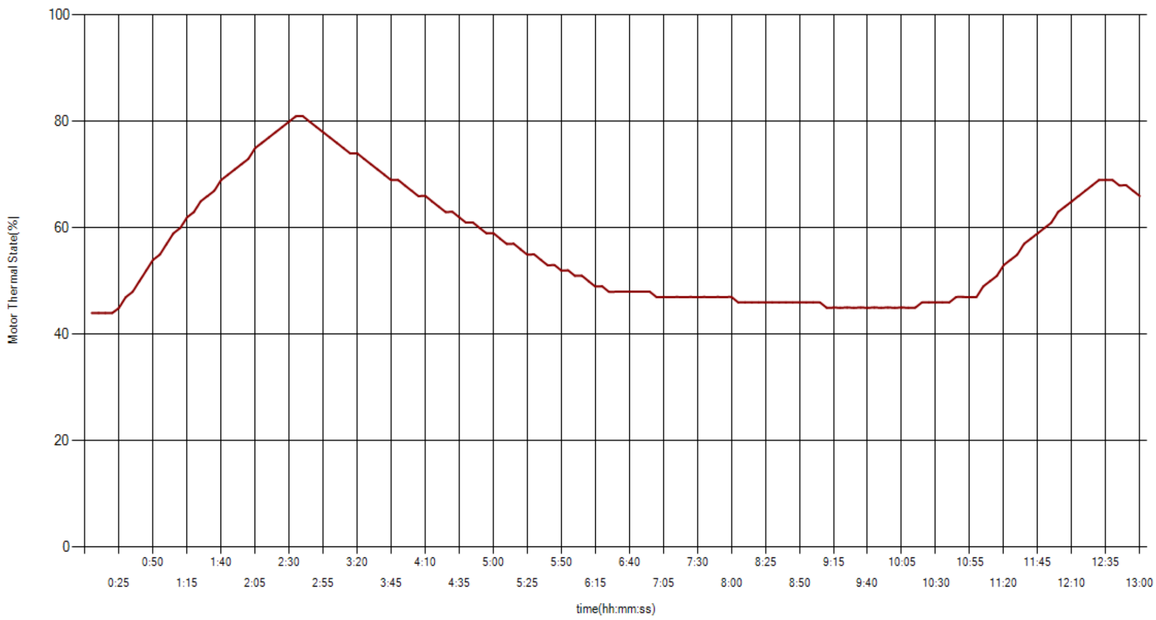


*Figure 5-20 S3 Intermittent-periodic Duty Motor Thermal State (%) (motor with a **hot start**).*

The Motor Thermal State increases greatly during operation with near-rated load, to near thermal equilibrium. After stopping the motor's operation at 2 minutes and 30 seconds the thermal state begins to decrease (rest and de-energized period), reaching the motor thermal state of 45% (at 10 minutes mark), the motor thermal state corresponding to the cooling medium (at 0 seconds) is 44%, so each duty cycle there is a small increase in temperature. The difference between S_3 and S_2, is that, in the short time duty, the rest and de-energized period is long enough, so that during each duty cycle there is no increase of temperature (implies that the motor thermal state remains the same after each duty cycle) (Figure 5-20).

5.2.4. S_4 – Intermittent periodic Duty with Start

A sequence of indistinguishable duty cycles, with each duty cycle containing a relevant period of motor starting, followed by a period of motor operation at rated conditions. Before the start of the next duty cycle, there is a rest and de-energized period, hence the duty cycle is too short not allowing motor thermal equilibrium to be reached. In this induction motor duty cycle, the motor goes to rest by natural deceleration by the respective motor load, after the supple source has been disconnected, or by using mechanical braking which doesn't affect thermally the motor's load, hence not causing more heating to the windings. Usual applications for this induction motor duty cycle are lifts, cranes and hoists.

To define this duty cycle the following variables are needed:

- Number of duty cycles per hours (c/h)
- Cyclic Duration Factor (CDF)

The Cyclic Duration Factor is calculated by:

$$Cycle\ Duration\ Factor\ (\boldsymbol{CDF}) = \frac{D+N}{D+N+R} \tag{5-2}$$

where,

D = period of motor starting

N = motor operation under rated speed and load

R = motor rest and de-energized period

Both variables can be introduced by the user, the variables values considered were:

S_4 – 25 % - 6 c/h

Input: Number of duty cycles per hours (c/h) = 6 and Cyclic Duration Factor (CDF) = 25 %

With D = period of starting = 5 seconds, N = 2 minutes and 25 seconds, R = 7 minutes and 30 seconds.

$$CDF(\%) = \frac{5+145}{145+5+450} \times 100 = 25\% \tag{5-3}$$

The reference frequency was set to 50 Hz, to have a significant period of starting, the acceleration ramp time (ACC) was set to 5 seconds (amount of time from a motor speed of 0 Hz to the nominal motor speed of 50 Hz), thus increasing the starting current I_{st} and consequently increasing motor and winding heating (greater Motor Thermal State), the deacceleration ramp time (DEC) was set to 10 seconds (amount of time from a motor speed of 50 Hz (nominal motor speed) to 0 Hz). A sample time of 1 seconds was considering during the motor starting and then increased to 5 seconds when near-rated conditions are achieved.

Table 5-5 S4 Intermittent-periodic with start Duty Motor's Variables Values.

time (mm:ss)	Voltage (V)	Current (A)	Frequency (Hz)	Nr (rpm)	Ns (rpm)	Power (kW)	Torque (N.m)	Motor Thermal State (%)
00:01	119	2,539	17,29	1113	1035	0,449	3,530	29
00:02	201	2,700	28,10	1770	1701	0,779	4,185	30
00:03	289	2,769	39,50	2445	2385	1,125	4,464	31
00:04	324	2,809	44,00	2694	2637	1,259	4,560	31
00:05	375	2,760	49,09	2964	2949	1,365	4,575	32
00:10	389	2,740	49,79	2991	2988	1,365	4,509	33
00:15	386	2,750	49,40	2958	2964	1,350	4,550	36
…	…	….	…	…	…	…	…	…
02:20	389	2,660	50,00	3000	3000	1,320	4,317	76
02:25	389	2,650	50,00	3000	3000	1,304	4,367	77
02:30	389	2,650	50,00	3003	3000	1,304	4,266	78
02:35	225	2,410	26,00	1524	1563	0,600	3,901	78
02:40	39	2,079	1,100	30	69	0	3,464	79
02:45	0	0	0	0	0	0	0	78
02:50	0	0	0	0	0	0	0	77

As expected, decreasing the acceleration ramp time (ACC) (amount of time from a motor speed of 0 Hz to the nominal motor speed of 50 Hz) from 30 seconds to 5 seconds increased the starting current I_{st}, to the maximum value of 2,81 A, thus causing more heating to the windings.

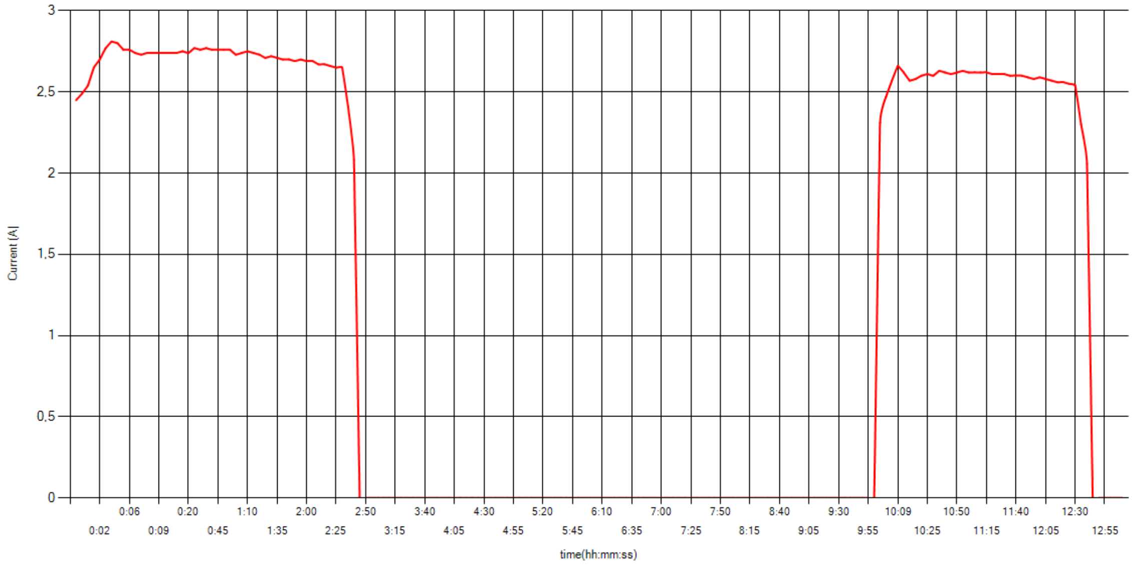


Figure 5-21 S4 Intermittent-periodic with start Duty Motor Current (A).

With a noticeable short period of starting, the current has a small peak during each staring increasing to the value of 2,8 A, and then decreasing when near-rated conditions are achieved. The rotor mechanical speed is approximately 3000 rpm when the motor is running, with only small changes. The motor’s frequency increases gradually to the reference frequency of 50 Hz maintain this value while the motor is running (Figure 5-21, Figure 5-22, Figure 5-23 and Figure 5-24).

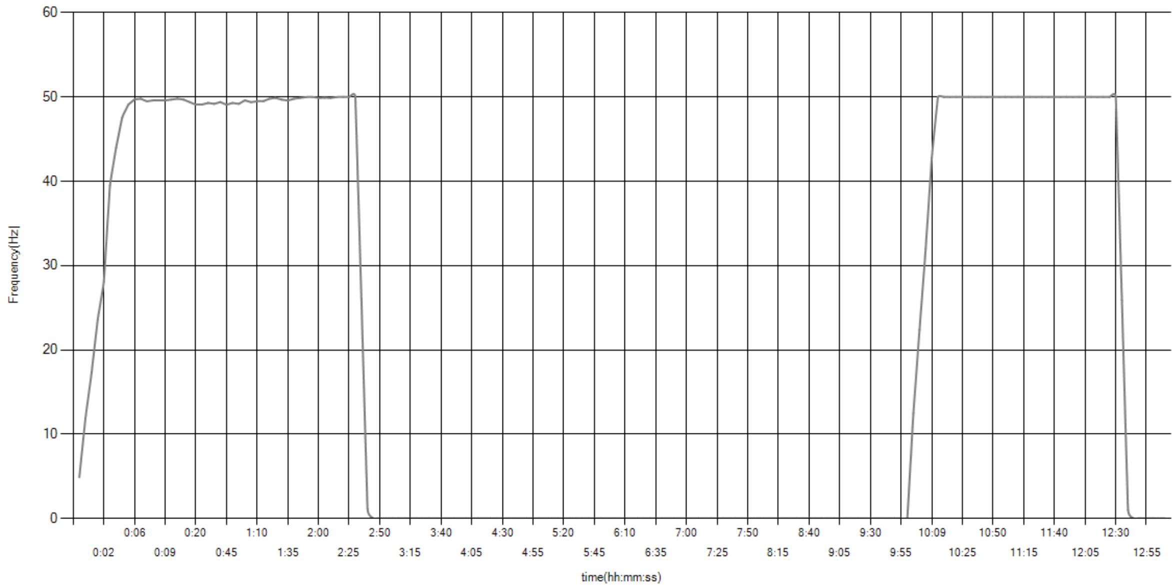


Figure 5-22 S4 Intermittent-periodic with start Duty Motor Frequency (Hz).

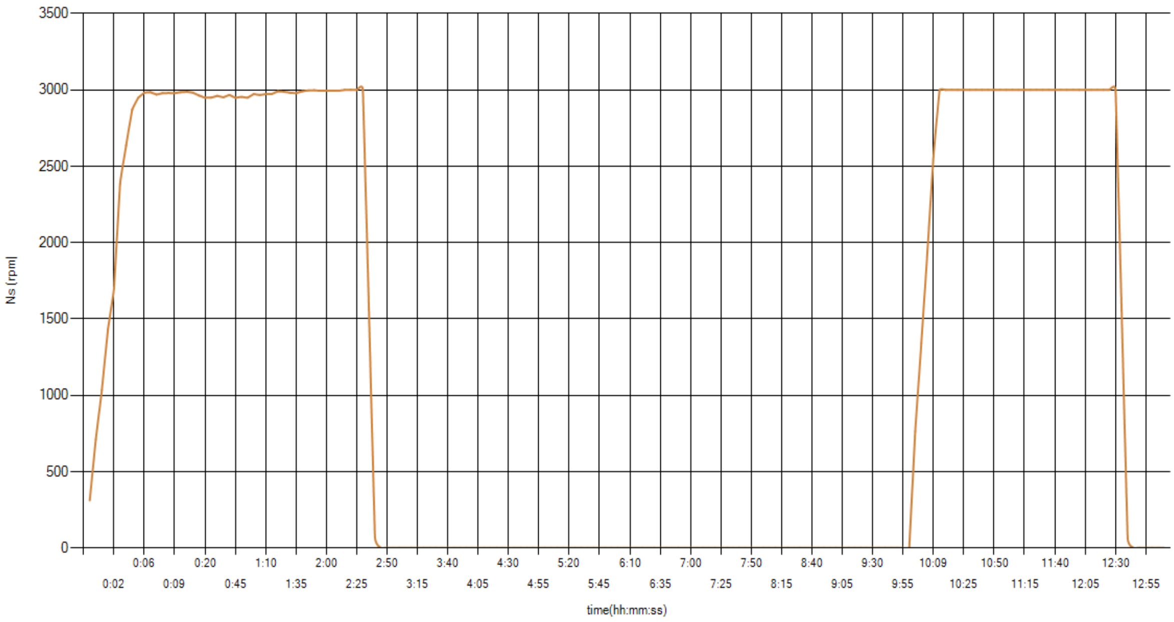


Figure 5-23 S4 Intermittent-periodic with start Duty Ns (rpm).

