TÉCNICO LISBOA

Technico-economical evaluation of the substitution of electric motors present at the IST Alameda Campus according to the Commission Regulation (EC) No 640/2009

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Thesis to obtain the Master of Science Degree in

Electrical and Computer Engineering

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May 2017

Acknowledgements

First I would like to thank to my supervisor, Prof. Paulo Branco, for all the guidance and support provided during the development of this thesis, as well as for all the knowledge that was shared with me over the last years of my degree.

I also thank to my co-supervisor, Eng. Mário Matos, and to the IST Sustainable Campus team, for all the help provided, mainly in the beginning of this thesis.

I am also grateful to the IST maintenance team, namely to the responsible Engineers and to Mr. Dino Neves, the technician that supervised all measurements performed on technical areas.

I would like to thank to all my colleagues and friends that were with me since the beginning of this life journey, for all the support on bad moments, but also for all the great moments shared over these years.

A special thanks to my parents, for all the patience and support.

Last but not least, thank you Catarina Chimeno, for being always by my side.

Resumo

Atualmente, preocupações relacionadas com o ambiente fazem parte do nosso quotidiano. O aumento das emissões de gases de efeito de estufa, causado pela atividade humana, está a conduzir a um aumento da temperatura média global.

As crescentes preocupações relacionadas com a poluição, as alterações climáticas e o desperdício dos recursos naturais do planeta levaram-nos ao conceito de eficiência energética. Nesta tese, o foco principal vai para a eficiência em motores elétricos, que constituem uma das cargas mais importantes. A eficiência energética pode ser melhorada nestes sistemas, levando a uma redução do consumo de eletricidade, o que provoca diretamente um impacto positivo no ambiente. A União Europeia tem tomado medidas neste âmbito, sendo um exemplo o Regulamento (CE) n.º 640/2009, que serve de base para esta tese.

Pelo mundo fora, a introdução de medidas de eficiência energética em *campus* universitários tem sido prática comum. Nesse campo, o IST não é diferente; o projeto Campus Sustentável foi criado para gerar melhorias nesta área. Esta tese está integrada nesse projeto.

Nesta tese, é desenvolvido um método não-invasivo, barato, simples e fiável, que permite determinar a eficiência de motores de indução. Este método é aplicado a motores que fazem parte dos sistemas de AVAC do Campus Alameda do IST. Os resultados obtidos são analisados, e, se verificadas eficiências baixas, a substituição por motores de alto rendimento é estudada. Variadores de velocidade e arrancadores suaves também são considerados, mas não em detalhe.

Palavras-chave: Eficiência Energética, Motor de Indução, Monitorização Não-invasiva, Campus Sustentável, Bombas de AVAC.

Abstract

Nowadays, concerns regarding environment are part of our daily lives. The global average temperature is rising due to human induced increase of greenhouse gases emissions.

The growing concerns regarding pollution, climate change and the wastage of our planet's natural resources led to the concept of energy efficiency. In this thesis, electrical energy efficiency is the one that is going to be the focus, regarding electric motors, which are one of the most important loads. Energy efficiency can be improved in these systems, and these improvements are directly related with the reduction of electricity consumption, which has a direct, positive impact on the environment. The EU has taken several measures regarding this issue, and one example is the Commission Regulation (EC) No 640/2009, which serves as a base for this thesis.

Seeking energy efficiency and other environmentally friendly policies in an university campus has been a common trend all over the world. In this matter, IST is no different; the IST Sustainable Campus Project was created bearing in mind this growing need, seeking for improvements in this area. This thesis is integrated in that project.

In this thesis, a non-invasive and cheap, but simple and reliable methodology of determining induction motors efficiency is defined, and then it is applied to motors that are part of IST Alameda Campus HVAC systems. The obtained results are analysed and if low efficiencies are verified, high-efficiency induction motors introduction is studied. Variable speed drives and soft-starters are also considered, but not in detail.

Keywords: Energy Efficiency, Induction Motor, Non-invasive Monitoring, Sustainable Campus, HVAC Pumps.

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List of Abbreviations

AC	Alternating Current
AEE	Association of Energy Engineers
DC	Direct Current
DSM	Demand Side Management
EN	European Norm
EPBD	Energy Performance of Buildings Directive
EU	European Union
HVAC	Heating, Ventilation and Air Conditioning
IST	*Instituto Superior Técnico* (University)
PPE	Personal Protective Equipment
RMS	Root Mean Square
ROI	Return on Investment
VSD	Variable Speed Drive

Chapter 1

Introduction

The reason for the development of this thesis is presented, introducing the reader to the problem that is to be studied.

An overview regarding energy efficiency foundations is performed. Energy efficiency is then linked with electric machines and buildings, and an introduction regarding energy efficiency in universities is made.

This chapter is also dedicated to present the objective of this thesis, as well as the structure followed over the report, in order to organize the presentation of the subject and the results.

1.1 Background

Nowadays, concerns regarding environment are part of our daily lives. Either on TV news, or on the Internet, mainly in social networks, people all over the world discuss the environment and the near future ahead.

"The current warming trend is of particular significance because most of it is very likely human-induced and proceeding at a rate that is unprecedented in the past 1300 years" [7]. Data retrieved regarding ice cores drawn shows that "large changes in climate have happened very quickly, geologically-speaking: in tens of years, not in millions or even thousands" [7]. Greenhouse gases emissions are rising, and so is the global average temperature [8]. It is estimated that Earth's average temperature rises by more than three degrees Celsius this century [8].

Evidence regarding this issue is undeniable and of big concern [7]:

- Sea level rise: about 17 cm [7]. The Netherlands, Florida and Maldives, for example, as well as other near-shore places, are vulnerable to this rise.

- Global temperature rise: Earth's temperature is rising since 1880, and the past 35 years were the most critical [7].

- Shrinking ice sheets: "Greenland and Antarctic ice sheets have decreased in mass" [7]. In Greenland they decreased 150 to 250 km^3 of ice per year between 2002 and 2006, and in Antarctica they decreased 152 km^3 of ice between 2002 and 2005 [7].

- Declining Arctic sea ice and worldwide glacial retreat [7].
- Extreme events, especially high temperature events, like intense rainfall [7].
- Ocean acidification: "since the beginning of the Industrial Revolution, the acidity of surface ocean waters has increased by about 30%" [7]. This is directly related to the increase in carbon dioxide emissions, which, consequently, leads to an increase in the amount of carbon dioxide absorbed by the oceans [7]. This absorption is growing by about 2 billion tons per year [7].

"In its Fifth Assessment Report, the Intergovernmental Panel on Climate Change, a group of 1300 independent scientific experts from countries all over the world under the auspices of the United Nations, concluded there's a more than 95 percent probability that human activities over the past 50 years have warmed our planet. The industrial activities that our modern civilization depends upon have raised atmospheric carbon dioxide levels from 280 parts per million to 400 parts per million in the last 150 years" [7].

Several measures have been taken in order to mitigate this worldwide problem. One of the most famous agreements is the Kyoto Protocol.

The Kyoto Protocol is an international agreement, directly related with the United Nations Framework Convention on Climate Change, that has the objective of setting emission reduction targets within several countries [9]. The Kyoto Protocol was adopted in Kyoto, Japan, on 11 December 1997 [9]. This Protocol is more severe with developed countries, since they are mainly responsible for the current levels of emissions, as a consequence of having more than 150 years of industrial activity [9]. During the first commitment period, 37 industrialized countries and the European Community agreed to reduce greenhouse gases emission levels to an average of 5% against 1990 levels. During the second commitment period, participating countries agreed to reduce emissions by at least 18% below 1990 levels, from 2013 to 2020.

Another important measure is the Paris Agreement, also directly related with the United Nations Framework Convention on Climate Change. On 5 October 2016, an agreement regarding target definitions between the participating countries was achieved [9]. This agreement was a success, as 129 Parties have ratified the agreement, of 197 Parties that were summoned to the Convention [9]. "The Paris Agreement's central aim is to strengthen the global response to the threat of climate change by keeping a global temperature rise this century well below 2 degrees Celsius above pre-industrial levels and to pursue efforts to limit the temperature increase even further to 1.5 degrees Celsius" [9]. The agreement also has the objective of helping countries to deal with the impacts of climate change, especially developing countries [9].

"Sustainability is an important part of counteracting climate change" [8]. The growing concerns regarding pollution, climate change and the wastage of our planet's natural resources led to the concept of energy efficiency. Energy efficiency means energy savings, seeking to avoid energy losses and waste. This is a broad concept used in many and different areas.

In this thesis, electrical energy efficiency is the one that is going to be the focus, regarding electric motors. ”Electric motors are by far the most important electric load, and therefore should be one key priority in large-scale market transformation and Demand Side Management (DSM) programs designed to achieve cost-effective electricity savings” [10]. Electric motor systems represent about 70% of electricity consumption in the EU industry [1], being one of the most important loads. Energy efficiency can be improved in these systems, and these improvements are directly related with the reduction of electricity consumption, which has a direct, positive impact on the environment. The EU has taken several measures regarding this issue, and one example is the Commission Regulation (EC) No 640/2009, which serves as a base for this thesis, and will be discussed in further chapters.

Buildings in the EU are responsible for 40% of total energy consumption [11]. Energy consumptions in buildings are on the table for discussion, being integrated in the EU efficiency initiatives. Taking actions in this area can prove to be a right choice. Regarding the several problems caused by pollution and climate change, European Governments are taking a step forward and want state-held buildings to become a model for energy efficiency, encouraging private companies to follow their steps. Buildings included in universities' campi are, of course, part of these referred buildings.

Motors are widely used in industry, but also in buildings, spreading through HVAC systems. They are part of pumps, fans, coolers, air conditioning systems, etc. They are also present in elevators, for example. These facts prove that energy efficiency in electric motors is a key factor when it comes to buildings' energy efficiency improvement. Taking into account the elevated share that electric motors represent on electricity consumption, improving their efficiency in a building can definitely improve its general efficiency.

1.1.1 Energy Efficiency in Universities

Seeking energy efficiency and other environmentally friendly policies in an university campus has been a common trend all over the world. For example, the International Sustainable Campus Network, which has as objective the widespread of ideas related with this issue, counts with the world's finest universities as members, such as Harvard, Yale, Oxford and Cambridge. In this matter, IST is no different; the Sustainable Campus Project, an initiative that joins IST and an external company - Galp - was created bearing in mind this growing need, seeking for improvements in this area.

IST Sustainable Campus Project

The Sustainable Campus Project is part of IST Energy Initiative. The objective of this project is to improve energy efficiency on IST campi facilities, and also to provide knowledge and to move the IST community regarding resources usage and energy saving practices. With this, it is possible to save electricity and water, and consequently reduce costs, while contributing to a better environment.

One of the ideas that came from this project was the creation of a ”Knowledge Laboratory” in energy efficiency, promoting a space to debate and propose ideas, as well as the creation of a digital repository of documents related with energy efficiency, that can be useful to develop studies on this field and projects on IST facilities. This idea led the IST Sustainable Campus Project to win the international award International Energy Project of the Year - 2014, attributed by the Association of Energy Engineers (AEE).

1.1.2 Instituto Superior Técnico

Instituto Superior Técnico (IST) is a Portuguese public higher education institution founded in 23 May 1911 by Alfredo Bensaúde [2]. It is integrated in the University of Lisbon, and it counts more than 10000 students [2]. IST is composed by three campi: Alameda Campus, Taguspark Campus and Technological and Nuclear Campus.