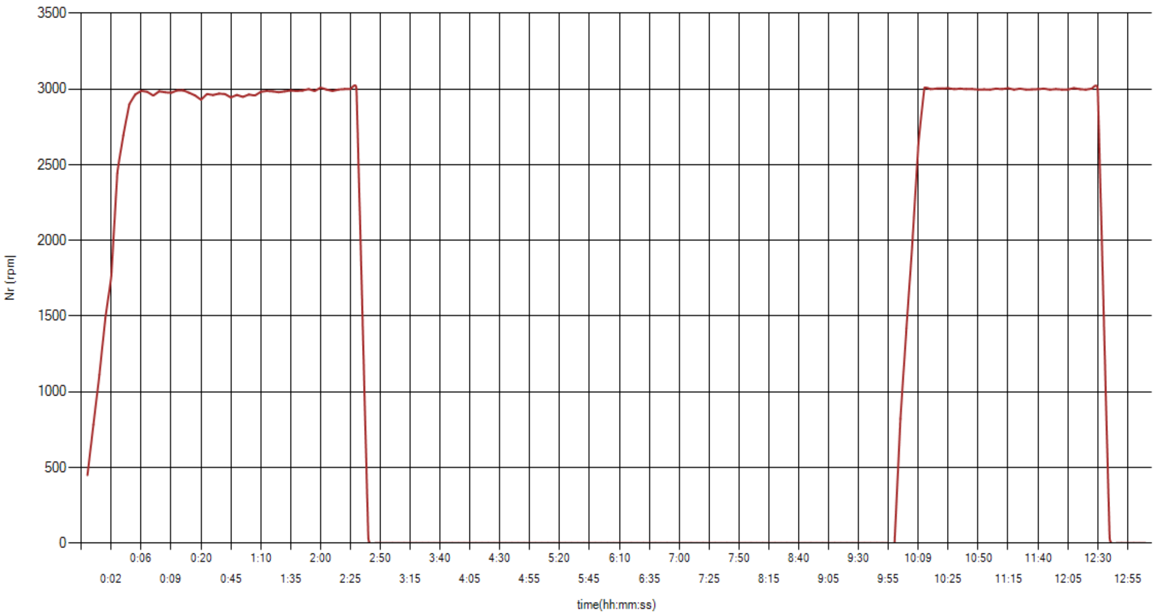


Figure 5-24 S4 Intermittent-periodic with start Duty Motor Rotor Speed Nr (rpm).

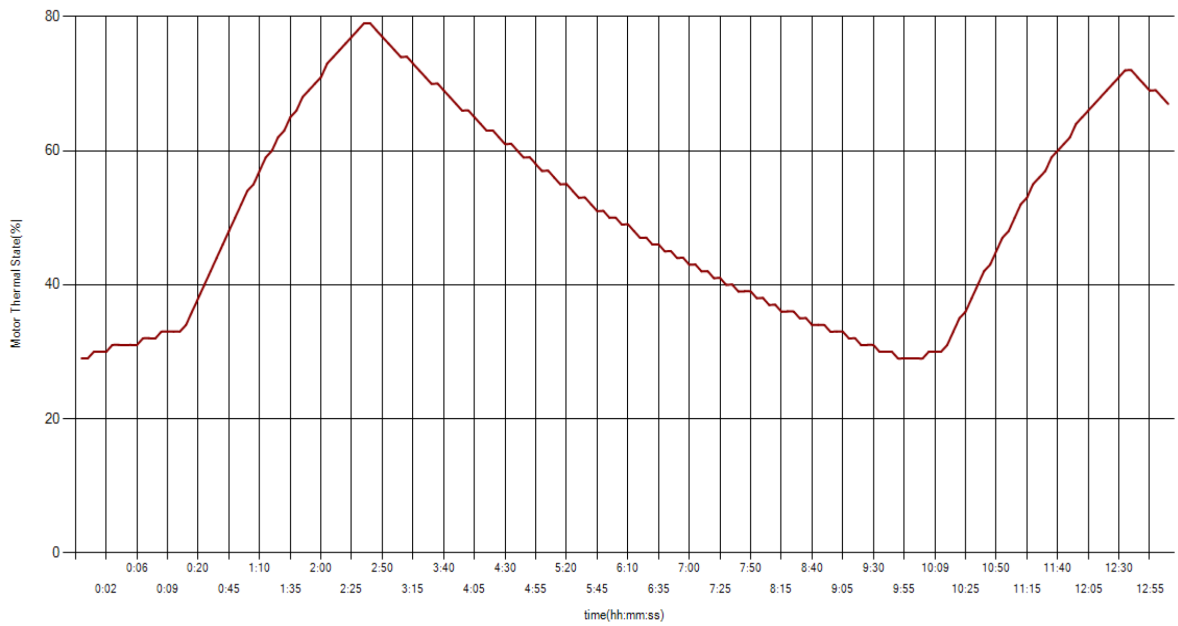


*Figure 5-25 S4 Intermittent-periodic with start Duty Motor Thermal State (%) (motor with a **cold start**).*

In this test, the motor's thermal state begins with a value of 29%, and after the starting/working in near-rated conditions for the duty cycle duration, this variable increased to 79%, meaning an increase of 50% in the motor thermal state (opposed to an increase of 36% in the previous test S_3, meaning that the higher starting current greatly increases motor/windings heating). To notice that in this test, the motor thermal state began at a value of 29%, meaning the motor had a cold start, opposed to the previous S_3 test, where the motor thermal state had in the beginning the value of 44% meaning the motor had a hot start (Figure 5-25).

5.2.5. S_5 – Intermittent periodic Duty with Start and Electrical Brake

A sequence of indistinguishable duty cycles, with each cycle containing a period of motor starting, followed by a period of motor operation at a constant load (with rated-conditions), and a period of electrical braking. Before the beginning of the next duty cycle, there is a motor de-energized rest period, hence motor thermal equilibrium is not reached. Usual applications for this induction motor duty cycle are cranes, rolling mills and hoists.

To define this duty cycle, the following variables are needed:

- Number of duty cycles per hours (c/h)
- Cyclic Duration Factor (CDF)

The Cyclic Duration Factor is calculated by:

$$Cycle\ Duration\ Factor\ (\boldsymbol{CDF}) = \frac{D + N + F}{D + N + R + F} \tag{5-4}$$

with,

D = period of motor starting
N = operation under motor rated conditions
F = electrical braking
R = motor rest and de-energized periods

Both variables can be introduced by the user, the variables values considered were:

S_5 – 15 % - 6 c/h

With D = period of starting = 5 seconds, N = 1 minute and 24 seconds, F = 1 second, R = 8 minutes and 30 seconds.

$$CDF(\%) = \frac{5 + 84 + 1}{5 + 84 + 510 + 1} \times 100 = 15\% \tag{5-5}$$

Input: Number of duty cycles per hours (c/h) = 6 and Cyclic Duration Factor (CDF) = 15 %

The reference frequency was set to 50 Hz, to have a significant period of starting, the acceleration ramp time (ACC) was set to 5 seconds (amount of time from a motor speed of 0 Hz to the nominal motor speed of 50 Hz), thus increasing the starting current I_{st} and consequently increasing motor and winding heating (greater Motor Thermal State). A sample time of 1 seconds was considering during the motor starting and then increased to 5 seconds when near-rated conditions are achieved. In this duty the load was decreased to 56%, so the electrical braking would stop the motor more easily.

The [**Type of Stop**] was changed from [**Stop on Ramp**] in 10 seconds to **[DC Injection]** with the following characteristics:

Table 5-6 DC Injection 1

DC Injection Level 1	DC Injection Time 1
2 A	0,5 seconds

If DC Injection Time 1 expires and the rotor has not stopped, DC Injection level 2 is activated:

Table 5-7 DC Injection 2

DC Injection Level 2	DC Injection Time 2
1,5 A	0,5 seconds

Table 5-8 S5 Intermittent-periodic Duty with start and braking Motors's Variables values

time (mm:ss)	Voltage (V)	Current (A)	Frequency (Hz)	Nr (rpm)	Ns (rpm)	Power (kW)	Torque (N.m)	Motor Thermal State (%)
00:05	380	2,099	50,00	3000	3000	0,870	2,965	26
00:10	385	1,990	50,00	2997	3000	0,870	2,901	27
00:15	385	1,980	50,00	2997	3000	0,855	2,935	27
00:20	385	2,000	50,00	2997	3000	0,870	2,856	27
…	…	…	…	…	…	…	…	…
01:20	384	1,960	50,00	2997	3000	0,839	2,779	36
01:25	384	1,950	50,00	3000	3000	0,839	2,739	37
01:30	384	1,950	50,00	2997	3000	0,839	2,764	37
01:35	0	0	0	0	0	0	0	0
01:40	0	0	0	0	0	0	0	0

The machine's variables values charts obtained during S_5 - Intermittent periodic duty with starting and electrical braking, are represented below (with a cyclic duration factor of 15% and duration of one duty cycle of 10 minutes):

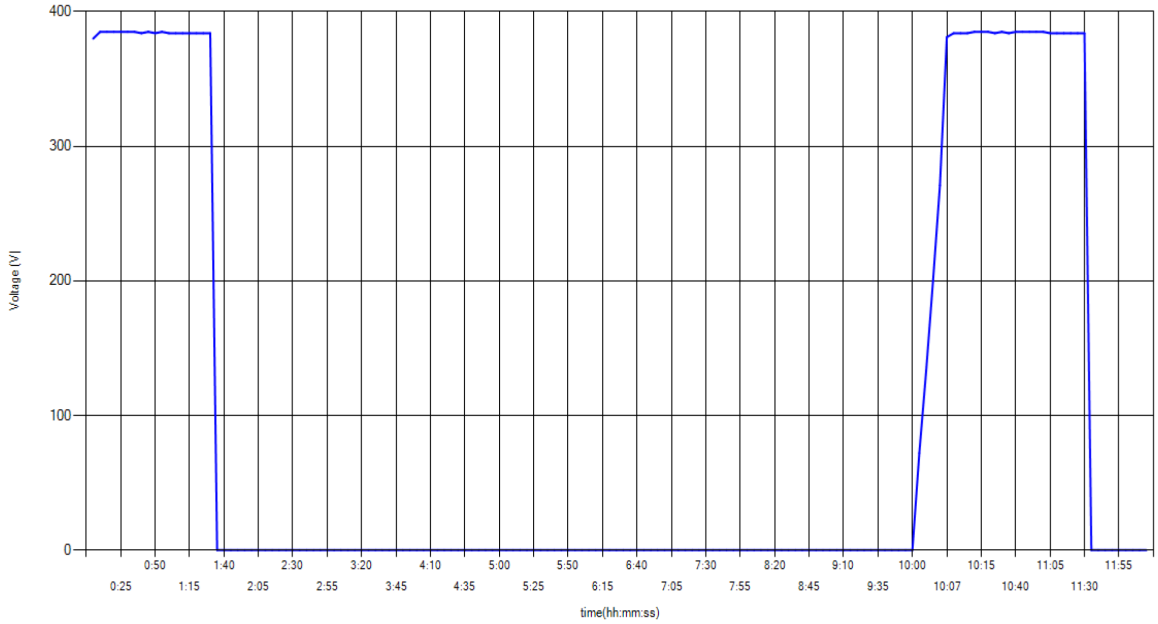


Figure 5-26 S5 Intermittent-periodic Duty with start and braking Motor's Voltage (V).

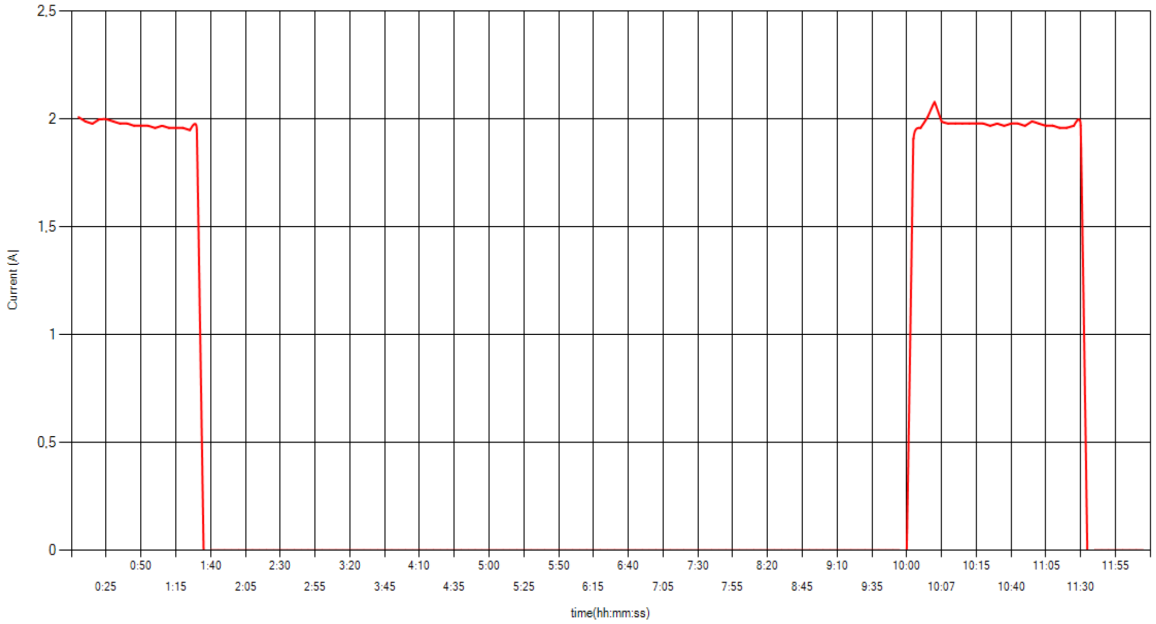


Figure 5-27 S5 Intermittent-periodic Duty with start and braking Motor's Current (A).