Alameda Campus (see Figure 1.1) construction was concluded in 1937 [2], and it is located in the heart of the city of Lisbon, between Saldanha and Alameda D. Afonso Henriques. Projected initially for a maximum period of occupation of 40 years, this area is still home of IST main campus [12]. Since 1936 several expansions and construction projects have been performed in order to keep up with the growth of the institution [12].

Figure 1.1: IST Alameda Campus [2].

Taguspark Campus (see Figure 1.2) construction was concluded in 2009 [2], and it is located in Porto Salvo, Oeiras, in Lisbon Metropolitan Area. This was a historical project, allowing to strengthen the relationship between the University and companies, since this campus is located into the largest Science and Technology Park in Portugal [2].

Technological and Nuclear Campus (see Figure 1.3) is part of IST since February 2012 [12], and it is located in Loures, in Lisbon Metropolitan Area. This is one of the most important technology centers in Portugal regarding nuclear sciences and safety, and it is where the Portuguese Research Reactor is located [2].

It is on IST Alameda Campus that this study takes place. Being the oldest campus, it is composed by buildings that are several years old, and so are the systems that include motors. Nowadays, maximum consumptions are regulated by law, but several of the existing systems were incorporated years ago, before the growing concerns regarding energy efficiency and the reduction of the environmental footprint. Therefore, it is imperative to verify if motors that are operating on campus facilities are efficient, according to the standards defined on Regulations.

Figure 1.2: IST Taguspark Campus [2].

Figure 1.3: IST Technological and Nuclear Campus [2].

1.2 Objective

The objective of this thesis is to verify if a determined number of induction motors, which are part of the IST Alameda Campus HVAC systems, are operating efficiently. If inefficiency is verified, the substitution of the existing motor by a high-efficiency one is studied. Although the main objective is to study high-efficiency motors introduction, other motor efficiency improvement solutions (variable speed drives and soft-starters) are also considered, but not in detail.

A methodology for efficiency determination on induction motors is defined, since the analysis must be performed using a non-invasive method. Non-invasiveness is crucial, as the objective is to conduct measurements without taking the motors to a laboratory, and consequently disassembling the system, and stopping it for a period of time. The methodology must also be cheap, allowing it to be applied anywhere, on a large scale if needed, simple and accurate.

In this thesis, a non-invasive, simple, cheap and reliable methodology of determining induction motors efficiency is defined, and then it is applied to motors that are part of HVAC systems. After that, the results obtained are analysed, and solutions, in case low efficiencies are verified, are provided. That said, this thesis serves as a guide that can be followed by any user that wants to perform an energy efficiency analysis on induction motors. The final purpose is to improve IST Alameda Campus energy efficiency, contributing to a greener university.

1.3 Structure

This thesis is organized in 6 chapters, in order to present the work performed in a clear and progressive manner.

In Chapter 1 a brief introduction is performed regarding the background that led to the development of this thesis, as well as the motivation. The objectives of this thesis are also presented.

Chapter 2 presents a brief overview regarding energy efficiency in the EU, with a special focus on electric machines. The Commission Regulation (EC) No 640/2009, which serves as a base for this thesis, is here presented. The overview also focus on the specific case of Portugal, and allows some comparisons between the country and the EU in general, when energy efficiency is concerned.

In Chapter 3 simple key concepts on induction motors are presented. These concepts include an overview on motor operation principles, and a special focus on motor efficiency, where the main solutions used to improve it are presented.

In Chapter 4 the methodology developed and used to assess induction motors efficiency is presented. It includes the technical part, as well as the economical analysis approach used.

Chapter 5 is where studied motors' analysis is performed, applying the methodology described in Chapter 4. The case study is presented, and each motor is analysed, in order to verify if it is operating efficiently or not, and if solutions have to be provided.

In Chapter 6 conclusions regarding the work performed are drawn, and proposals for future works are made.

Chapter 2

Energy Efficiency in the EU: an overview regarding electric machines

In this chapter, a brief overview is performed regarding energy efficiency in the EU, taking into special account the specific case of electric machines.

The analysis is performed for the EU in general, and for Portugal in particular. Since Portugal is an EU member, certain laws and norms defined for all members have to be followed and applied. Nevertheless, each country has its own energy consumption distribution, as well as different levels of energy efficiency methods integration and application. That said, it is important to look not only for the EU, but also for the specific case of Portugal.

The overview is also focused on the case of electric machines that are integrated in buildings, such as in HVAC systems. This specification is justified since the motors analysed in this work are included in that particular scenario.

2.1 European Union

The EU set a target of saving 20% of energy by 2020, which is equivalent to turning off 400 power supply stations [13]. This target is basically the guideline for European energy policies [13]. In 2014, a future target of 27% or more of energy efficiency was established [13].

As it can be seen, the EU and its leaders are very committed with energy efficiency, and there is a clear objective of increasing energy savings. A common European citizen is nowadays, on the majority of cases, a person that has some knowledge about energy saving practices, as well as about other environmentally friendly practices, such as recycling.

Systems that include electric motors are responsible for about 69% of the electricity consumed in industry in the EU [10]. In the services sector, they are responsible for about 38% of the electricity consumed [10]. Of these systems, pumps, fans and compressors represent the most important systems regarding electricity consumption [10]. In the industrial sector, they represent 62% of total motor electricity consumption, and in the services sector 82% [10].

Energy consumption in buildings in Europe is about 40% of the total consumption, being HVAC systems the ones that require more energy [11]. These HVAC systems are composed by pumps, fans, compressors, which were presented above as the main cunsumers. The main power source for buildings is natural gas, which represents 36% of the consumption, followed by electricity, that represents 32% of the consumption [11].

Despite representing a large parcel of the consumption, only 25% of all buildings in Europe have an energy performance above the Energy Performance of Buildings Directive (EPBD) requirements [11]. It is estimated that buildings' energy consumption can be reduced by 50% if energy efficiency actions are taken, leading to a yearly reduction of 400 million tons of carbon dioxide emissions, almost achieving the value agreed by the EU on the Kyoto Protocol [11].

2.1.1 Commission Regulation (EC) No 640/2009

This Regulation is presented as it serves as a base for this thesis. It allows to understand the important role that electric motors play on energy efficiency, particularly in the case of Europe, as well as to set thresholds for motor efficiency level assessment.

This Regulation is included in the group of measures that are set by the EU regarding the creation of requirements for ecodesign of energy-using products [1]. These requirements target products that represent a significant market, and with potential of reducing environmental impact without incurring in excessive costs [1]. Electric motors are included in this set of products. Cost-effective improvement of electric motors systems' energy efficiency can be achieved, by about 20% to 30%, either by the usage of energy efficient motors, as well as by applying drives [1]. That said, for the EU, "electric motors represent a priority product for which ecodesign requirements should be established" [1].

Motors use-phase energy consumption is the most significant environmental aspect of all life-cycle phases. In the majority of cases, this can be improved if motors are equipped with drives [1]. Consumption improvements are to be achieved using "cost-effective technologies that can reduce the total combined costs of purchasing and operating" the motor [1].

This Regulation intends to save 135 TWh of electricity by 2020, and it is applyed to three-phase squirell cage induction motors under certain specifications [1]. "This Regulation establishes ecodesign requirements for the placing on the market and for the putting into service of motors, including where integrated in other products" [1]. It is established that, from 1 January 2017, "all motors with a rated output of 0,75-375 kW shall not be less efficient than the IE3 efficiency level, (...) or meet the IE2 efficiency level (...) and be equipped with a variable speed drive" [1].

This Regulation clarifies how motors are important when general energy savings are concerned, and that justified and necessary efforts are being done in order to make motors more efficient machines.

On January 2014 Commission Regulation (EU) No 4/2014 was published, amending Regulation No 640/2009. Bearing in mind the experience developed during the implementation of this Regulation, certain aspects had to be amended, in order to "avoid unintended impacts on the motor market and on the performance of the products covered by that Regulation" [14]. These aspects include changes on limit values for which a motor is considered to be operating on extreme conditions, as well as some changes regarding the nameplate information required.

2.2 Portugal Case

The Portuguese Republic is the westernmost country of Europe. It is constituted by the mainland, and by two archipelagos, Azores and Madeira. The Kingdom of Portugal was established in 1139, and its independence was recognized in 1143 [15]. The Portuguese borders were defined in 1297, making Portugal one of the oldest nation-states in Europe [15]. Portugal became a member of the EU in 1986.

Energy consumption in buildings in Portugal is about 30% of the total consumption [11]. This value is lower when compared with the rest of Europe, as Portuguese climate is more balanced, and so HVAC systems' consumption is not so high [11].

The main power source for buildings in Portugal is electricity, which represents 55% of the consumption, and again this differs from the EU average, as natural gas only represents 10% of buildings' energy consumption in Portugal [11]. This again is directly related to the less need for HVAC usage, especially on Winter, as natural gas is used on boilers or on other heating systems.

Although the construction market in Portugal had a boom in the 90's (now being more in crisis), Portuguese buildings are old on their majority, especially on the residential sector [11]. Several problems affect the buildings, such as the natural wearing of materials, lack of maintenance, buildings characteristics and the lack of knowledge of buildings' users about energy saving practices [11].

Government buildings' main power source is also electricity, and the Portuguese Government is responsible for 13% of all electricity consumption on the services sector [11]. On the last years, with the growing concerns regarding climate change and greenhouse gases emissions, decree-laws have been developed in Portugal regarding buildings' energy efficiency. The Portuguese Government wants their buildings to be seen as a model for privately held buildings regarding energy efficiency [11].

Several programs on energy efficiency have been implemented in Portugal. *Plano Nacional de Ação para a Eficiência Energética* (PNAEE 2016) - National Energy Efficiency Action Plan, predicted 8.2% savings until 2016 [16]. These savings are distributed over several sectors, such as transports, residential and services, industry, government/state and agriculture [16]. Regarding the PNAEE state sector, *Programa de Eficiência Energética na Administração Pública* (ECO.AP) - Energy Efficiency in Public Administration Program was launched with the objective of reaching an increase of 30% in energy efficiency until 2020, on state-held buildings, services and equipments [16]. This program allows the Portuguese Government to decrease the energy bill, as well as to reduce greenhouse gases emissions [16]. This has to be performed without increasing public expenses, and while energy sector companies market is stimulated [16]. This program also contemplates the change that is required regarding people habits and behaviours when energy savings are concerned [16], especially in work or in public buildings, where the energy bill does not get directly to the users, and so wrong and bad habits tend to occur.

The Portuguese Government is, as the EU, very committed with the issue of energy efficiency, and measures are being taken in order to take Portugal to the next level regarding this issue.

Chapter 3

Induction Motor

This chapter intends to present simple key concepts on induction motors. This has the objective of introducing the theoretical foundations used in this work for motor efficiency analysis.

”The origin of the electric motor can be traced back to 1831 when Michael Faraday demonstrated the fundamental principles of electromagnetism. The purpose of an electric motor is to convert electrical energy into mechanical energy” [17].

There are various types of electric motors, and in Figure 3.1 the most common cases are represented.

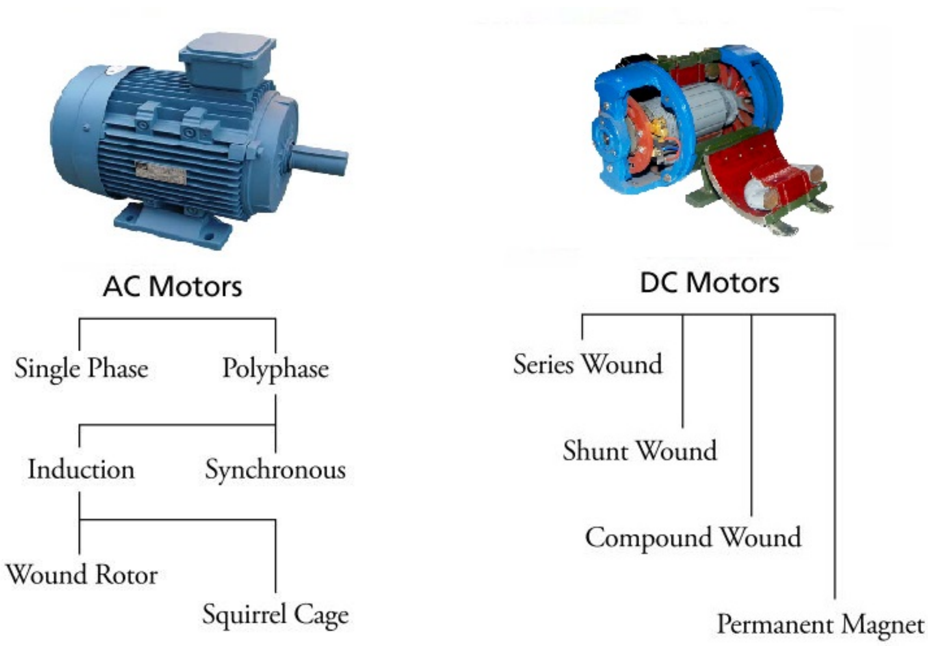


Figure 3.1: Types of electric motors [3], [bennelec.com, 2017], [shellmax.made-in-china.com, 2017].

Motors can be divided in two main categories regarding power supply: Alternating Current (AC) or Direct Current (DC). AC motors can be divided into single-phase and polyphase.

Single-phase motors are the most common motors to find in residential and commercial applications, due to the fact that single-phase current is the one available [3]. These motors, however, present some disadvantages, such as high starting currents, low efficiency when compared with polyphase motors, and they are not available for high power applications [3]. This leads to the fact that polyphase motors are the most used in industry, as well as in pumps, fans, compressors, etc. "The most common type of motor in use today is the polyphase induction motor, over 90% of which are squirrel cage induction motors. Because of their prevalence throughout the industrial (and commercial) sector, polyphase induction motors offer a great potential savings opportunity in both energy and operational costs during the motor's useful life" [3].

All motors studied in this thesis correspond to the commonly used three-phase, squirrel cage induction motor (see Figure 3.2).

Figure 3.2: Three-phase, squirrel cage induction motor [directindustry.com, 2016].

These motors have a lot of advantages that play on their favour, as they are robust, reliable, cheap, a low maintenance level is required, and no sparks are produced during operation, making them a safe choice for explosive atmospheres [18]. Of course these motors also present disadvantages, such as fixed speed, low efficiency out of the defined rated operating point, and high starting current peaks [18], that on some situations can prove to be hazardous to other equipments connected to the same network.

The operation principles for these motors are presented, followed by an overview regarding their efficiency. This overview will lead to the presentation of the high-efficiency motor, as well as of the power electronics related with the induction motor: variable speed drives and soft-starters.

3.1 Motor Operation Principles

Figure 3.3 depicts a three-phase, squirrel cage induction motor with a transversal cut, which allows to visualize the interior components of the motor.

This motor is composed by two main parts: the stator, and the rotor.

The stator, as the name suggests, is the static part of the motor. It is composed by the parts that do not have movement during motor operation, which includes:

- Motor Frame - it is the outer part of the motor, and protects all the inner parts. Generally it is made in cast iron [18], and presents some prominences that increase the area in contact with the air, allowing heat dissipation.

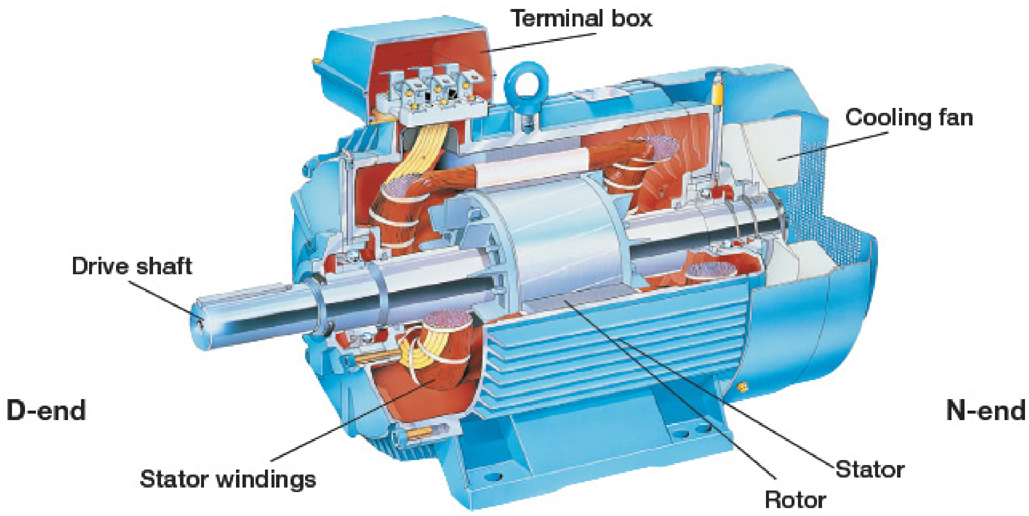


Figure 3.3: Three-phase, squirrel cage induction motor with a transversal cut [tesinasalvatorecoppola.altervista.org, 2017].

- Stator core - the core is composed by laminated sheets made generally in steel, or in iron silicon if the quality is superior [18]. These sheets are isolated and compressed, allowing the stator magnetic field to circulate, reducing the eddy currents. The core has slots, where the three-phase stator windings are inserted [18].

- Stator windings - generally in copper, but also can be found in aluminium, there are three equal windings present in the stator, one per phase, and with an electric phase shift of 120º between them [18]. When connected to a three-phase electric current supply, they are responsible for the creation of the stator magnetic field [18].

The rotor, as the name suggests, is the moving part of the motor. It is composed by the parts that move and rotate during the motor operation, which includes:

- Rotor core - the rotor core is similar to the stator core, allowing to close the magnetic circuit of the stator magnetic field [18]. This core also has slots, where the rotor bars are inserted [18].

- Rotor bars - the rotor bars are made of aluminium, and are short-circuited on both sides by rings, making this the so-called squirrel cage [18], which names the motor type. This construction allows rotor current induction and circulation, which will be responsible for the creation of the force that induces movement [18].

- Shaft - made in steel, it is responsible to deliver mechanical power to the loads [18].

The base principles of motors functioning rely on electromagnetic phenomena. An electric current generates a magnetic field, and a varying magnetic field towards a conductor generates back a varying electric current [18]. The interaction between the current generated and the magnetic field itself, generates a force, called torque (a Lorentz force), responsible for moving the motor.

When a three-phase voltage is applied to the stator, from the terminal box (see Figure 3.3), a "rotating" sinusoidal magnetic field is generated on the stator [19], [20]. This magnetic field presents a

”rotating” pattern, due to the phase shifts of the voltages applied, and presents a frequency ω_{stator}, equal to the frequency of those voltages. This stator magnetic field then induces a sinusoidal electromotive force on the rotor bars, with frequency ω_{rotor} equal to the difference between ω_{stator} and rotor speed [19], [20]. Since the rotor bars are short-circuited, this allows a current, named the rotor current, to flow through the rotor [19], which creates the torque. The current distribution on the stator and on the rotor is the same, only differing on their frequencies [20]. The rotation direction of the motor depends on the rotation direction of the stator magnetic field [19].

In the beginning of the operation, the motor is stopped. When the motor is stopped, stator and rotor currents have the same frequency ($\omega_{stator} = \omega_{rotor}$) [19]. As the motor starts rotating and accelerates, the rotor current frequency starts to decrease [19]. This rotor current amplitude and frequency then depend on the load, as the load creates a resisting torque: the smaller the load, the smaller the amplitude and frequency of the rotor currents. If the motor is unloaded, the current amplitude and frequency will be almost zero [19], as the resisting torque is only composed by the air resistance and bearings friction; as the load increases, the resisting torque increases, and so does the current frequency and amplitude, in order to produce a torque that can ”beat” the resistance.

An induction motor can have two or more poles. These poles are basically created depending on the stator windings distribution around the stator core [18]. This number of poles has a direct influence on motor synchronous speed value, defined by the frequency of the input voltages divided by the number of pairs of poles of the motor.

All principles introduced now allow to specify a mathematical approach to the induction motor, which will clarify everything presented. The rotor frequency is represented in Equation 3.1 [20]:

$$\omega_{rotor} = \omega_{stator} - p\dot{\theta} \quad [rad/s] \tag{3.1}$$

where p denotes the number of pairs of poles and $\dot{\theta}$ the motor rotating speed in rad/s.

The slip is introduced in Equation 3.2 [20]:

$$s = \frac{\omega_{stator} - p\dot{\theta}}{\omega_{stator}} \tag{3.2}$$

It is now clear, analysing Equations 3.1 and 3.2, that when the motor load increases, the rotor frequency starts to increase, and so the motor speed decreases, increasing the slip in the process.

The mechanical power delivered by the motor to the load, as well as the torque, are represented in Equations 3.3 and 3.4, respectively [20]:

$$P_m = 3R_{rotor}\frac{1-s}{s}I_{rotor}^2 = T\dot{\theta} \tag{3.3}$$

$$T = 3pR_{rotor}\frac{1}{s\omega_{rotor}}I_{rotor}^2 \tag{3.4}$$

where R_{rotor} denotes the rotor resistance and I_{rotor} the RMS value of the rotor current.

The typical induction motor curves are represented in Figure 3.4. These curves allow a mathematical vision of the motor operating processes, which are described. When the motor is stopped, a starting torque must be applied, in order to beat the initial inertia, and start to move the motor. A high-valued starting current is requested, in order to create this torque, as well as to magnetize the inductive circuit (which explains the high amplitude of the current and the low power factor); the amplitude of this current can be ranged between five to seven times the rated current, depending on the motor. The motor accelerates, until a steady-state is achieved, with a lower value of current requested, with a higher power factor, and with a torque that is created in order to beat the load and air resistances, as well as the bearings friction. The speed stabilizes, with a low slip.