As excepted during the duty cycle duration, the voltage and current have near-rated values, when the duty cycle ends, the voltage and current go to zero, beginning then, the rest and de-energized period [21]. Applying the Stop command (in electrical DC braking configuration) at around 11 minute and 30 seconds (and 1 minutes and 30 seconds), makes the voltage and current go almost instantly to zero (as opposed as taking 10 seconds with stop on ramp) as it is visible in the charts (Figure 5-26 and Figure 5-27).

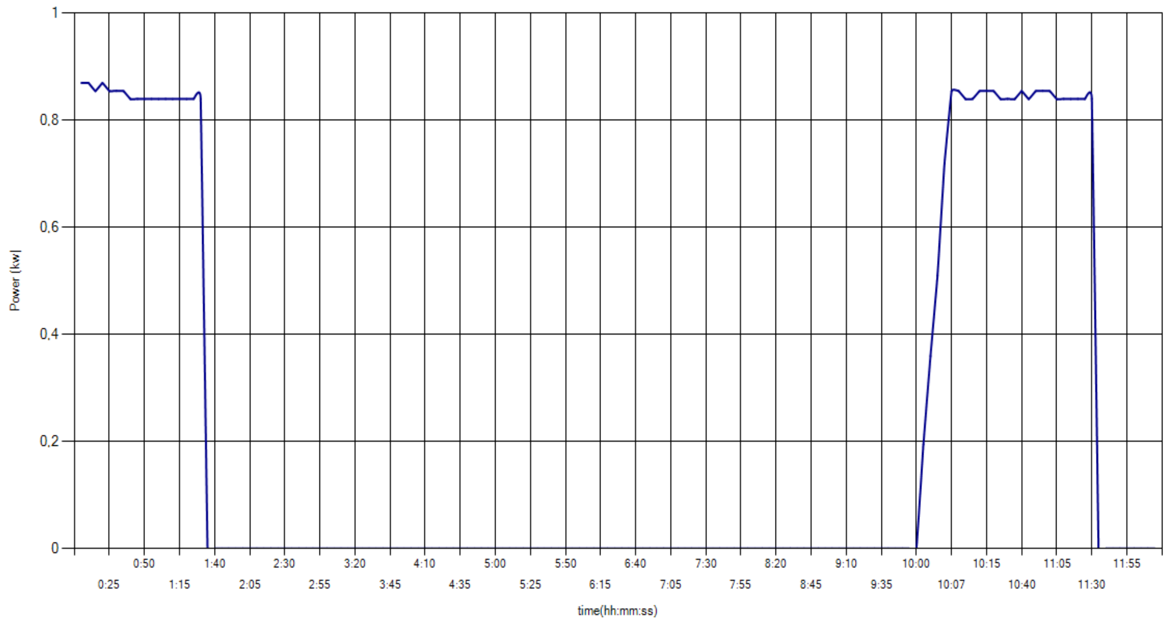


Figure 5-28 S5 Intermittent-periodic Duty with start and braking Motor's Power (kW).

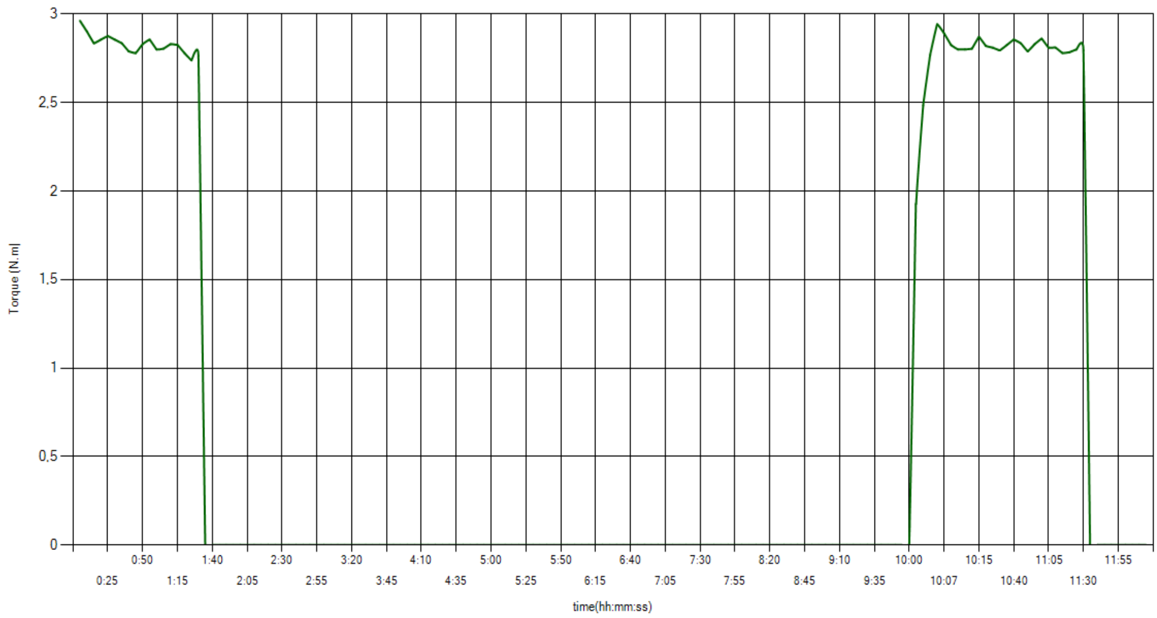


Figure 5-29 S5 Intermittent-periodic Duty with start and braking Motor's Torque (N.m).

Similarly, the power and torque after the stop command go almost immediately to zero (not taking the 10 seconds as the previous tests) (Figure 5-28 and Figure 5-29).

To see in detail the motor's variables during the electrical DC braking, the sample time was reduced to 1 seconds obtaining:

Table 5-9 -S5 Motor's Variables in detail during electrical braking.

time (mm:ss)	Voltage (V)	Current (A)	Frequency (Hz)	Nr (rpm)	Ns (rpm)	Power (kW)	Torque (N.m)	Motor Thermal State (%)
…	…	…	…	…	…	…	…	…
01:30	385	1,897	50,00	2997	3000	0,847	2,879	27
01:31	86	0,601	0	2796	0	0	0	27
01:32	5	0,457	0	2796	0	0	0	27
01:33	0	0	0	0	0	0	0	27
01:34	0	0	0	0	0	0	0	27
31:35	0	0	0	0	0	0	0	26

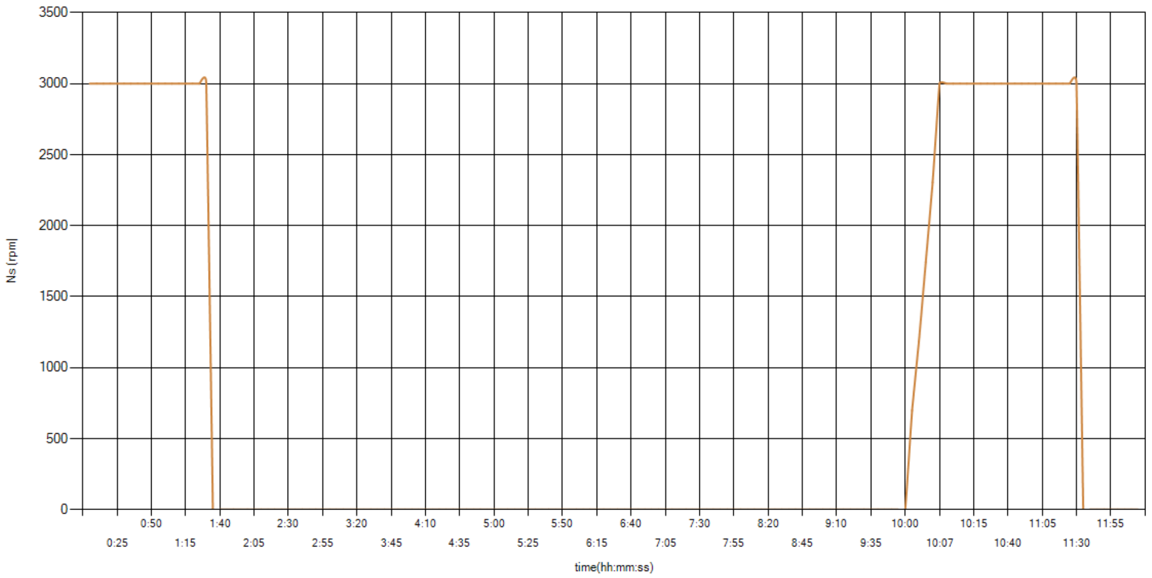


Figure 5-30 S5 Intermittent-periodic Duty with start and braking Ns (rpm).

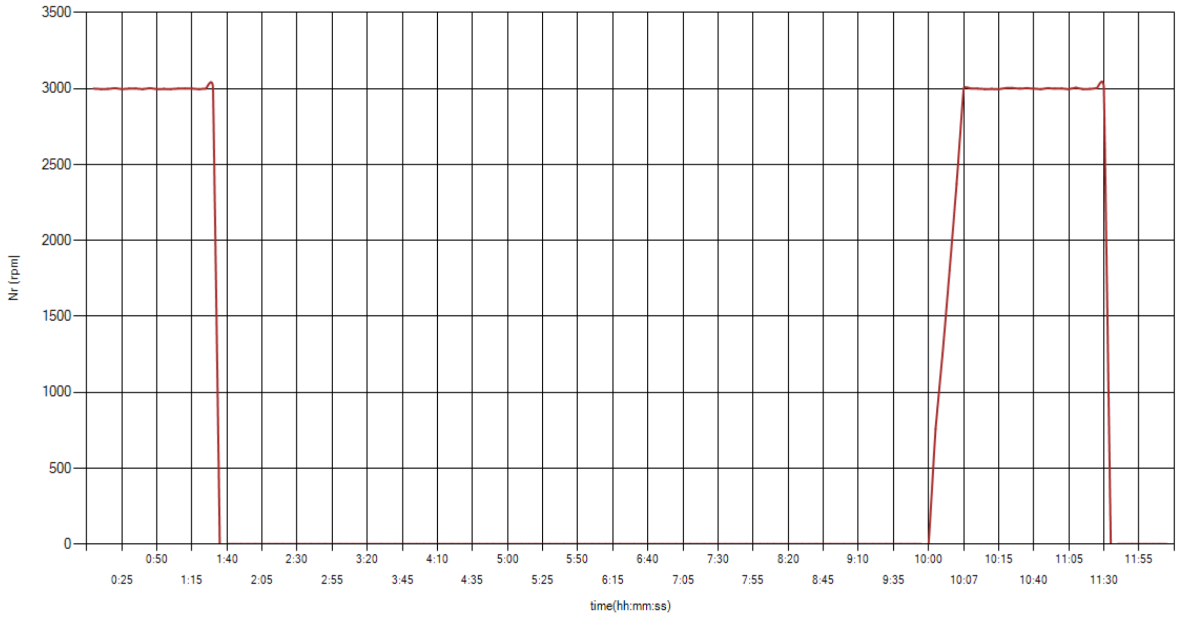


Figure 5-31 S5 Intermittent-periodic Duty with start and braking Motor's rotor speed (rpm).

The motor speed (N_s) has the constant value of 3000 rpm during motor operation, but the variable motor mechanical speed (N_r) has very small variations around 3000 rpm, hence giving a small slip (Figure 5-30 and Figure 5-31).

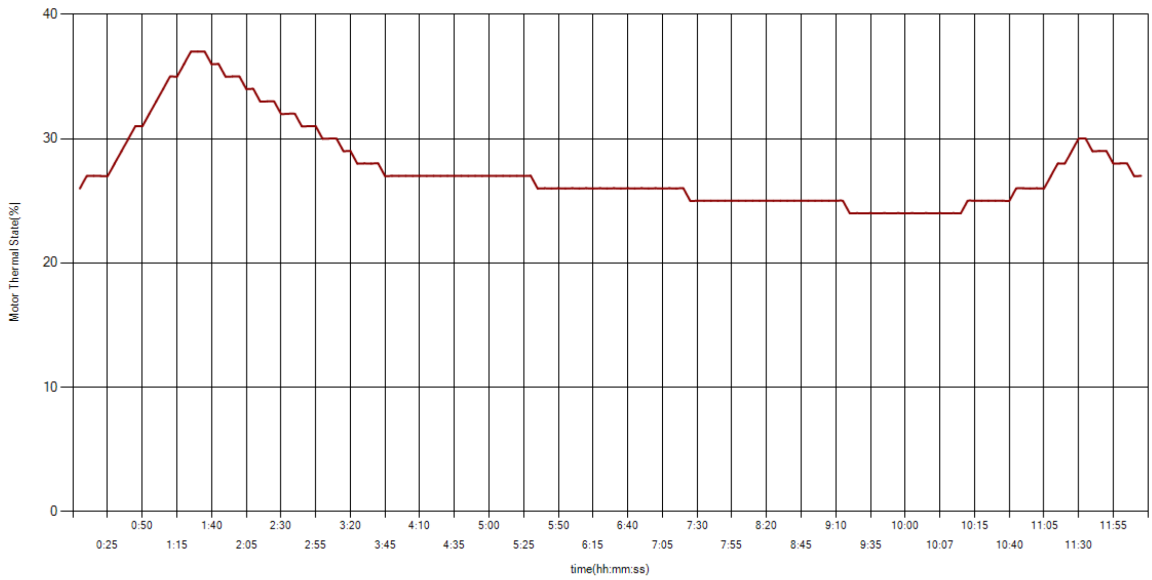


*Figure 5-32 S5 Intermittent Duty start braking Motor's Thermal State (%) (motor with a **cold start**).*

Although the electrical DC braking increases winding/motor heating, the motor thermal state didn't increase as much as the other tests, because the load was lowered so the DC braking runs softer. Similarly, to other tests while the motor is running the motor thermal state increases rapidly, in the rest period, the thermal state decreases slowly (Figure 5-32).

5.2.6. S_6 – Continuous-operation periodic loading

The induction motor duty cycle S_6 (continuous-operation periodic loading) is a sequence of indistinguishable motor duty cycles, with each motor duty cycle containing a period of motor operation at a constant load (N) and a period of motor operation with no-load (V), motor thermal equilibrium is not reached during this duty cycle [20].

The recommended values for the cyclic duration factor (CDF) are 15 %, 25 %, 40 % or 60 %, the duration of the duty cycle should be 10 minutes.

The cyclic duration factor (CDF) is calculated as:

$$CDF = \frac{N}{N+V} \qquad (5\text{-}6)$$

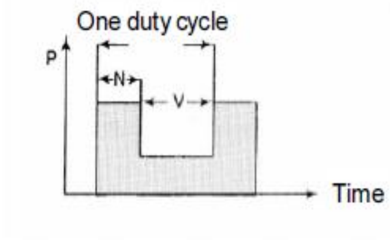


Figure 5-33 Power in S6 Continuous periodic loading.

where,

N = operation under rated load and speed

V = operation at no-load

In the simulation the duration of the duty cycle was 10 min and a cyclic duration factor (CDF) of 40% was considered, hence the designation in this case is:

$$S_6 - 40\%$$

(with N = 4 minutes and V = 6 minutes).

In this duty the acceleration ramp time (ACC) (time in seconds, from a motor speed of 0 Hz to the nominal motor frequency (50 Hz)) applied was 30 seconds, and the deceleration (DEC) (time in seconds, from nominal motor frequency (50 Hz) to 0 Hz) was 10 seconds. In this duty a sample time of 5 seconds was considered.

During the machine's starting process and with load, the variables values obtained are:

Table 5-10 S6 Continuous operation periodic loading Motor's Variables (with load).

time (mm:ss)	Voltage (V)	Current (A)	Frequency (Hz)	Nr (rpm)	Ns (rpm)	Power (kW)	Torque (N.m)	Motor Thermal State (%)
00:05	78	2,130	8,699	540	519	0,180	3,388	43
00:10	139	2,190	16,89	1032	1014	0,360	3,464	43
00:15	201	2,269	25,20	1530	1524	0,540	3,591	44
00:20	263	2,369	33,70	2037	2019	0,7649	3,759	44
00:25	325	2,470	41,90	2532	2514	1,0049	3,936	44
00:30	383	2,529	49,90	3000	2994	1,215	4,058	44
00:35	384	2,519	50,00	3003	3000	1,230	4,053	44
00:40	384	2,519	50,00	2997	3000	1,230	4,038	45
00:45	384	2,529	50,00	2997	3000	1,230	4,068	45
00:50	384	2,529	50,00	2997	3000	1,230	4,078	45
00:55	385	2,529	50,00	2997	3000	1,230	4,068	45
01:00	385	2,549	50,00	2997	3000	1,230	4,032	46

After working for 4 minutes in near-rated conditions, the load (of about 82%) was removed from the machine, the variables values obtained after removing the load are:

Table 5-11 S6 Continuous operation periodic loading Motor's Variables (no load).

time (mm:ss)	Voltage (V)	Current (A)	Frequency (Hz)	Nr (rpm)	Ns (rpm)	Power (kW)	Torque (N.m)	Motor Thermal State (%)
…	…	…	…	…	…	…	…	…
03:50	385	2,400	50,00	2997	3000	1,139	3,809	75
03:55	385	2,390	50,00	3000	3000	1,139	3,708	75
04:00	385	2,380	50,00	2994	3000	1,125	3,764	76
04:05	375	1,259	50,00	3000	3000	0,119	0,563	75
04:10	375	1,259	50,00	3000	3000	0,104	0,385	74
04:15	375	1,259	50,00	3000	3000	0,119	0,405	73
04:20	375	1,259	50,00	3000	3000	0,119	0,400	72
04:25	375	1,259	50,00	3000	3000	0,119	0,385	71
04:30	375	1,269	50,00	2994	3000	0,119	0,400	70

The machine's variables values charts obtained during S_6- Continuous-operation duty periodic loading are represented below:

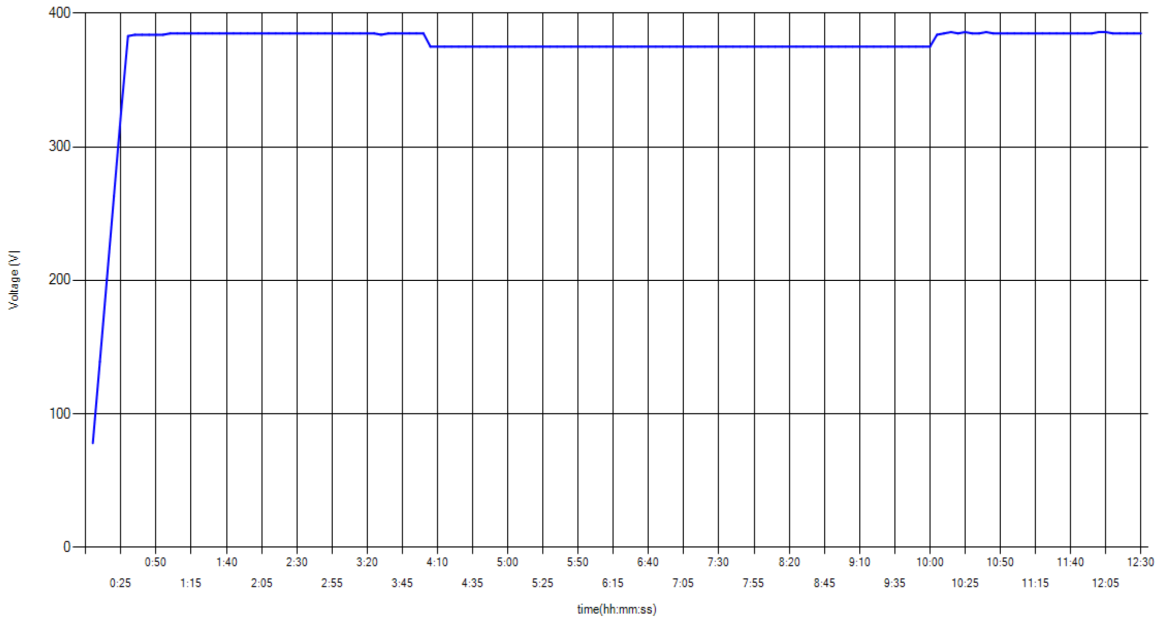


Figure 5-34 S6 Continuous operation periodic loading Motor Voltage (V).

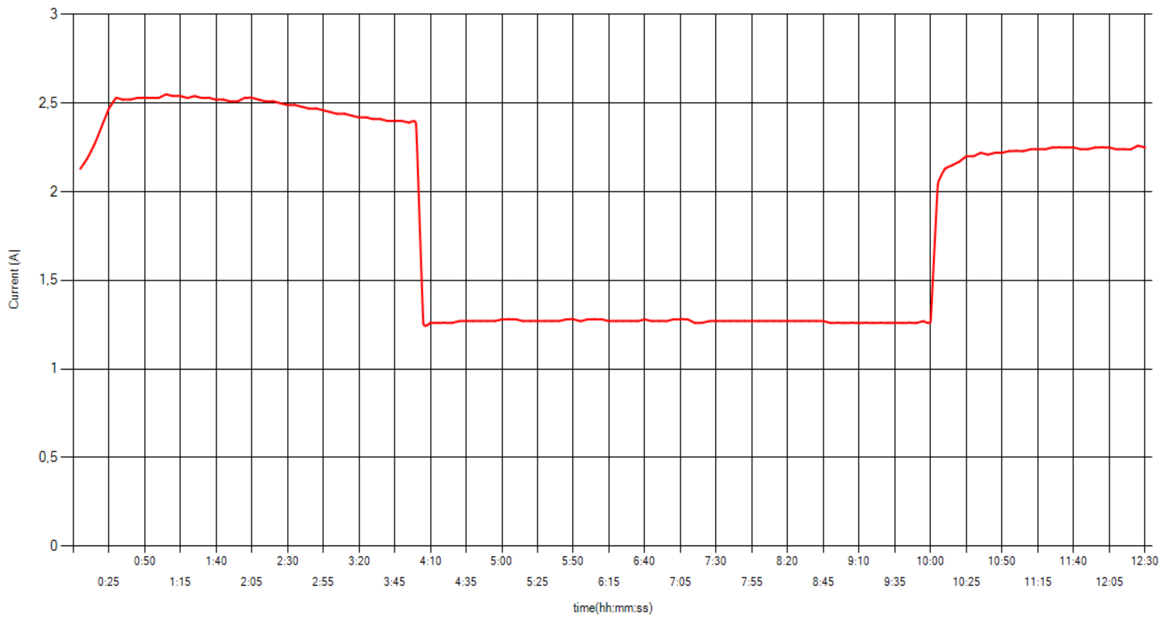


Figure 5-35 S6 Continuous operation periodic loading Motor Current (A).

The voltage dropped from a value of 385 V to a value of 375 V after the load was removed from the motor (small decrease of 10 V), the motor's current while running with a load of approximately 82% had the average value of 2,5A, after removing the load the current decreased to a value of approximately 1,27 A. In the beginning of the second duty cycle the current increases again, as the load was re-applied with a similar load value (approximately 70%) (Figure 5-34 and Figure 5-35).

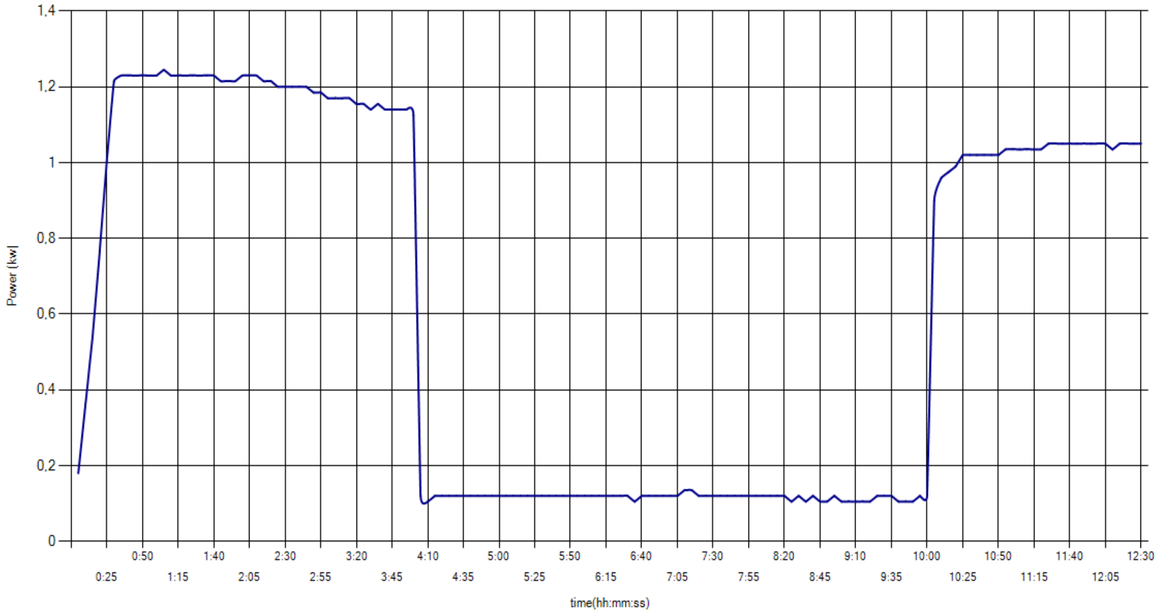


Figure 5-36 S6 Continuous operation periodic loading Motor Power (kW).