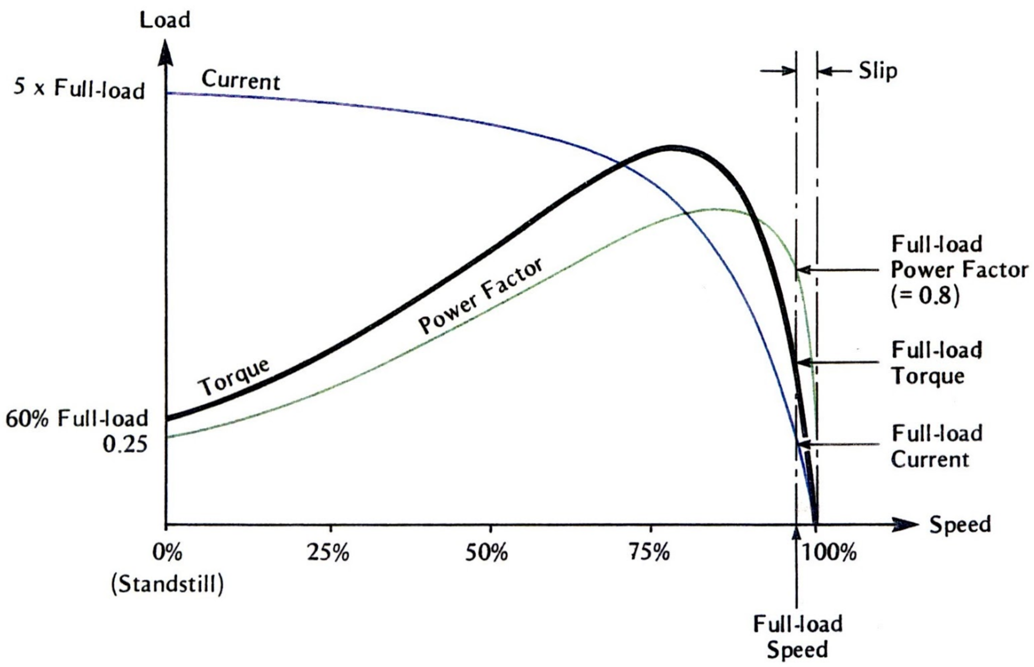


Figure 3.4: Typical torque-speed, current-speed and power factor-speed curves for an induction motor [emadrlc.blogspot.pt, 2017].

There are two main motor operating points regarding its load: unloaded and rated load.

When the motor is unloaded, as stated before, the resisting torque is only composed by the air resistance and bearings friction, and so the torque required to ”beat” it is very small. That justifies that the current amplitude is very small, as is the input power [18]. The motor speed, however, is almost equal to the synchronous speed, having its maximum achievable value [18].

The rated load is the maximum load for which the motor was conceived to operate, meaning that, in this situation, the motor is at 100% load. The values of the voltage, current, speed, mechanical power, etc. for this point (rated values) are presented on the motor nameplate, and serve as a guidance to choose the motor, according to the load that it is going to move.

A motor is generally operating between these two points. If a motor is operating relatively below the rated load, it is said that the motor is over-dimensioned. A motor can also be operating above its rated operating point, and in this situation it is said that the motor is overloaded.

3.2 Motor Efficiency Principles

When speaking about efficiency, it is implied that during the motor operating process, not all the electrical power provided is going to turn into mechanical power. There are losses in the process, but, as Antoine Lavoisier once stated: ”in nature nothing is created, nothing is lost, everything changes”. For the sake of understanding motor efficiency, it is important to analyse and dissect these losses, and understand what each one of them represents. Squirrel cage induction motor losses can be grouped in two categories: fixed losses, that are not dependent on the motor load, and losses proportional to the motor load [21]:

- Fixed losses:
  - Core losses, consequence of the creation of a magnetic field, include hysteresis losses and eddy current losses.
  - Friction losses, due to air resistance and to the bearings.
- Losses proportional to the motor load:
  - Copper losses in the stator and rotor conductors, due to Joule effect caused by electric current circulation.
  - Stray-load losses, due to high-frequency losses in the core; harmonic losses and leakage fluxes induced by load current.

Motors are dimensioned and built in order to minimize losses. As an example, the motor WEG W22 - Cast Iron Frame - Standard Efficiency, 15 kW [4] is analysed. The motor curves are represented in Figure 3.5 [4]. From Figure 3.5, it can be seen that the highest and better efficiencies (in this case, around 90%) are achieved between 75 and 100% of the rated load. ”The optimal operating region for the motors is above 75% of the rated power” [22], and ”this is the same when considering the power factor” [22].

This shows that motors are indeed designed to minimize losses, and are efficient machines, but if they are used on their rated conditions, defined on the nameplate. Other values, such as the power factor, also present better values near the rated load. A high power factor means that the apparent power requested by the motor is reduced, freeing up capacity in the power system [22]. Outside these conditions, efficiency, and, if overloaded, even the motor, deteriorate. ”Motors are employed just as people are and they work as an individual or as a team. They will perform their best if cared for, maintained, evaluated and rewarded” [17].

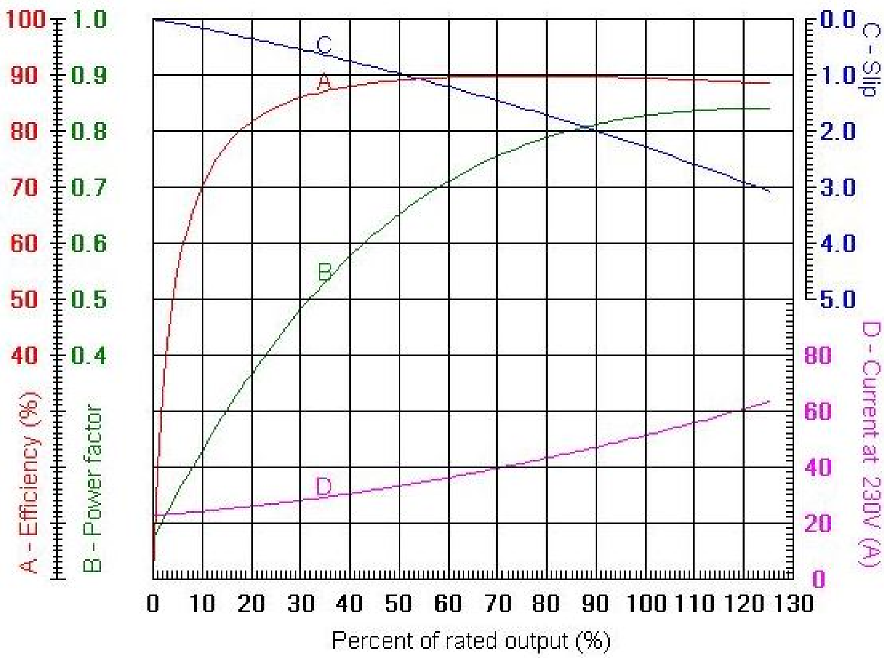


Figure 3.5: WEG W22 - Cast Iron Frame - Standard Efficiency, 15 kW curves [4].

3.2.1 High-Efficiency Motors

As can be seen in Figure 3.5, a standard motor can be efficient, but, in response to the concerns about inneficiency in electrical systems, a solution has been introduced: the high-efficiency motor, even more efficient than a standard motor. This motor can be 2 to 8% more efficient than a standard motor [21]. This is possible "because of their better design, materials, and manufacturing" [21], such as [21]:

- Improved steel properties.
- Thinner laminations.
- Increased conductor volume.
- Modified slot design.
- Narrowing air gap.
- Improved rotor insulation.
- More efficient fan design.

Figure 3.6 depicts these high-efficiency motors' characteristics presented above. In Figure 3.7 it is possible to verify the construction differences between three different types of motors regarding efficiency.

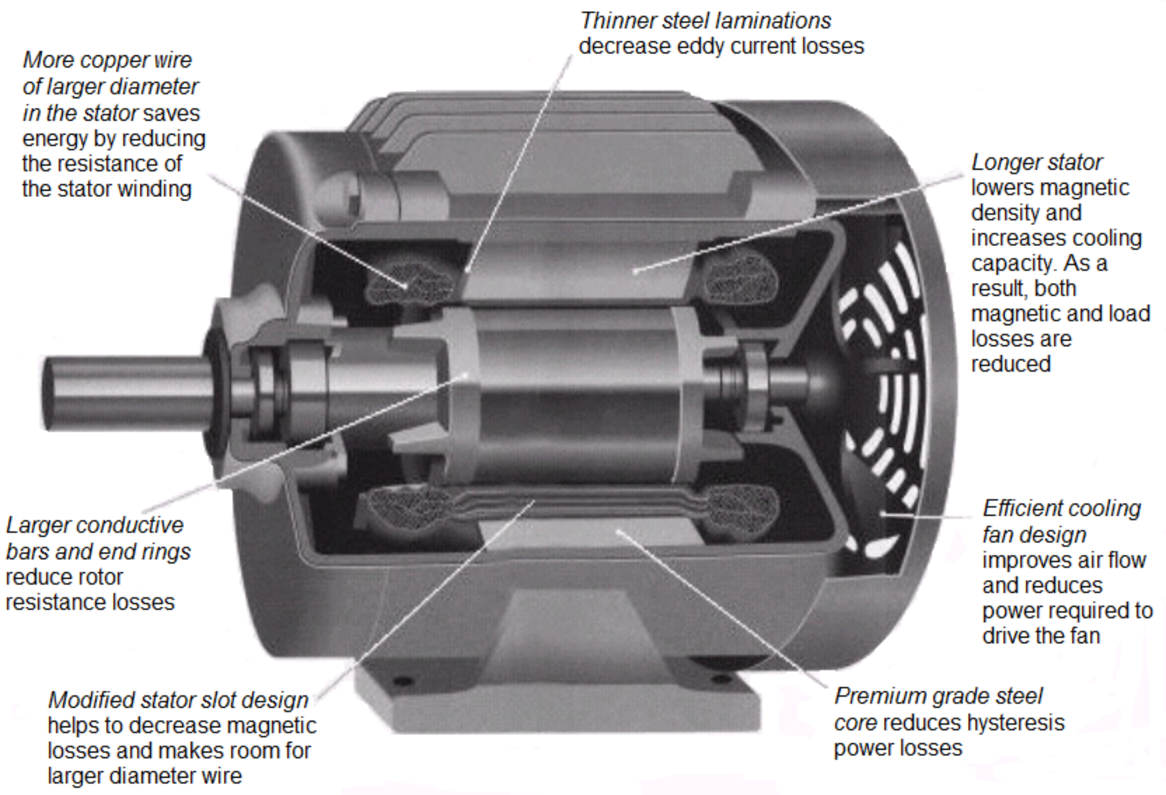


Figure 3.6: High-efficiency motor construction details [5].

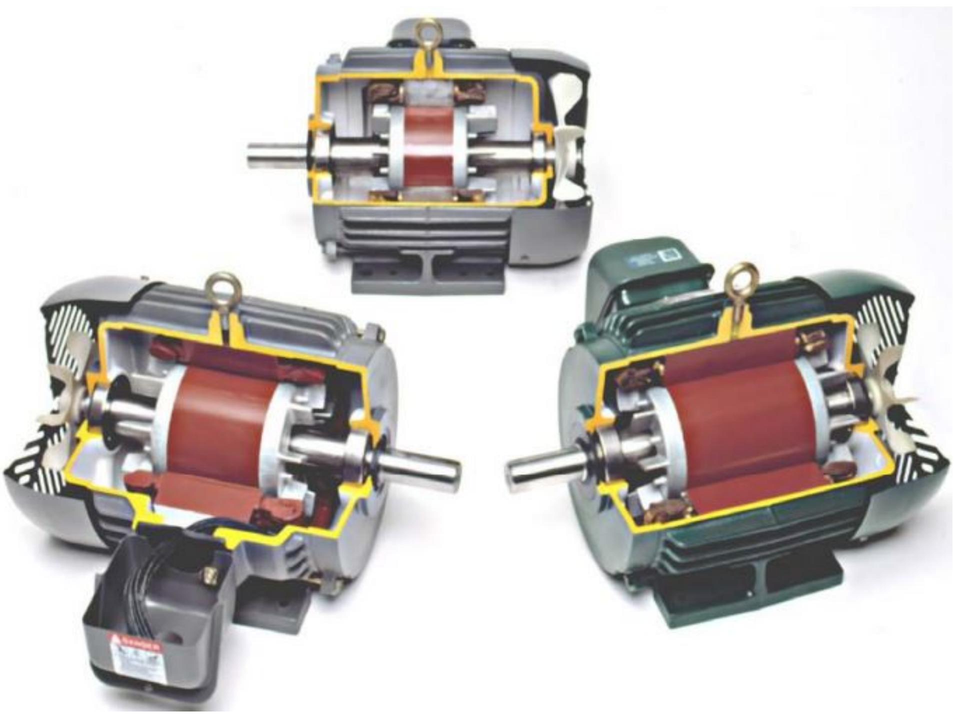


Figure 3.7: Motors construction details comparison: standard motor is on top, high-efficiency motor is on the bottom-left and premium-efficiency motor is on the bottom-right [5].