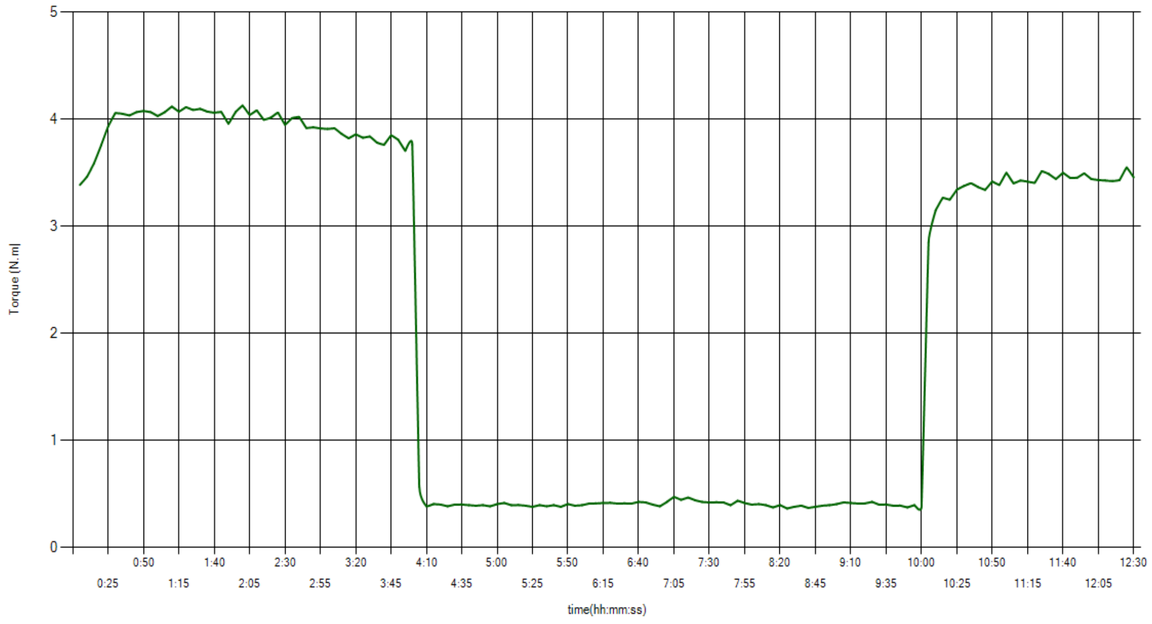


Figure 5-37 S6 Continuous operation periodic loading Motor Torque (N.m).

The power averaged approximately 1,2 kW (corresponding to a load of 82%) while the motor was running with load, after the load was removed it dropped to a value of approximately 0,12 kW corresponding to the no-load motor power operation. The torque while running with a load of 82% averaged approximately 4 N.m (which is approximately 80% of the nominal's motor torque), after removing the load, the toque decreased to a value of approximately 0,4 N.m, which is the running with no load torque value (Figure 5-36 and Figure 5-37).

At the end of the duty cycle (at 10 min mark) the load was re-applied (in this duty cycle we have N= running at rated conditions = 4min and V = operation with no load = 6min corresponding with a cyclic duration factor of CDF = 40%) and the motor's variables values are:

Table 5-12 S6 Continuous operation periodic loading Motor's Variables (next cycle).

time (mm:ss)	Voltage (V)	Current (A)	Frequency (Hz)	Nr (rpm)	Ns (rpm)	Power (kW)	Torque (N.m)	Motor Thermal State (%)
…	…	…	…	…	…	…	…	…
09:50	375	1,259	50,00	2997	3000	0,104	0,375	47
09:55	375	1,269	50,00	3000	3000	0,119	0,395	47
10:00	375	1,269	50,00	3000	3000	0,119	0,385	47
10:05	384	2,039	50,00	3003	3000	0,899	2,856	47
10:10	385	2,130	50,00	3000	3000	0,959	3,150	47
10:15	386	2,150	50,00	3000	3000	0,975	3,266	47
10:20	385	2,170	50,00	3003	3000	0,990	3,251	47
10:25	386	2,200	50,00	3003	3000	1,019	3,343	47
10:30	385	2,200	50,00	3006	3000	1,019	3,378	48
10:35	385	2,220	50,00	2997	3000	1,019	3,403	48
10:40	386	2,210	50,00	2997	3000	1,019	3,368	48

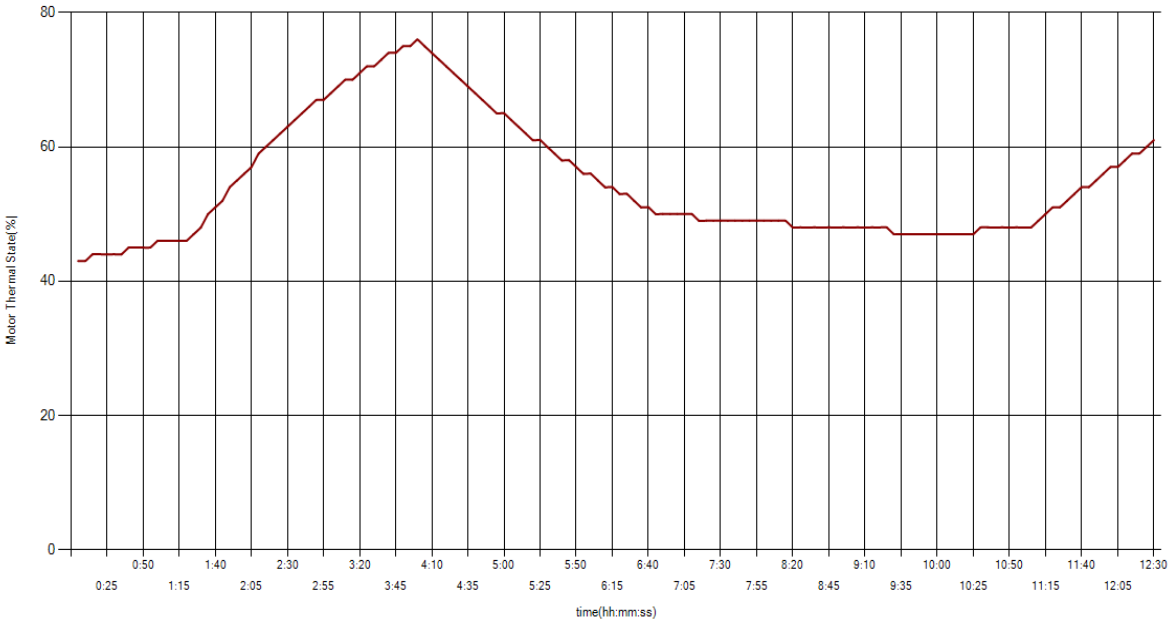


*Figure 5-38 S6 Continuous periodic loading Motor Thermal State (%) (motor with a **hot start**).*

The Motor Thermal State increases rapidly during the motor's load operation (with 81% of the motor's load), from the temperature of the cooling medium (which corresponds to a motor thermal state of 43%) to almost the value of thermal equilibrium (reaches the motor thermal state of 76%). After the load is removed, the motor thermal state begins to decrease, and at the end of the duty cycle (around 10 minutes) it has reached almost the value of the temperature of the cooling medium. However even working with no-load, the motor is unable to reach this value (temperature of the cooling medium), because it is still working with no-load (opposed of being at total rest), hence a motor working in continuous-operation loading S_6, has a temperature rise of θ_t each motor operation duty cycle, corresponding to a no-load motor heating (Figure 5-38).

The values of the motor thermal state are:

At 0 minutes and 5 seconds: Motor thermal State [%] = 43%

At the end of the duty cycle [10 minutes and 0 seconds]: Motor thermal State [%] = 47%

A motor running in this duty (continuous-operation loading) in between duty cycles, has a temperature rise in each cycle corresponding to an increase of 4% in the motor thermal state.

5.2.7. S_7 – Continuous Duty with Start and Electrical Brake

A sequence of indistinguishable duty cycles, each cycle containing a period of motor starting, a time of motor activity at a constant load, and a period of electrical braking, hence there is no motor rest-period. This duty cycle is too short for motor thermal equilibrium to be reached, to define this duty cycle only the variable duty cycles per hour (c/h) is needed (introduced by the user). The cycle duration factor is calculated by:

$$Cycle\ Duration\ Factor\ (\boldsymbol{CDF}) = \frac{D+N+F}{D+N+F} = 1 \tag{5-7}$$

where

D = period of starting

N = operation under rated conditions

F = electrical braking

In this duty, the number of duty cycles per hour (c/h) is usually high, as likely applications are machine tools, the number of starts and stops of the motor are high, here 150 duty cycles per hour was considered (24 seconds each duty cycle).

The values considered were:

D = 5 seconds, N = 17 seconds and F = 2 seconds.

Input: Number of duty cycles per hour (c/h) = 150

Table 5-13 S7 Continuous duty with start and brake Motor's Variables

Time (mm:ss)	Voltage (V)	Current (A)	Frequency (Hz)	Nr (rpm)	Ns (rpm)	Power (kW)	Torque (N.m)	Motor Thermal State (%)
00:01	9	1,149	3,29	93	195	0,003	0,319	29
00:02	30	2,059	10,80	627	684	0,075	1,004	29
00:03	79	1,440	21,60	1320	1332	0,165	1,242	29
00:04	114	1,379	27,29	1668	1653	0,224	1,324	29
00:05	287	1,429	46,79	2826	2853	0,449	1,532	29
00:06	347	1,429	50,09	2982	3006	0,389	1,491	29
00:07	374	1,470	50,00	2985	3000	0,389	1,369	29
..	…	…	…	…	…	…	…	…
00:22	378	1,460	50,00	2994	3000	0,389	1,354	29
00:23	378	1,460	50,00	2970	3000	0,375	1,332	29
00:24	129	1,299	0	2925	0	0	0	29
00:25	46	1,600	4,19	111	267	0	0,497	29
00:26	29	2,029	10,50	579	824	0,06	0,993	29
00:27	136	1,399	24,29	1479	1476	0,194	1,278	30
00:28	306	1,450	48,59	2931	2970	0,449	1,526	30
…	…	…	…	…	…	…	…	…

In this duty, the load considered was approximately 30% as the number of starts and stops are too high for high load applications.

The number of cycles per hour considered was 150 (meaning a duty cycle duration of 24 seconds), hence the Start/Stop of the motor has a time difference of 24 seconds (start motor every 24 seconds and stop the motor every 23 seconds). As the previous duties the stop configuration used was electrical braking, for almost instant motor stop (Figure 5-39 and Figure 5-40).

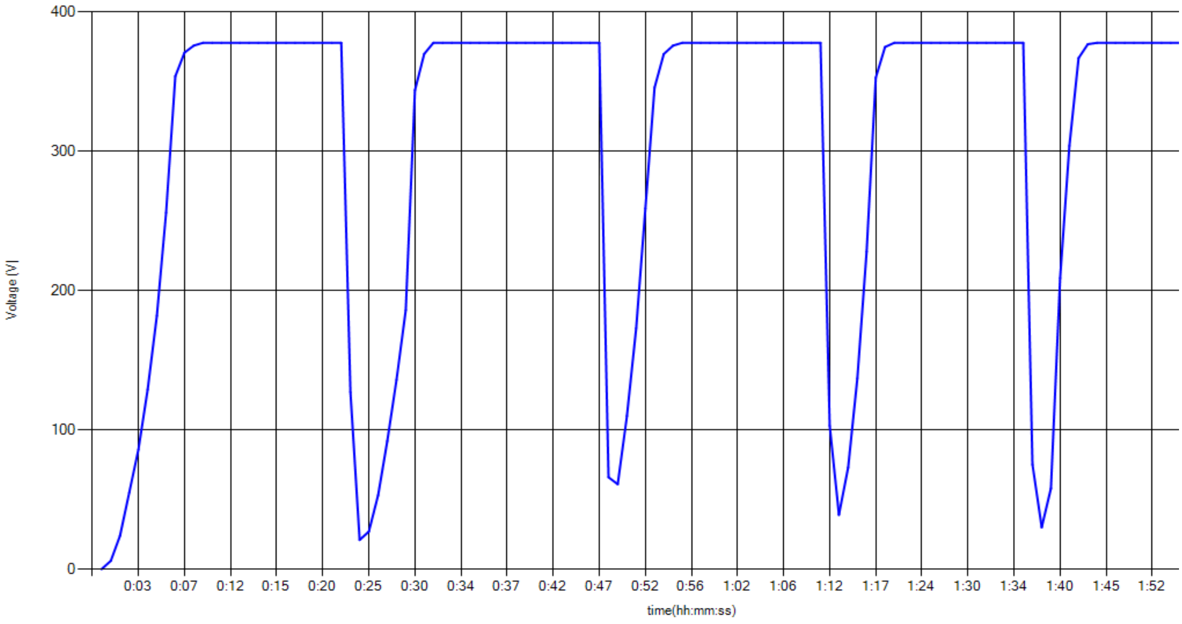


Figure 5-39 S7 Continuous duty with start and brake Motor Voltage (V).