These motors require less input power than standard motors to produce the same output power [21]. Less losses means less heat, and these motors have a wider lifespan when compared with the standards, with less need for maintenance; they are more reliable when it comes to extreme conditions, such as input power and voltage imbalance or poor ventilated instalation spaces [21]. The drawbacks of these motors are the higher price, and lower starting torque and/or power factor [21].

Since these motors are more efficient, in this thesis, the replacement of standard motors by high-efficiency ones is analysed and detailed in the next chapter.

3.2.2 Variable Speed Drives and Application on Pumps

Focusing on the induction motor disadvantages presented before, one can overcome them thanks to the developments verified in power electronics. The motor variable speed drive (VSD) (see Figure 3.8) has the ability to adapt the motor to the real needs [23]. These drives change the input voltage and its frequency, and consequently, the motor speed [23].

One of the most common controls used on VSDs is the V/f control. This method actuates on the input voltage frequency to influence motor speed, and at the same time it actuates on the input voltage amplitude, allowing the motor to achieve a high range of different speeds without compromising the magnetization level, and, consequently, the torque provided [20].

Figure 3.8: Variable speed drive [factorycontrols.com.au, 2016].

The advantages of VSDs usage are: preventing low efficiency usage and energy economization, preventing start current peaks, and the implementation of protection against short-circuits and over-currents [23]. The disadvantages of these drives are: lower ventilation capabilities, especially if running at low speeds, and the introduction harmonic content on the motor [6], [23].

This technology is mainly used when motors are associated to systems in which the load is variable. This is the case of ventilation [23], as well as, in some cases, water pumps.

On water pumps, sometimes, choking valves are used in order to control the flow. The valves, installed in series with the pump, can be opened, or partially closed [6], in order control the water flow through the pump. As the valve is closed, the flow is reduced, and the pressure rises, leading to load losses [6]. This valve does not affect the motor, and so, as the flow is reduced, the pressure grows needlessly [6]. That said, the usage of a VSD allows to adjust motor speed, without losing efficiency, and so make flow and pressure proportional, avoiding load losses in these systems [6].

The usage of VSDs clearly allows to save energy on pumping systems that require flow variations [6], as it can be seen on Figure 3.9. For example, for a flow of 80% of the rated flow, speed must be reduced by 80% as well [6]. The power required by the motor will be of, approximately, 50% the rated power, and so the energy economization corresponds to 45% [6].

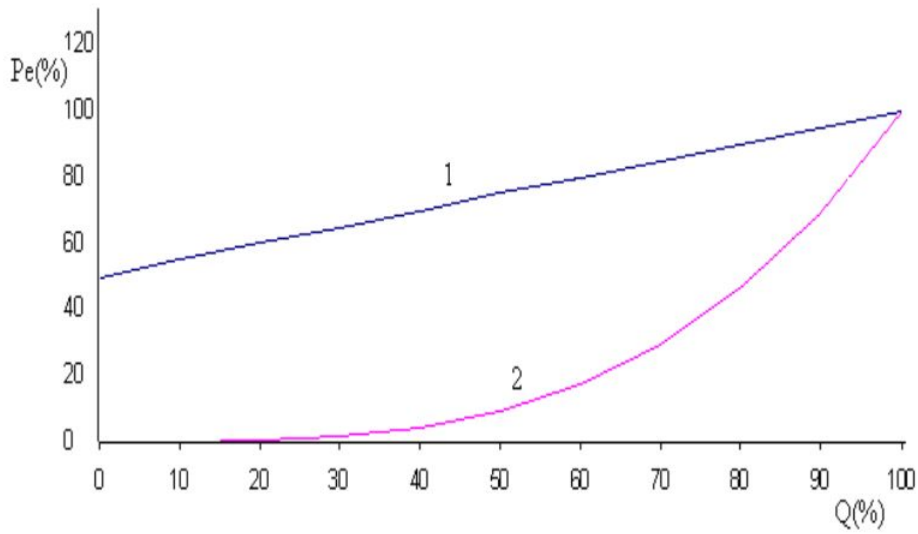


Figure 3.9: Electric Power vs. Flow for two flow control methods: 1 - Choking Valve; 2 - VSD [6].

All this analysis proves that, when speaking about energy efficiency, the integration of VSDs on systems that require motor speed control is indispensable and of crucial importance.

3.2.3 Soft-Starters

If one is not interested in speed variations, the motor start can be controlled using a soft-starter (see Figure 3.10), which prevents current peaks and saves energy in the starting process. The soft-starter allows a gradual, configurable rise in the motor input voltage amplitude, preventing the initial current peaks. It is also possible to configure a gradual voltage fall during motor stops, preventing sudden stops. The disadvantage is that, when using the soft-starter, the motor takes more time to start, depending on how much time the input voltage takes to achieve its full value.

Since VSDs also allow to mitigate starting current peaks, this technology is applicable when motor speed variations are not required during the motor operation, and when the motor starts and stops several times per day.

Figure 3.10: Soft-starter [4].

As stated along this section, electric motors are efficient equipments, as long as they are used arround their rated operating point. Otherwise, efficiency levels drop significantly. Generally, motors are oversized, because of the difficulty that one can have determining the actual load, and because it means a longer motor lifespan [23], but this, of course, leads to low efficiencies and increases the energy bill. Sometimes motors are overloaded, which can damage the motor in the long term, leading to overheat, and to inefficiency, and, of course, being also costly.

Therefore, in this thesis, the main focus is to determine the motors' operating point, and check if the motor is correctly sized and operating efficiently. If it is not, one has to validate the hypothesis of replacing the installed motor by a new motor, perhaps a high-efficient one, or to install power electronics technology to improve efficiency. "The efficiency data can be used in the identification of opportunities for improving energy efficiency by replacing inefficient motors with high-efficiency motors and improving the motor-driven processes" [24].

Chapter 4

Induction Motor Efficiency Assessment

Based on the theoretical foundations developed and presented until now, a methodology for assessing energy efficiency in induction motors is developed. This methodology is presented step by step, and is built focusing on four main factors: non-intrusiveness, simplicity, accuracy and cost.

The methodology can be applied by any professional, at any time, not requiring intrusive or difficult interventions. On the majority of the applications, the systems where motors are embedded can be operating while measurements are performed, without the need to stop the motors, or to detach them from their systems. This methodology also proves to be low-cost and accuracy is not neglected, making it reliable. All these characteristics make this a non-invasive, easy to apply, low-cost and reliable powerful methodology for induction motor efficiency estimation, allowing to overcome logistic or economic barriers that many times compromise efficiency assessment in general.

After the methodology for induction motor efficiency analysis is presented, a few considerations are taken regarding motor electric energy consumption and costs. Finally, the path that is proposed to be followed in case motor malfunctions or low efficiencies are verified is presented. This includes the investment payback analysis regarding the substitution of the operating motor by a high-efficient one, which takes an important role on the decision making process.

4.1 Induction Motor Analysis

In this section, the proceedings used in this thesis for induction motor analysis, in order to retrieve their loads and efficiencies, are presented.

4.1.1 Nameplate and Connection Type

A motor nameplate (see Figure 4.1) can provide several information. In this thesis, it is analysed to verify:

- Rated Input and Output Powers.
- Rated Voltage.
- Rated Current.
- Rated Power Factor.
- Rated Speed.
- Rated Efficiency.

Figure 4.1: Example of a three-phase induction motor nameplate - motor of a pump located on the rooftop of the IST Alameda Campus Mathematics Building.

When applying this part of the procedure, it is verified that not all motors maintain their nameplates on. There are also cases where some motors still have their nameplates on, but those are simply not readable (see Figure 4.2). This is a normal situation to occur on the field. However, without access to the rated values, the methodology described for motor analysis cannot be applied.

It is not easy to verify a motor operating point without having its nameplate information. A possible solution is to try to find that information on the Internet, or to contact the manufacturer, otherwise it is only possible to estimate these values if laboratory tests are performed. The motor can be tested applying the defined standard methods, and from those tests rated values can be retrieved. Of course, this is an invasive procedure, which involves stopping the motor, maybe even removing it form its place, which, in some cases, can prove to be costly or inappropriate.

All motors analysed in this thesis have their nameplates on and those are understandable.

Figure 4.2: Example of an induction motor unreadable nameplate - motor of a pump located on the Cold Central of the IST Alameda Campus North Tower.

The rated input power generally is not present on the nameplate. If that is the case, it can be determined applying Equation 4.1:

$$P_{in_r} = 3\,V_{star_r}\,I_{star_r}\,PF_r = 3\,V_{delta_r}\,I_{delta_r}\,PF_r \tag{4.1}$$

where P_{in_r} denotes the rated input active power, V_{star_r} and V_{delta_r} the rated input voltage, with star and delta connection, respectively, I_{star_r} and I_{delta_r} the rated input current, with star and delta connection, respectively, and PF_r the rated power factor.

Sometimes, the rated efficiency is not provided on the nameplate. When this happens, it has to be calculated applying Equation 4.2:

$$\eta_r = \frac{P_{mec_r}}{P_{in_r}} \tag{4.2}$$

where η_r is the motor rated efficiency and P_{mec_r} denotes the rated output power (mechanical) available on the nameplate.

The windings connection type has now to be obtained. Opening the motor junction box (see Figure 4.3), it is possible to check the connection type, and so determine which rated values (star or delta) to consider in the analyses. Information regarding how the star and delta connections are performed on the junction box can be present on the nameplate (see Figure 4.4). However, the way of connecting windings in star or delta depicted in Figure 4.4 is almost a standard, and, if it is not specified on the nameplate, it can be inferred that this way of connecting the terminals is the one that applies. Nevertheless, resistances between each terminal can be measured using a multimeter, and by doing this it is possible to know in which way the terminals must be connected in order to obtain a star or delta connection.

Figure 4.3: Example of an induction motor junction box showing a star windings connection - motor of the IST Energy Laboratory.

Figure 4.4: Example of a three-phase induction motor nameplate with star and delta connections information [electricneutron.com, 2017].

In the end of this proceeding, the applier shall have the following information:

- Rated Output Power - P_{mec_r} $[W]$.
- Rated Input Voltage - V_{in_r} $[V]$.
- Rated Input Current - I_{in_r} $[A]$.
- Rated Power Factor - PF_r.
- Rated Speed - N_r $[rpm]$.
- Rated Input Active Power - P_{in_r} $[W]$.
- Rated Efficiency - η_r $[\%]$.
- Connection Type - star or delta.