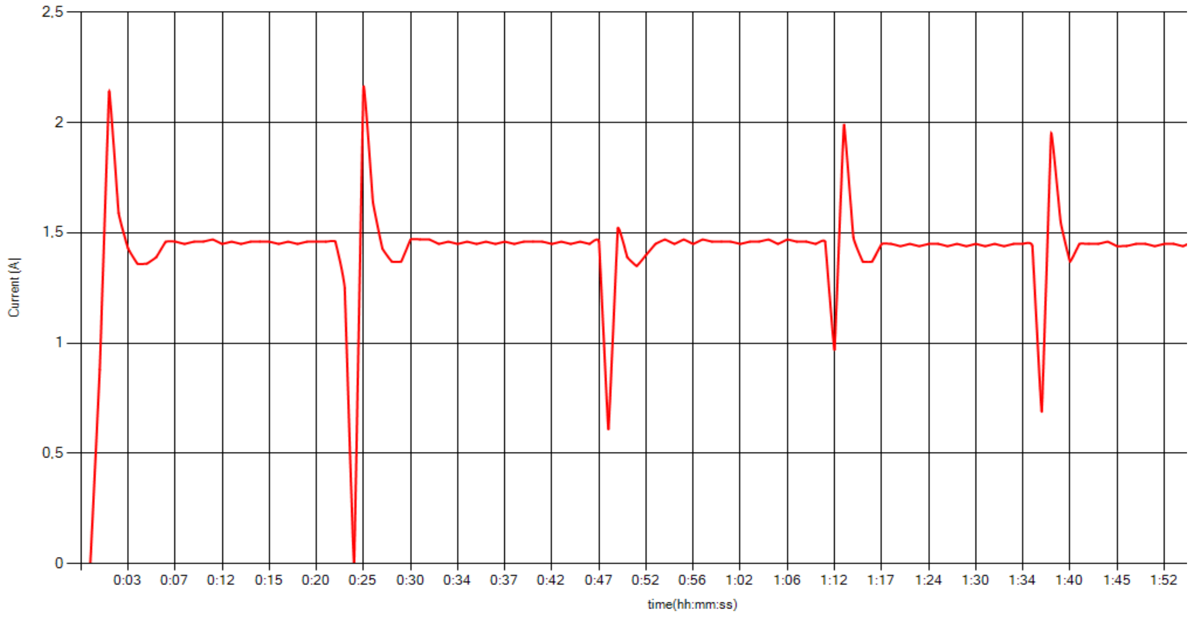


Figure 5-40 S7 Continuous duty with start and brake Motor Current (A).

5.2.8. S_8 – Continuous Duty with periodic speed changes

A sequence of indistinguishable duty cycles, each cycle contains a starting period, a period of activity at a steady load corresponding to a pre-set motor speed, followed by one or more periods of motor operation at other constant loads and speeds, during the duty cycles there is no motor rest or de-energized periods and the motor thermal equilibrium is not reached. Usual applications are when the motor is required to run at different speeds [19].

The Cycle Durations Factors (CDF) are calculated as:

$$Cycle\ Duration\ Factor\ (\boldsymbol{CDF}) = \frac{D + N_1}{D + N_1 + F_1 + N_2 + F_2 + N_3} \quad \text{(5-8)}$$

at speed Nr_1 for load P_1, and

$$Cycle\ Duration\ Factor\ (\boldsymbol{CDF}) = \frac{F_1 + N_2}{D + N_1 + F_1 + N_2 + F_2 + N_3} \quad \text{(5-9)}$$

at speed Nr_2 for load P_2, and

$$Cycle\ Duration\ Factor\ (\boldsymbol{CDF}) = \frac{F_2 + N_3}{D + N_1 + F_1 + N_2 + F_2 + N_3} \quad \text{(5-10)}$$

at motor speed Nr_3 for the motor load P_3. Where,

$F_1,\ F_2$= change of speed and consequently acceleration

D = electrical braking, Nr_3 to Nr_1

$N_1,\ N_2,\ N_3$ = operation under rated conditions

Input: Number of duty cycles per hour (c/h) = 6 and Cyclic Duration Factor (CDF) = 15 %

In this duty we have considered 6 cycles per hour, with the motor running 3 different speeds of 10, 30 and 50 Hz with 3 different loads. Also, the motor worked 2 minutes at a speed of 10 Hz and 4 minutes at the speeds of 30 and 50 Hz. The motor's variables values obtained are:

Table 5-14 Continuous duty with periodic speed changes - Motor's Variables.

time (mm:ss)	Voltage (V)	Current (A)	Frequency (Hz)	Nr (rpm)	Ns (rpm)	Power (kW)	Torque (N.m)	Motor Thermal State (%)
00:05	0	0	0	0	0	0	0	24
00:10	80	1,409	10,00	603	600	0,029	0,700	24
00:15	80	1,409	10,00	597	600	0,029	0,694	25
00:20	80	1,409	10,00	597	600	0,029	0,689	25
…	…	…	…	…	…	…	…	…
01:50	80	1,389	10,00	597	600	0,029	0,634	26
01:55	80	1,389	10,00	600	600	0,029	0,634	26
02:00	80	1,409	10,00	594	600	0,029	0,644	27
02:05	225	1,299	30,00	1815	1800	0,104	0,639	27
02:10	228	1,340	30,00	1794	1800	0,119	0,700	27
02:15	228	1,330	30,00	1794	1800	0,119	0,740	27
02:20	228	1,320	30,00	1794	1800	0,119	0,735	27
…	…	…	…	…	…	…	…	…
05:50	228	1,340	30,00	1797	1800	0,135	0,791	28
05:55	228	1,340	30,00	1800	1800	0,135	0,791	28
06:00	228	1,340	30,00	1979	1800	0,135	0,781	28
06:05	377	1,580	50,00	3000	2997	0,540	1,668	28
06:10	381	1,659	50,00	2988	3000	0,600	1,968	28
06:15	381	1,659	50,00	2997	3000	0,600	1,988	29
06:20	381	1,659	50,00	2994	3000	0,600	1,983	29
…	…	…	…	…	…	…	…	…
09:55	382	1,679	50,00	2997	3000	0,615	2,064	42
10:00	382	1,669	50,00	2994	3000	0,615	2,064	42
10:05	0	0	0	0	0	0	0	43

The Cycle Durations Factors (CDF) are:

$$Cycle\ Duration\ Factor\ (\boldsymbol{CDF}) = \frac{1+120}{1+120+5+240+5+240} \simeq 0{,}2 \qquad (5\text{-}11)$$

at speed Nr_1 for load P_1, and

$$Cycle\ Duration\ Factor\ (\boldsymbol{CDF}) = \frac{5+240}{1+120+5+240+5+240} \simeq 0{,}4 \qquad (5\text{-}12)$$

at speed Nr_2 for load P_2, and

$$Cycle\ Duration\ Factor\ (\boldsymbol{CDF}) = \frac{5+240}{1+120+5+240+5+240} \simeq 0{,}4 \qquad (5\text{-}13)$$

The electrical braking duration considered was 1 seconds (braking injection 1 + braking injection 2), the changeover of speed by acceleration has the duration of approximately 5 seconds each (from 600 rpm to 1800 rpm and from 1800 rpm to 3000 rpm).

Hence, the duty cycle can be described as:

Table 5-15 – Variables Values used in S8 – Continuous periodic duty with speed changes.

$\boldsymbol{c/h}$	$\boldsymbol{kW}$	$\boldsymbol{Speed}$ **(rpm)**	$\boldsymbol{CDF}$(%)
6	0,03	600	20
6	0,12	1800	40
6	0,62	3000	40

The machine's variables values charts obtained are represented below:

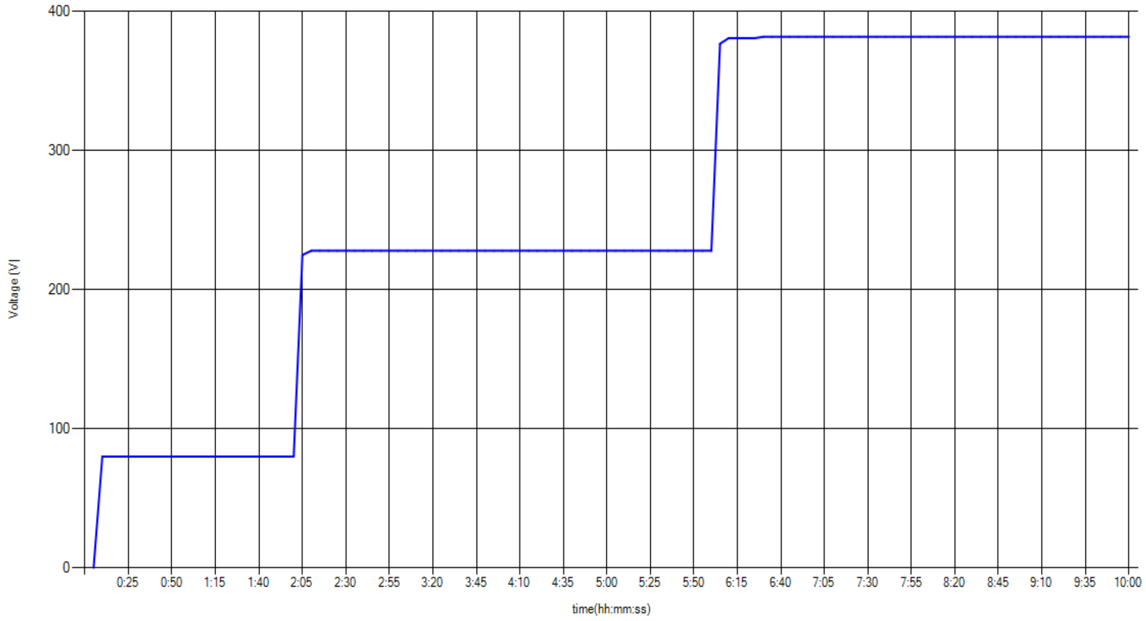


Figure 5-41 S8 Continuous Duty with periodic speed changes – Motor Voltage (V).

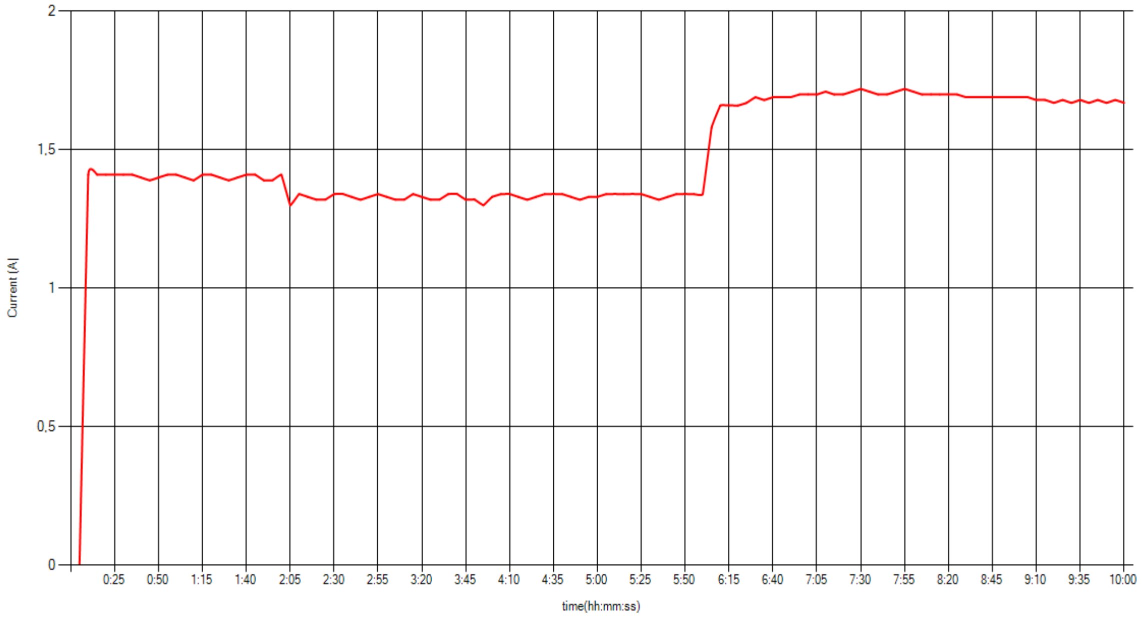


Figure 5-42 S8 Continuous Duty with periodic speed changes – Motor Current (A).

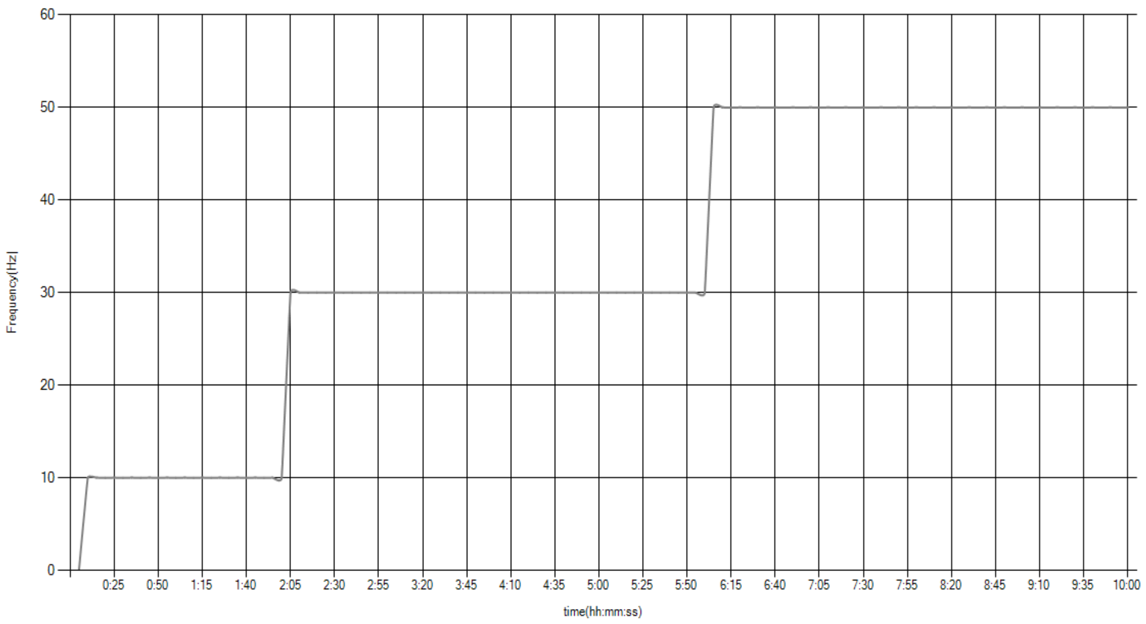


Figure 5-43 S8 Continuous Duty with periodic speed changes – Motor Frequency (Hz).

The frequency increases proportionally with the rotor speed, hence to a frequency of 10 Hz corresponds to a stator speed (Ns) of 600 rpm, a frequency of 30 Hz to 1800 rpm, and 50 Hz to 3000 rpm, to calculate the rotor speed (Nr) the slip must be subtracted (Figure 5-43). The voltage is also increased with the frequency, 10 Hz corresponds to a voltage of 80 V, 30 Hz to 228 V, and the rated frequency of 50 Hz to the rated voltage of 382 V (Figure 5-41), the current has an average value of 1.4 A in the first load (of 0,03 kW), decreasing to 1,34 A in the second load (0,12 kW), and in the last load (0,62 kW) increasing to 1,65 A. The current in the first load is greater than in the second load (despite the second load being larger) due to the starting effect (Figure 5-42).

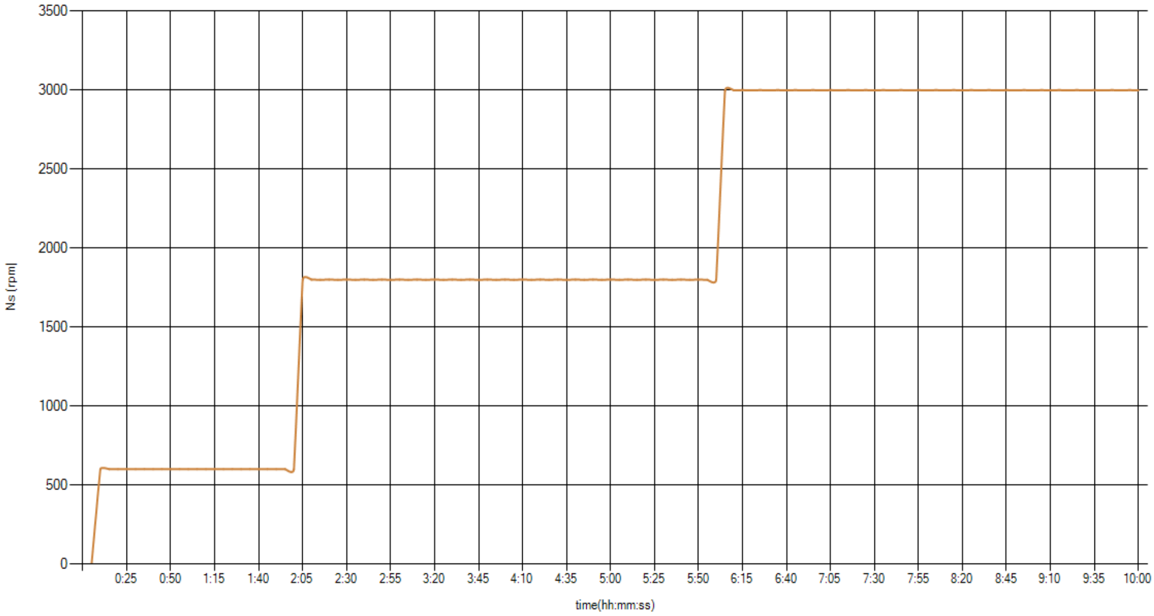


Figure 5-44 S8 Continuous Duty with periodic speed changes – Ns (rpm).

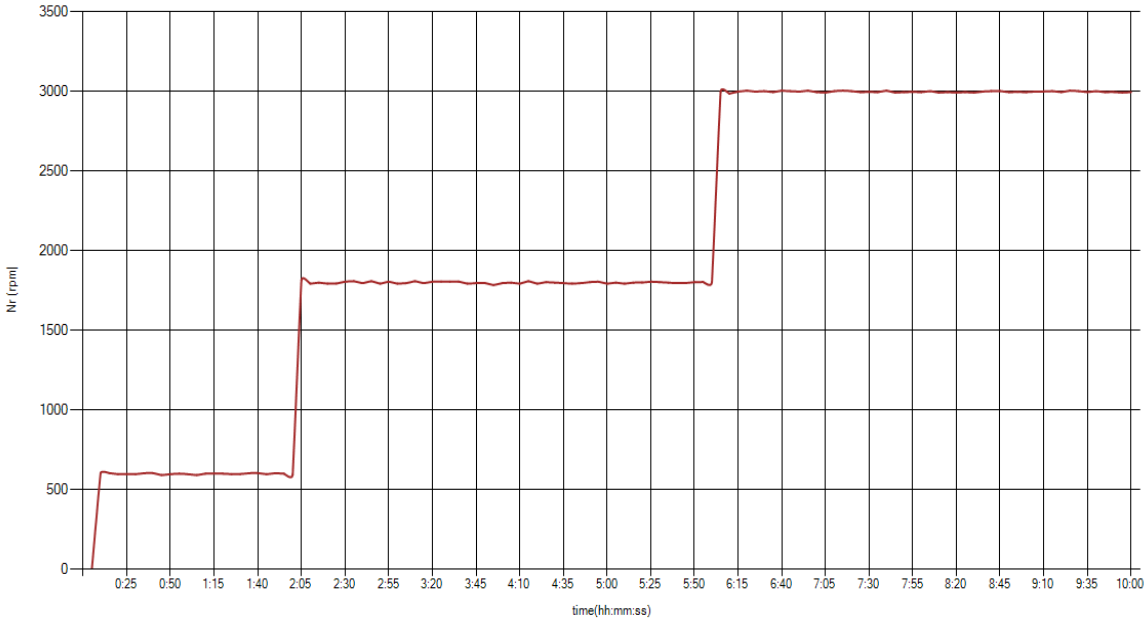


Figure 5-45 S8 Continuous Duty with periodic speed changes – Rotor Speed Nr (rpm).

The motor's speed is 600 rpm in the first cyclic duration factor (with 2 minutes duration), increasing to 1800 rpm in the second cyclic duration factor (with 4 minutes duration) and then increases to 3000 in the third cyclic duration factor (with 4 minutes duration). The changeover of speed by acceleration duration is notable by the charts and has the duration of 5 seconds (Figure 5-44 and Figure 5-45).

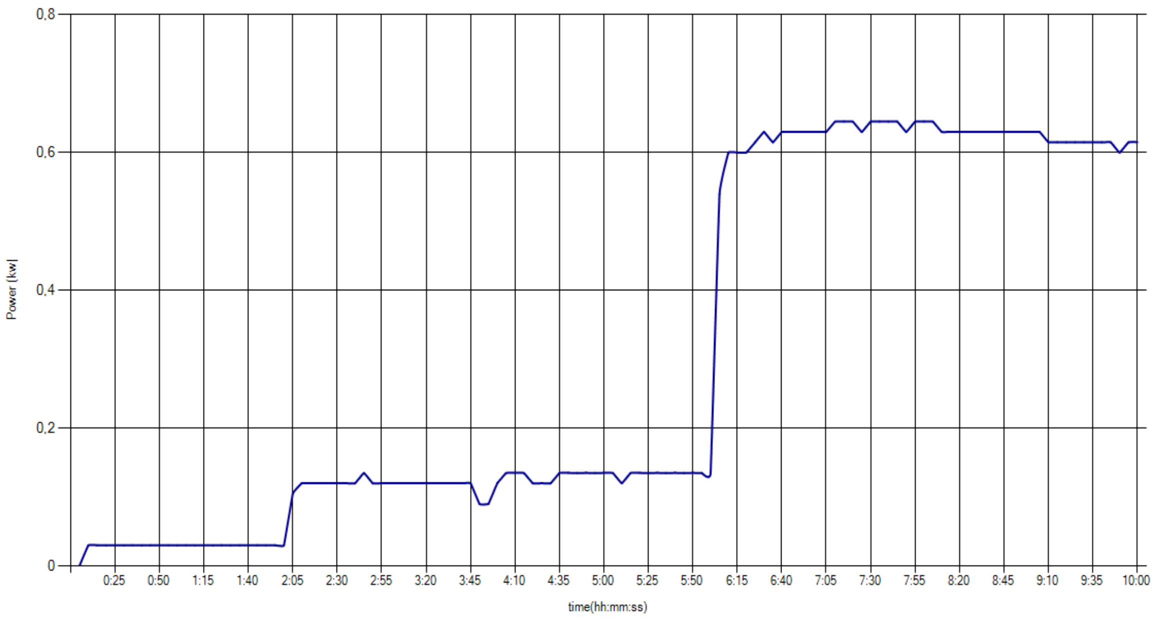


Figure 5-46 S8 Continuous Duty with periodic speed changes – Motor Power(kW).

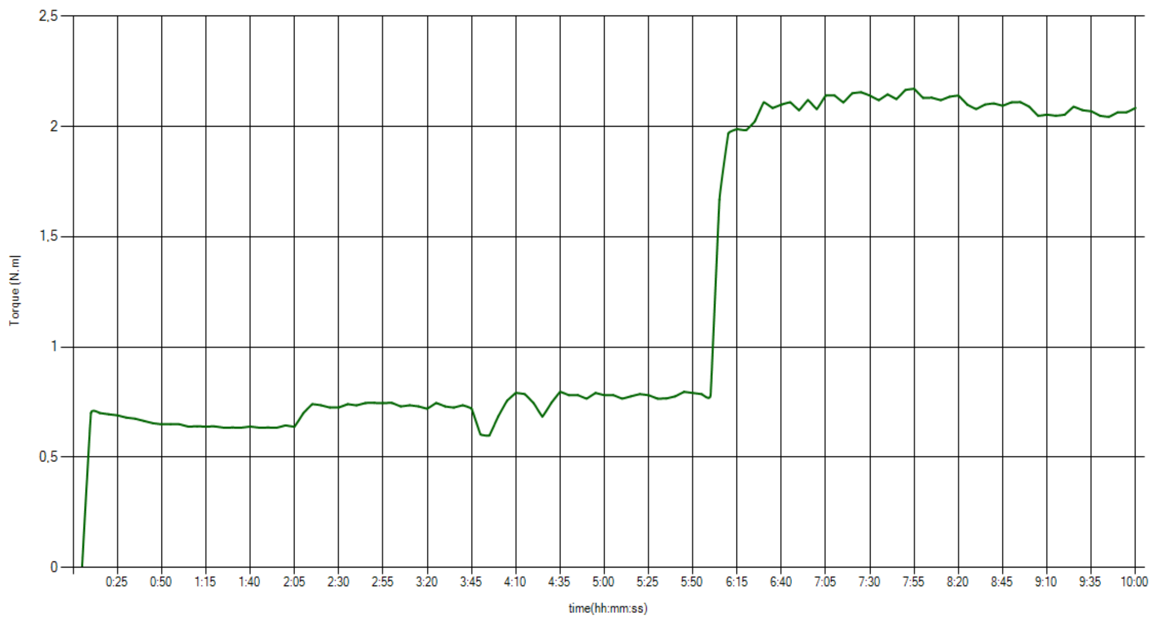


Figure 5-47 S8 Continuous Duty with periodic speed changes – Motor Torque (N.m).

Each cyclic duration factor had a different load, consequently changing the motor's power and torque, in the first cyclic duration factor the motor's power averaged 0,03 kw and the torque averaged 0,06 N.m, in the second cyclic duration factor 0,12 kw and 0,08 N.m, in the third cyclic duration factor 0,6 kw and 2,06 N.m (Figure 5-46 and Figure 5-47).

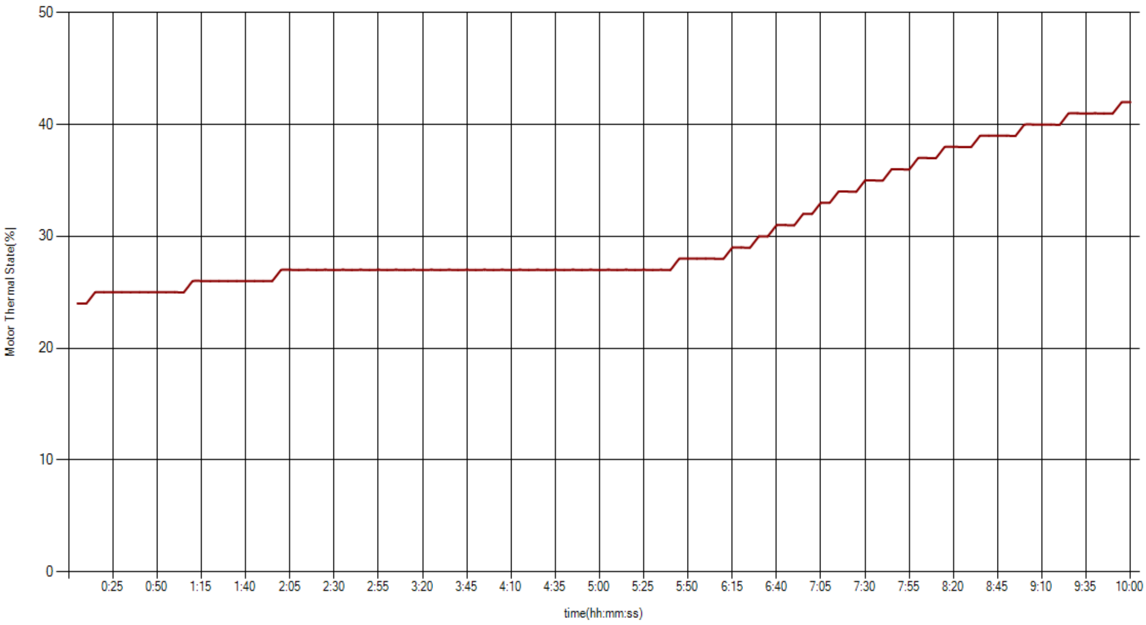


Figure 5-48 S8 Continuous Duty with periodic speed changes – Motor Thermal State (%) (motor with a ***cold start****).*

The motor thermal state increases slightly when running at a frequency of 10 Hz, and then stabilizes at a frequency of 30 Hz. At the rated speed (of 50 Hz) and with the highest load, this variable has a huge increase, from 29% to 42% (Figure 5-48).