4.1.2 Measurements

Measurements are crucial for this study. To determine the motors' efficiencies, one needs to know on what conditions they are functioning (or malfunctioning), and compare those conditions with the rated operating points. Measurements are conducted bearing in mind the scope of this methodology, which, as stated before, is to provide the largest amount of information about the motors without interfering on their regular tasks.

Measurements performed in this work are introduced, along with the equipment used to perform them. Note that the equipment presented can be substituted by other types or brands of equipment, as long as they provide the required information and serve the same purpose. All measurements are conducted with equipment provided by the Energy Scientific Area of IST Electrical and Computer Engineering Department, and include two energy analysers, a tachometer and the Personal Protective Equipment (PPE).

PPE and Safety

Measurements are performed on the field. These measurements are conducted with the motors operating, and so a voltage is applied. Sometimes, depending on the conditions, the electric panel must be accessed in order to connect the energy analyser. On these conditions, on any technical area, the first step to take concerns safety.

In Portugal, where this study is conducted, there are Regulations, National and European, regarding safety when working with electricity. Theoretically, close to the electric panel, it must be visible on safety signals the required PPE to access it. Unfortunately, sometimes this information is not updated, or simply it is not present at all.

It is wise to be informed about safety procedures when performing measurements and accessing technical areas in general. The danger is not only present on the voltages applied, but is also present on the technical areas spaces themselves. It is normal to find pipes, or sharp corners, that can prove to be dangerous to the head or torso areas of the body. Sometimes, these pipes are located near the floor, making it easy for someone to fall, if not paying attention. Theoretically, these dangers need to be correctly marked, but on the field that is not always verified. A protective helmet is, on some cases, a good solution to avoid accidents.

It is important not to forget, safety always comes on first place. If at some point of the application of this methodology safety has to be discarded, it must not be applied. Note that this methodology is developed for easily accessible areas and motors.

All measurements in this thesis are performed in low-voltage. The visits to the technical facilities and the measurements are supervised by trained personnel, provided by the IST Maintenance Staff.

When arriving to a technical area, the first step is to look around and find the safety signals. The safety signals found on both areas visited are represented in Figure 4.5. The safety requirements demand the use of protective gloves, goggles and noise-cancelling headphones for prolonged noise exposure. Although not present on the signals, wearing a protective helmet is always a safe choice. The gloves used in this work can be seen on Figure 4.6. It is very important to use gloves, as they are crucial for our safety while performing measurements on the electric panel.

Figure 4.5: Safety signals - Cold Central of the IST Alameda Campus North Tower.

Figure 4.6: Regeltex Class 0 insulating gloves.

Energy Analysers

Two energy analysers are used in this work. The reason for using two different analysers is merely for the sake of proving that this method can be applied using a different set of equipment. The first energy analyser presented is the Fluke Power Logger 1735, represented in Figure 4.7. The other energy analyser used is the Chauvin Arnoux C.A 8332B, represented in Figure 4.8.

Figure 4.7: Fluke Power Logger 1735 [myflukestore.com, 2016].

Figure 4.8: Chauvin Arnoux C.A 8332B.

These equipments are directly connected to the electric panel. Those connections are illustrated in Figures 4.9 to 4.12. Some motors are tested with Fluke, and others are tested with Chauvin. Since both provide the same kind of data, it is not important to differentiate the results, or to state which motor was tested with each one of them.

Figure 4.9: Two Flukes retrieving data over time - Cold Central of the IST Alameda Campus North Tower.

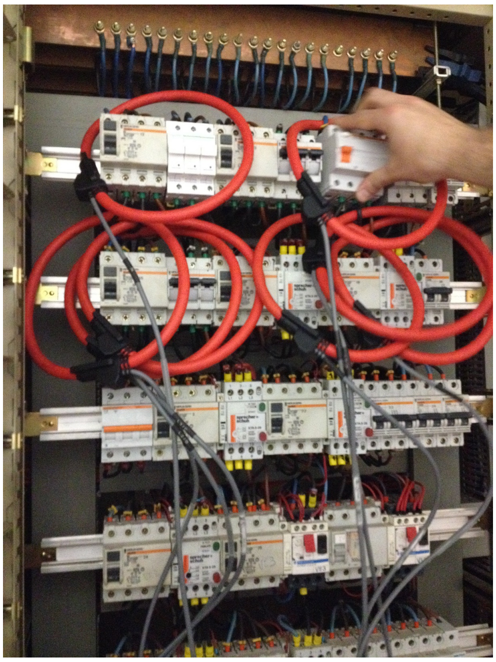


Figure 4.10: Fluke connected to the electric panel - electric panel of the Cold Central of the IST Alameda Campus North Tower.

Figure 4.11: Chauvin retrieving data over time - Garage Technical Area of the IST Alameda Campus Civil Engineering Building.

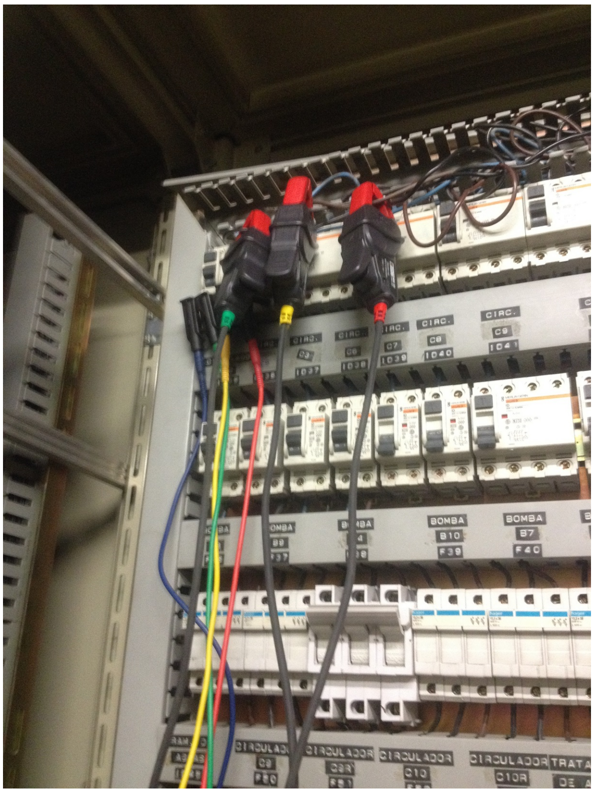


Figure 4.12: Chauvin connected to the electric panel - electric panel of the Garage Technical Area of the IST Alameda Campus Civil Engineering Building.

After being connected, all energy analysers shall gather data regarding the steady-state of each motor. The objective is to measure voltage per-phase, current per-phase, power factor per-phase, and, consequently, the three per-phase electrical powers (active (P), reactive(Q), apparent (S)).

The first step to take is to analyse the values obtained to check if the motor has any kind of phase imbalance. This can be achieved comparing the currents and the power factors in each phase, or even the powers. Note that there is always an imbalance between the phases, but, in some cases, the disparity of values is very large. If this happens, the motor should be analysed to check what is causing this imbalance. There are several ways of diagnosing malfunctions on induction motors. In sectors where electrical machines play an important role, ”there is a great interest in detection methodologies and diagnosis processes relative to the premature appearance of faulty operating conditions in electrical machines”, mainly in induction motors [25]. That analysis is out of the scope of this thesis. If an imbalance is not verified, then the work can proceed, otherwise the motor should be evaluated following induction motors malfunction detection processes [25].

The data retrieved is then analysed in order to verify if the values obtained are solid and consistent with an efficient motor operation. This initial qualitative analysis requires performing comparisons between measured values and rated values. By looking at these comparisons, some inquisitions can be performed if the applier has experience and knowledge in electric machinery. Nevertheless, a quantitative analysis is presented in a further section, in order to explain in detail how to analyse the motor data retrieved.

The energy analysers are also used to obtain a motor load profile. That is possible if the consumed power is measured over a determined period of time. That said, the applier shall leave the equipment measuring and recording the obtained values over a period of time, with the objective of retrieving information about the motor operating pattern, which is indispensable for further economical analysis. This will be further developed in Section 4.2.

After measurements using these equipments, the applier shall have the following information:

- Steady-state Input Voltage per phase - $V_{in}\,[V]$.
- Steady-state Input Current per phase - $I_{in}\,[A]$.
- Steady-state Power Factor per phase - PF.
- Steady-state Input Active Power per phase - $P_{in}\,[W]$.
- Steady-state Input Reactive Power per phase - $Q_{in}\,[VAr]$.
- Input Active Power evolution over time - $p_{in}(t)\,[W]$.

Tachometer

A digital photo/contact tachometer RS 163-5348 (see Figure 4.13) is used to determine the steady-state rotating speed of the motors' shafts. Another brand of tachometer can, of course, be used.

This tachometer allows direct contact and optical measurements. In this study, this measurement is performed using the direct contact, by removing the motor cooling fan protection (Figure 4.14).

Figure 4.13: Tachometer RS 163-5348.

Figure 4.14: Motor speed measurement by direct contact using the tachometer - motor of a pump of the Garage Technical Area of the Alameda Campus Civil Engineering Building.

This proceeding requires a special attention concerning safety. By removing the protection, the cooling fan is exposed. When the motor is running, it can achieve a very high speed, and cause injury if it gets in contact with someone's hands. The best practice for this proceeding is to follow these steps:

1. If possible, stop the motor.

2. Remove the cooling fan protection carefully, as it is possibly dusty.

3. Clean a bit of the dust present on the fan, so when the motor starts running, it does not get

scattered around the room, and so avoid breathing it.

4. Place the point of the tachometer on the center of the cooling fan, which has a small hole in the majority of cases. This is the measurement by direct contact. If the tachometer offers the possibility of performing optical measurement, then a reflecting band must be placed in the fan, and the tachometer must be pointed to the fan, in order to measure the speed.

5. Start the motor. Make sure nobody, except the person with the tachometer, gets near the motor.

6. Wait until the motor reaches its steady-state, then remove the tachometer from the fan (in case the measurement is performed by direct contact). Register the value obtained.

7. Stop the motor. If the optical measurement is performed, remove the reflecting band from the fan.

8. Place again the protection on the cooling fan.

Note that it is not imperative to follow the steps above. Motor speed can be measured with the motor running, but it has to be performed extra carefully, to avoid any kind of accident. If there is the possibility to freely stop and start the motor, the proceeding presented should be applied. In case the measurement is made with the optical part, the motor must be stopped in order to allow the placement of the reflecting band on the fan.

Speed is a very important resource that later is applied in order to determine the motors' operating points.

In the end of this proceeding, the applier shall have:

- Steady-state Speed - $N\,[rpm]$.

4.1.3 Operating Point and Efficiency

With all the information gathered, it is now possible to determine the motors' operating points.

To get more precise results with this method, some conditions must be followed [17]:

- Input voltage must not vary more than 5% of the rated value.
- The motor should not have been rewounded.
- The motor should be operating at steady-state.

If these conditions are matched, motor load can be determined applying Equation 4.3 [17]:

$$Load\,[\%] = \frac{N_{synch} - N}{N_{synch} - N_r} \cdot 100\% \tag{4.3}$$

where N_{synch} denotes the motor synchronous or no load speed.