Having no rest or de-energized period in this duty, there is a huge increase in motor's temperature in each duty cycle (in this case, corresponding to an increase of 13% in the variable motor's thermal state).

5.2.9. S_{10} – Duty with discrete constant loads

Operating mode that does not include more than four particular load values, wherein no-load operation and being at rest can be included. A thermal steady state is reached under each of the loads (even no-load operation and being at rest). The maximum loading must not exceed 1.2 times the S1 loading.

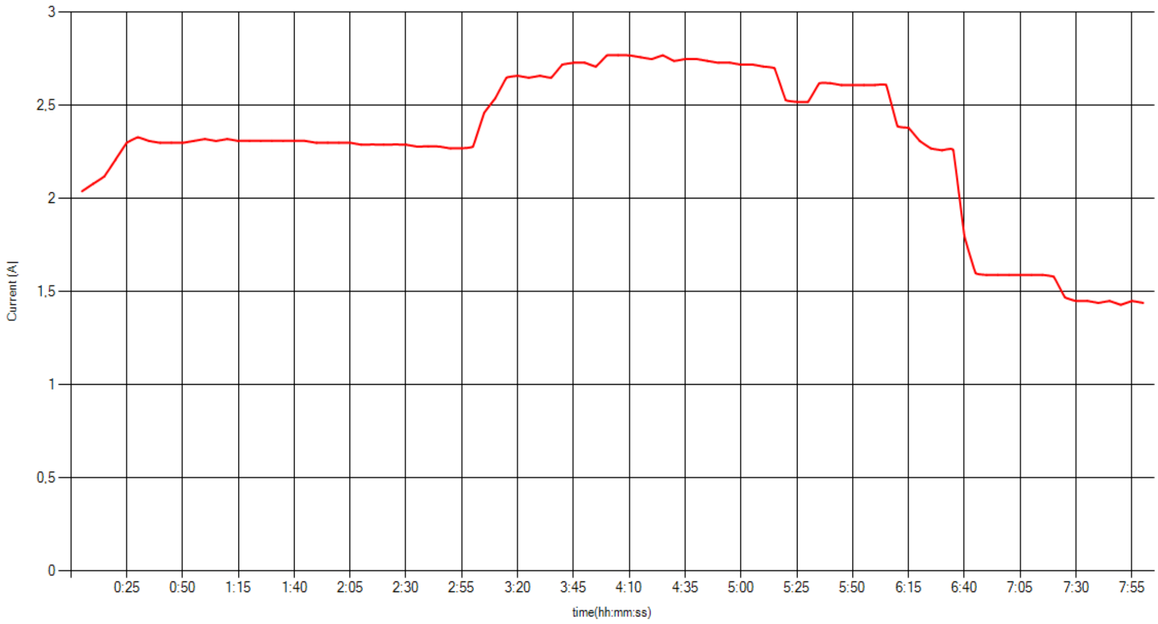


Figure 5-49 S10 Duty with discrete constant loads – Motor Current (A).

In this duty, the motor's load was approximately 72% for three minutes, then increased to 92% the next 4 minutes, and during this heavy load the motor obtained thermal equilibrium (the motor thermal state reached almost 100%), the third load was 86% and the fourth 36%. The motor's current is in average 2,4 A in the first load, increasing to 2,8 A in the second load (almost rated load) and decreasing to 1,6 A and 1,4 A in the third and fourth load respectively (Figure 5-49).

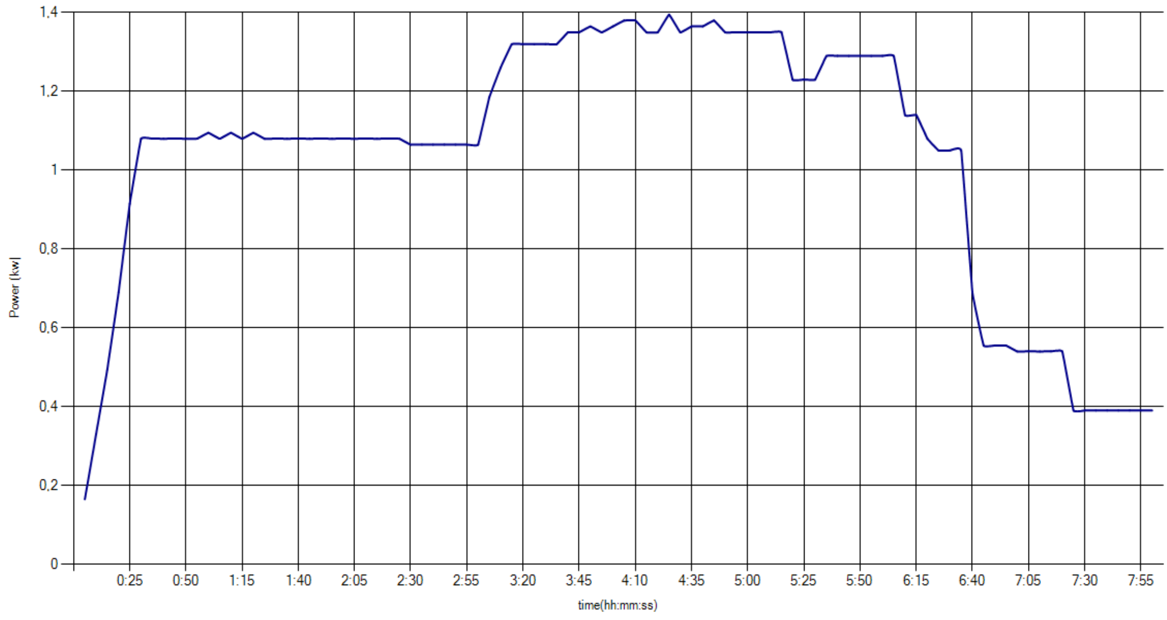


Figure 5-50 S10 Duty with discrete constant loads – Motor Power (kW).

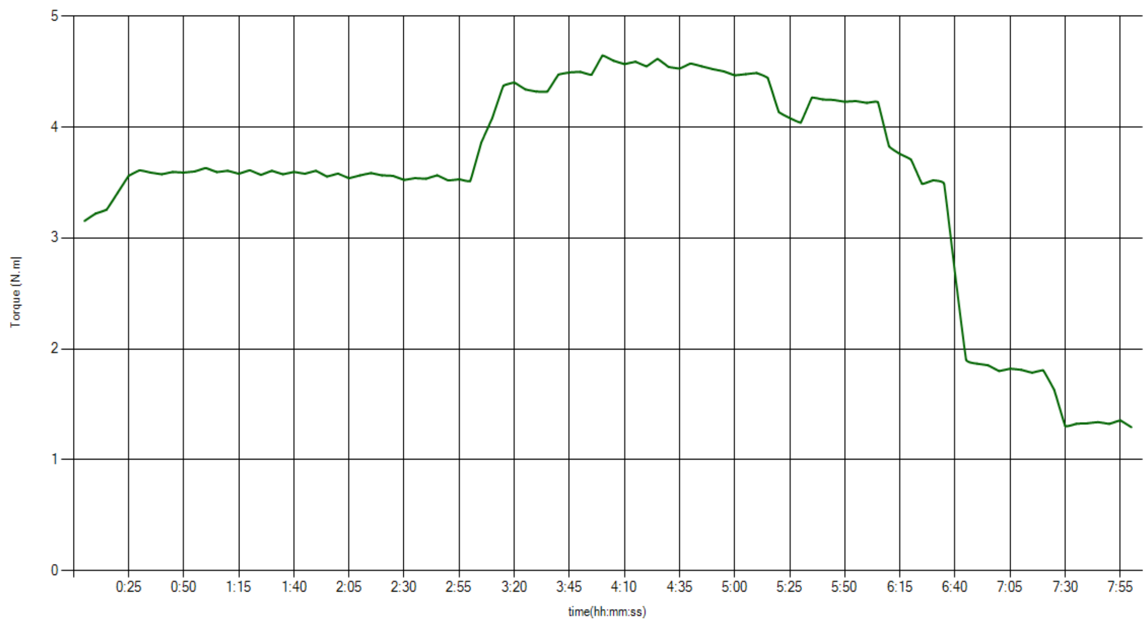


Figure 5-51 S10 Duty with discrete constant loads – Motor Torque (N-m).

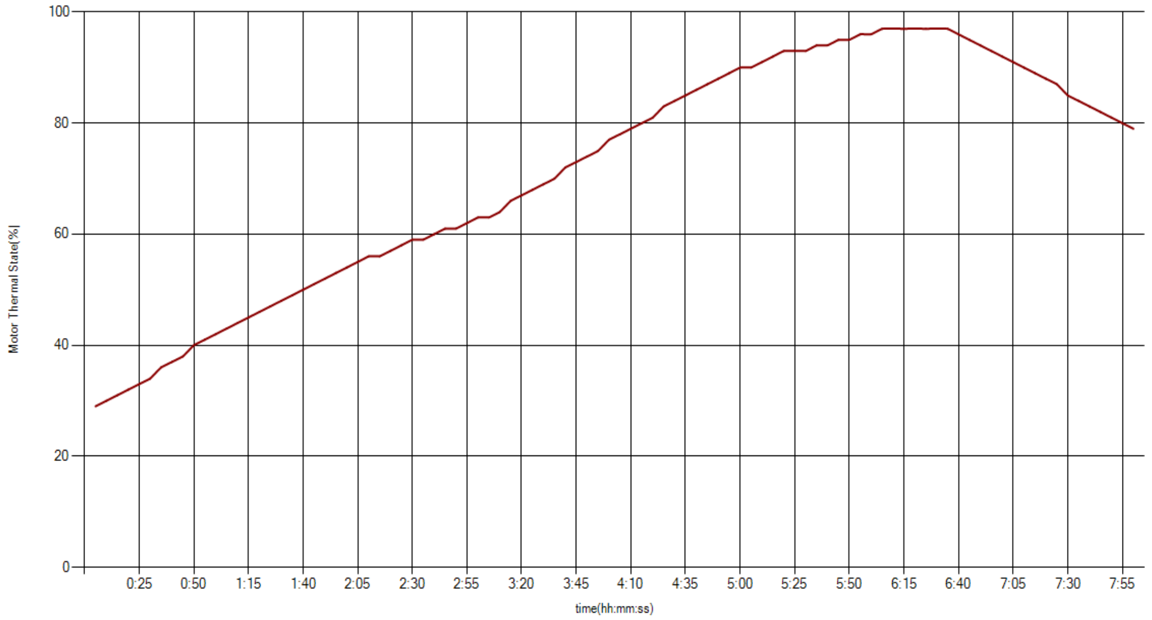


Figure 5-52 S10 Duty with discrete constant loads –Motor Thermal State (%) (motor with a ***cold start****).*

In the first load (of 72% and duration of 3 minutes) the motor power is on average 1,1 kW and the torque 3,5 N.m, in the second load (near-rated load and duration of 4 minutes) the power and torque achieve near-rated values (of 1,4 kW and 4,5 N.m), hence working in near-rated conditions, in the third and fourth load these values are greatly reduced (Figure 5-50 and Figure 5-51)

The motor thermal state increases steadily during the first 2 loads, until thermal equilibrium is achieved (in the second load of 92%). Reducing the load (third and fourth loads) the motor thermal state begins to decrease (Figure 5-52).

6. Conclusion

The main objective of this project is to develop an E-learning module of an induction motor, allowing the motor's variables monitoring and the control of an induction motor. The variable speed drive ATV 630 from Schneider was used to control the motor, using this technology the user can start/stop the motor, set reference speeds, monitor real-time motor variables and motor thermal state through a website, this website was implemented in HTML5/CSS using asp.net environment in Microsoft Visual Studio.

Using this E-learning module, the students can also monitor the motor's variables in real-time through charts and perform a secure thermal monitoring of the induction motor, not allowing the machine to perform in an over-load scenario that can decrease the machine's life expectancy. Secure conditions for starting and stopping the load are also assured, as the variable speed drive ATV600 does not allow motor starting with more than 1.2 times the nominal current value.

Hence this platform for E-learning, allows a simple motor management and control through a web page, allowing the user with an easy motor management and with secure conditions guaranteed, such as thermal safety and soft motor start/stops.

A module with the electric machine's working duties DIN VDE 0530 was developed, to determine if an induction motor can perform effectively in any duty. For this, the user only introduces the variables: cyclic duration factor (CDF), and the number of duty cycles per hour (c/h). The user is also capable of saving the motor's variables values in an excel file (.xlsx). Using this module, the user can pre-determine if an induction motor is appropriate to perform in a working duty different than the standard S1-Continuous Duty.

6.1. Future work

The following topics illustrate some of the possible future improvements to be made:

- Implement a similar module in a simple IoT device (such as Arduino or Raspberry Pi).
- Generalize the E-learning module to work with a Synchronous machine.
- Generalize the Webpage programmed (in HTML/CSS using asp.net) so it can work in any wireless device, enabling the user to control/monitor the machines in any wireless device.
- Create a Database, where the all the motor's variables value of all tests can be store, including thermal tests.

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