The motor actual output power can be estimated applying Equation 4.4:

$$P_{mec} = Load \cdot P_{mec_r} \tag{4.4}$$

After this, one can apply the efficiency formula, denoted in Equation 4.5:

$$\eta = \frac{P_{mec}}{P_{in}} \tag{4.5}$$

If the motor has ever been rewounded, one can apply this method, but take into account that the rewounding process, if not performed by qualified professionals and using the best tools and equipment, can lower motor efficiency [3]. If, for example, the stator core is not filled accordingly, motor efficiency can be reduced by 5 to 7.6% [3]. It is wise to consider this while applying the method described to rewounded motors and reduce the calculated efficiency in order to take this factor into account.

4.2 Electric Energy Consumption and Costs

A motor load profile can be easily obtained with an energy analyser by connecting it to the motor terminals, or to the electric panel, and leaving it measuring the input active power over a determined period of time. This profile corresponds, basically, to a graph that depicts a motor requested electrical power over time. An example of this diagram is represented in Figure 4.15. The vertical axis corresponds to the consumed power (input), and the horizontal axis corresponds to the hour of measurement. By integrating this curve over time, the total energy consumed by the motor on that period of time can be obtained.

Acknowledging the energy tariff, one can easily determine the cost that a motor represents over a determined period of time applying Equation 4.6:

$$Cost\,[€] = Energy\,[kWh] \cdot Price\,[€/kWh] \tag{4.6}$$

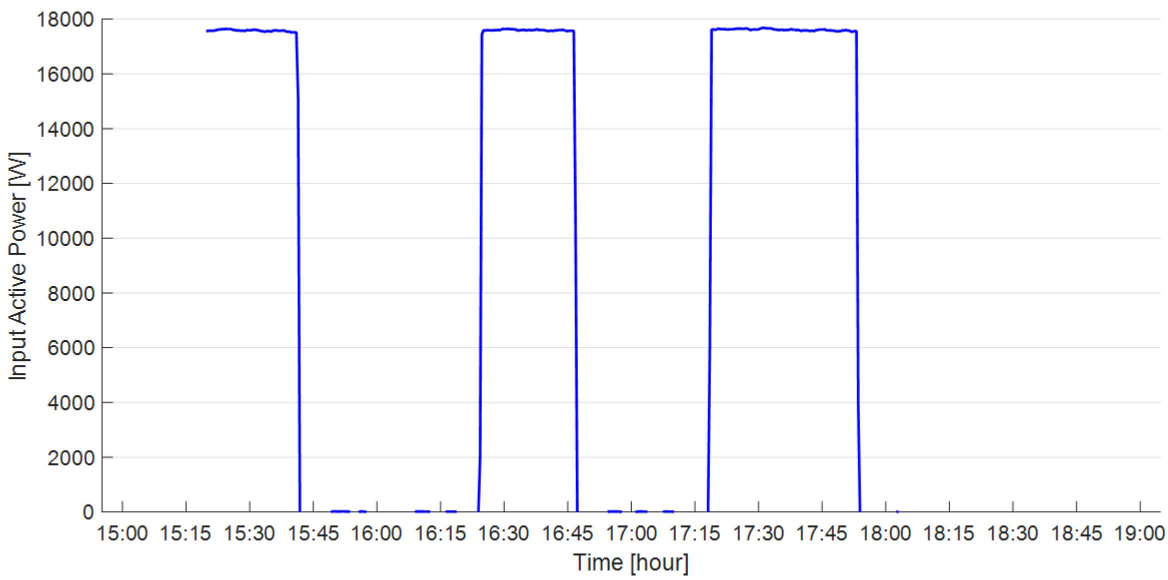


Figure 4.15: Example of an induction motor load profile, obtained from one of the motors analysed in this thesis (BPC1), located on the Cold Central of the IST Alameda Campus North Tower.

The situation now is that on the field, motors generally do not have a continuous, or known, or predictable operating time. They can, for example, operate during the week, and on weekends be stopped. Sometimes, depending on the application, motors can support different loads during the day, and consequently request different input power. In some cases, the motor operating profile is known, but on other cases that is not completely known with absolute certainty.

When calculating costs, it is useful that the cost is computed for a year period. Of course, unless one can do that, and has the time to perform measurements during an entire year, that situation is simply not practicable. Therefore, what is important is to have an approximate, or estimated, operating profile, that can give an idea of the cost that a motor represents over an entire year. How this profile is obtained is completely up to the applier, depending on the situation, on the known facts about the motors, and on the time available to perform measurements. As long as the approximation is not rude to the point of providing wrong and biased values, the applier is free to take decisions regarding this matter.

In this thesis, the first step for determining the operating profile of a motor is to obtain, from people that know and are responsible for the technical installations, information about the operating pattern of each motor. The second step is to retrieve, using, as stated before, an energy analyser, the load profile over a defined period of time. Having that, the data obtained can be extrapolated to an entire year, according to the information provided.

4.3 Efficiency Assessment and Solutions

After all data acquisition and calculations, motors' efficiencies and operating points are estimated, as well as their energy costs. If motors are operating at low efficiencies, measures should be taken; if they also present a high energy consumption, then it is even more important to do so. Note that low or high efficiency, or low or high energy consumption, are qualitative terms. The limit efficiency (or consumption) below (above) which a motor is considered to be inefficient is defined by the person that applies the method, based on the results expected, as well as on the budget available, since the measures taken to improve efficiency, sometimes, can prove to be expensive.

Sometimes, the budget available may not be sufficient to cover the expenses associated with all situations that require investment. In these cases, consumption takes an important role on the evaluation of which motors require attention more urgently. For example, imagining two fictitious similar motors that have a rated efficiency of 85%. Motor A is operating at 60% efficiency, and motor B is operating at 70% efficiency. Motor A only operates on weekends, and represents a cost of €90/month, and motor B operates everyday, and represents a cost of €400/month. Of course, the most urgent investment is in motor B, even being motor A the most inefficient. Basically, motor efficiency is important to flag the motors that can be improved. On the other hand, motor energy consumption is important to define the most urgent and main cases that need to be monitored.

In practical cases, sometimes, the Return on Investment (ROI) is not small enough to make the investment happen, or the company/institution cannot spare the money that is needed in the exact moment. When this happens, choices must be made.

In this thesis, when motors prove to be inefficient, three solutions are studied: the substitution of the motor by a high-efficiency motor, and the introduction of a variable speed drive or of a soft-starter.

The substitution of the existing motor by a high-efficiency motor is the main solution considered in this study. The advantages of the usage of these motors were presented before, but for motors that are operating and do not present any damage, it is important to calculate and consider the payback time of the investment, in order to verify the viability of the solution, as well as to justify it to the management. Payback calculation for this solution is introduced in the next subsection.

Although the main objective of this thesis is to verify the technical and economical viability of motor substitution, the installation of power electronics technology is also considered. Despite this, payback analysis is not presented for any of these solutions. A VSD is a complex equipment, and the selection of the right VSD to install, as well as the harmonic and filtering study, have to be performed, and that is out of the scope of this thesis. On the other hand, soft-starters are relatively cheap equipments, being easily acquired on the market from €100, and their benefits fully justify the investment. Note that a payback analysis for this kind of equipment would require start and stop energy monitoring, using an oscilloscope or other similar equipment, which is out of the scope of this first study on the IST. Additionally, soft-starters also prevent current peaks on motor starts, and protect the motor against sudden stops, and those advantages are difficult to quantify and turn into numbers.

4.3.1 High-Efficiency Motors - Investment Payback Analysis

When a new motor is required for a determined task, or when an operating motor is damaged and needs to be substituted by a new one, the acquisition of a high-efficiency motor is recommended [23], especially if it will be operating during many hours per day.

The substitution of a motor that is not damaged, but presents a low efficiency, caused by being over-dimensioned or overloaded, by a high-efficiency motor is also to be considered. ”Because a motor consumes energy worth 4 to 10 times its own cost each year, energy-efficient motors often make economic sense in a wide variety of applications” [21]. The payback is always guaranteed, and the payback time is small for motors that are big consumers on the analysed systems.

To consider the installation of a high-efficiency motor, Equations 4.7 and 4.8 are applied [23]:

$$Savings_{annual}\,[€] = \left(\frac{1}{\eta_{currentmotor}} - \frac{1}{\eta_{newmotor}}\right) \cdot P_{mec}\,[kW] \cdot WorkHours\,[h] \cdot Price\,[€/kWh] \quad (4.7)$$

$$Payback\,[years] = \frac{Cost_{newmotor}}{Savings_{annual}} \quad (4.8)$$

where $Savings_{annual}$ are the annual savings obtained when a high-efficiency motor is operating instead of the existing motor, $\eta_{currentmotor}$ denotes the currently installed motor measured efficiency, $\eta_{newmotor}$ is the high-efficiency motor efficiency, P_{mec} is the delivered mechanical power, $WorkHours$ are the number of hours per year in which the motor is operating and $Price$ is the energy tariff. For payback, $Cost_{newmotor}$ represents the full cost of the new motor, including the cost of the motor itself, as well as the installation cost.

The installation cost is, of course, a variable cost that depends on the company responsible for motor installation. In the case of this study, this cost is not considered, since IST has technical personnel capable of providing this kind of work. If on other applications that is not the case, then this cost must be considered, even if it is estimated.

After the calculation of these values, it is possible to take decisions about the acquisition of high-efficiency motors, in order to substitute other motors.

Chapter 5

IST Alameda Campus Induction Motors Analysis

In this chapter, the methodology defined in Chapter 4 is applied to the case study at IST Alameda Campus. All steps are applied gradually and explained.

5.1 Case Study

This section is dedicated to present and discuss the induction motors that are selected to be analysed in this thesis.

Bearing in mind that the main objective of this thesis is to improve energy efficiency at the IST Alameda university campus, it is a must that the analyses has a main focus on high power induction motors, since they represent the big electric energy consumers. The limit rated output power above which a motor is considered to be a high power motor is defined as being $P = 7.5\,kW$. That said, the motors are selected from a list provided in the beginning of the development of this thesis by the IST Sustainable Campus, containing all motors that are operating on IST facilities and their respective rated output powers.

5.1.1 Pumps

Pumps are chosen as the focus of this work. All pumps analysed are part of the IST Alameda Campus HVAC systems. As already stated, HVAC systems are considered the main electric energy consumers in buildings in the EU, and so this is the main reason for this choice. This choice is also related with the simplicity and autonomy of pumps, where motors can be easily accessed, and the methodology defined can be easily applied.

When working on the field, one can verify that not all motors have easy access, and that sometimes it is even impossible to access the nameplate, or to measure the motor speed. The objective of this thesis is not to analyse those extreme cases, but to show that in regular cases, with a low budget and in a very simple way of procedure, induction motor efficiency can be determined, and measures can be taken to improve buildings' energy efficiency.

Pumps composed by motors with rated output power $P \geq 7.5\,kW$ are considered, and two different buildings of IST Alameda Campus are taken into account for this study: the North Tower and the Civil Engineering Building.

North Tower

The North Tower (see Figure 5.1) is part of the IST Alameda Campus since 1994 [12]. It is home of the Electrical and Computer Engineering Department, and is one of the two twin towers that are part of this campus.

Figure 5.1: IST - North Tower [12].

In this building, five HVAC pumps are studied (see Figure 5.2). These pumps belong to two HVAC sub-systems: four - BPC1, BPC2, BPF1, BF1 - are part of the Cold Central, located in the basement (floor -1), and one - BQ1 - is part of the Heat Central, located in the 3rd floor. It is estimated that these pumps are on this building, and operating, since it was inaugurated in 1994.

This HVAC cooling system is composed by two chillers, one larger than the other. The larger chiller, that is referred as Big Chiller, is the main unit, and the smaller chiller, that is referred as Small Chiller, is a backup unit, operating when the Big Chiller is not capable of dealing with the needs. BPC1 is responsible for pumping water into the Big Chiller, and BPC2 is responsible for pumping water into the Small Chiller. BPF1 and BF1 are responsible for pumping water into the cold water circulation system.

The HVAC heating system is composed by two boilers. BQ1 is responsible for pumping water into the hot water circulation system.

As can be noted in Figure 5.2, all pumps in this building are composed by two motors: one main motor and one backup motor. The main motor is referred to with the pump ID name, and the backup motor is referred to with the pump ID name, followed by "(R)" (from Portuguese *Reserva*).

(a) BPC1 - pumps water into the Big Chiller.

(b) BF1 - pumps water into the cold water circulation system.

(c) BPC2 - pumps water into the Small Chiller.

(d) BPF1 - pumps water into the cold water circulation system.

(e) BQ1 - pumps water into the hot water circulation system (cooling fan protections are off the motors in order to allow direct contact speed measurement using the tachometer).

Figure 5.2: North Tower HVAC pumps.

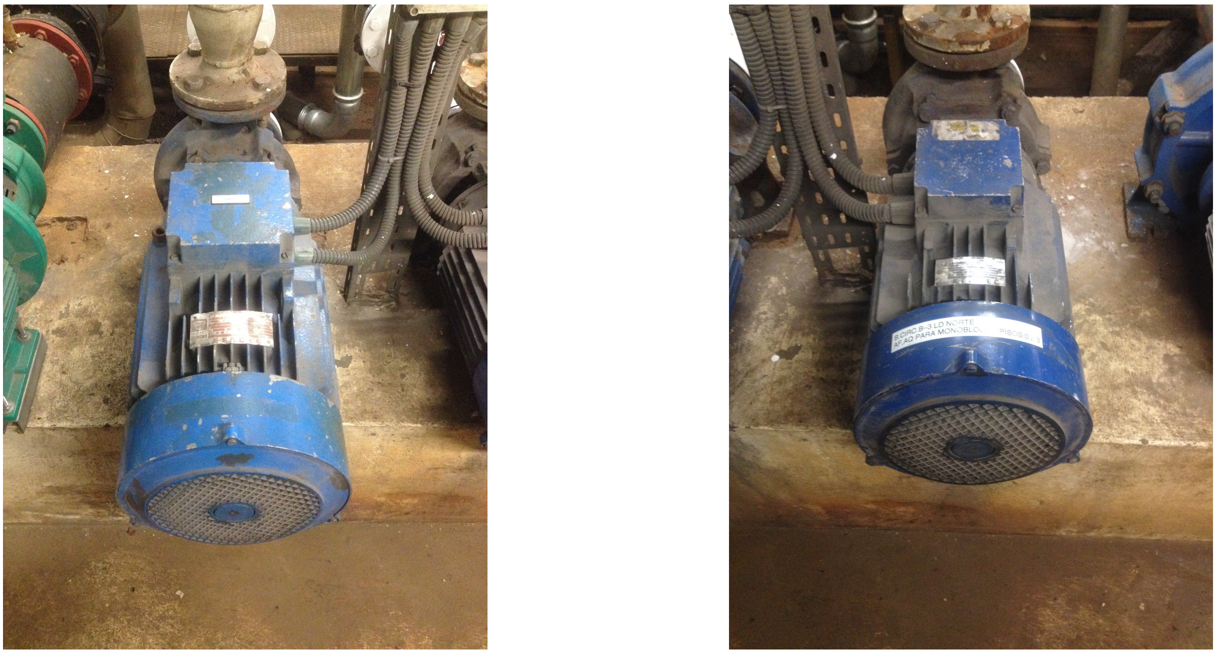
Civil Engineering Building

The Civil Engineering Building (see Figure 5.3) is part of the Alameda Campus since 1993 [12]. It is home of the Civil Engineering Department.

Figure 5.3: IST - Civil Engineering Building [docs.sinfo.org, 2016].

In this building, two HVAC pumps are studied (see Figure 5.4). These pumps - B3, B4 - are part of the air conditioning water circulation system, and are located in the garage technical area (floor -3).

As can be noted in Figure 5.4, these pumps are only composed by one motor. Each motor is referred to with the pump ID name.



(a) B4.

(b) B3.

Figure 5.4: Civil Engineering Building HVAC pumps - pump water into the air conditioning water circulation system.

5.2 Nameplate and Connection Type

The induction motors' nameplates are checked and their junction boxes are opened, in order to check the connection types.

North Tower Pumps Motors

The list of all North Tower motors is represented in Table 5.1, where all rated values, along with the connection types, are presented.

Table 5.1: North Tower - motors identifications, connection types and rated values.

Motor ID	Connection	$P_{mec_r}[kW]$	$V_{in_r}[V]$	$I_{in_r}[A]$	PF_r	$N_r[rpm]$	$P_{in_r}[kW]$	$\eta_r[\%]$
BPC1	Delta	18.5	380	34.5	0.9	1470	20.4	90.5
BPC1(R)	Delta	18.5	380	34.5	0.9	1470	20.4	90.5
BF1	Delta	15	380	31	0.84	1452	17.1	87.5
BF1(R)	Delta	15	380	31	0.84	1452	17.1	87.5
BPC2	Delta	7.5	380	15.7	0.85	1464	8.8	85.4
BPC2(R)	Delta	7.5	380	15.7	0.85	1464	8.8	85.4
BPF1	Delta	7.5	380	15.7	0.85	1464	8.8	85.4
BPF1(R)	Delta	7.5	380	15.7	0.85	1464	8.8	85.4
BQ1	Delta	7.5	380	15.7	0.85	1464	8.8	85.4
BQ1(R)	Delta	7.5	380	15.7	0.85	1464	8.8	85.4

All motors presented are produced by the same manufacturer - ITUR -, and backup motors are equal to the main motors, so, analysing Table 5.1, it is easy to perceive that there are essentially three different types of motors to analyse, regarding the rated values: motors $P = 18.5\,kW$, $P = 15\,kW$ and $P = 7.5\,kW$.

The rated input active power is calculated for each motor using Equation 4.1:

- $P = 18.5\,kW$:

$$P_{in_r} = 3 \cdot 380 \cdot \frac{34.5}{\sqrt{3}} \cdot 0.9 = 20.4\,kW \tag{5.1}$$

- $P = 15\,kW$:

$$P_{in_r} = 3 \cdot 380 \cdot \frac{31}{\sqrt{3}} \cdot 0.84 = 17.1\,kW \tag{5.2}$$

- $P = 7.5\,kW$:

$$P_{in_r} = 3 \cdot 380 \cdot \frac{15.7}{\sqrt{3}} \cdot 0.85 = 8.8\,kW \tag{5.3}$$

Note that the rated currents in all motors are divided by $\sqrt{3}$. This happens because, on these nameplates, the current depicted for the delta connection is the line current. One must be careful when analysing a nameplate, as the values presented by each manufacturer can differ. It is important to make sure that all data makes sense before proceeding to the next steps. Of course, nameplates tend to have similar templates and information, but, aside from the information that is demanded by Regulations, there are no defined rules.

The rated efficiency is not available on any nameplate, and so it has to be calculated using Equation 4.2:

- $P = 18.5\,kW$:
$$\eta_r = \frac{18.5}{20.4} \cdot 100\% = 90.5\% \tag{5.4}$$

- $P = 15\,kW$:
$$\eta_r = \frac{15}{17.1} \cdot 100\% = 87.5\% \tag{5.5}$$

- $P = 7.5\,kW$:
$$\eta_r = \frac{7.5}{8.8} \cdot 100\% = 85.4\% \tag{5.6}$$

From the rated speeds, it can be checked that all these motors have two pairs of poles.

Civil Engineering Building Pumps Motors

The list of all Civil Engineering Building motors is represented in Table 5.2, where all rated values, along with the connection types, are presented.

Table 5.2: Civil Engineering Building - motors identifications, connection types and rated values.

Motor ID	Connection	$P_{mec_r}[kW]$	$V_{in_r}[V]$	$I_{in_r}[A]$	PF_r	$N_r[rpm]$	$P_{in_r}[kW]$	$\eta_r[\%]$
B4	Delta	11	380	21.5	0.86	2915	12.2	90.4
B3	Delta	7.5	380	14.6	0.9	2890	8.7	86.7

B4 and B3 were both built by EFACEC.

The rated input active power is calculated for each motor using Equation 4.1:

- B4:
$$P_{in_r} = 3 \cdot 380 \cdot \frac{21.5}{\sqrt{3}} \cdot 0.86 = 12.2\,kW \tag{5.7}$$

- B3:
$$P_{in_r} = 3 \cdot 380 \cdot \frac{14.6}{\sqrt{3}} \cdot 0.9 = 8.7\,kW \tag{5.8}$$

Note that the motors' rated currents are divided by $\sqrt{3}$, like happened with the motors present on the North Tower (and for the same reasons).

The rated efficiency is not available on any nameplate, and so it has to be calculated using Equation 4.2:

- B4:
$$\eta_r = \frac{11}{12.2} \cdot 100\% = 90.4\% \tag{5.9}$$

- B3:
$$\eta_r = \frac{7.5}{8.7} \cdot 100\% = 86.7\% \tag{5.10}$$

From the rated speeds, it can be checked that the analysed motors have one pair of poles.

Using the Regulation No 640/2009 annex I.1, and analysing the rated efficiency of each motor, it can be concluded that the only high-efficient motor is the B4 motor. The limit values that define each efficiency level, for the motors analysed, are presented in Table 5.3.

Table 5.3: Limit values for efficiency levels definition [1].

Motor $P_{mec_r}[kW]$	Motor Poles	IE2 $\eta_r[\%]$	IE3 $\eta_r[\%]$
18.5	4	91.2	92.6
15	4	90.6	92.1
7.5	4	88.7	90.4
11	2	89.4	91.2
7.5	2	88.1	90.1

5.3 Measurements

The steady-state measurements performed with the energy analysers and with the tachometer are presented for each induction motor analysed. An initial qualitative analysis of the obtained data is also made.

North Tower Pumps Motors

The results of the steady-state analysis for the North Tower motors are presented in Tables 5.4 to 5.14.

Table 5.4: North Tower - BPC1 motor steady-state measurements.

Line	$V_{in}[V]$	$I_{in}[A]$	PF	$P_{in}[kW]$	$Q_{in}[kVAr]$
L1	230.9	28	0.85	5.6	3.3
L2	231.1	30	0.85	6.0	3.6
L3	230.6	30	0.84	5.8	3.7
Total	-	-	-	17.4	10.6

Table 5.5: North Tower - BPC1(R) motor steady-state measurements.

Line	$V_{in}[V]$	$I_{in}[A]$	PF	$P_{in}[kW]$	$Q_{in}[kVAr]$
L1	231.6	30	0.87	6.0	3.6
L2	232.0	32	0.87	6.3	3.7
L3	231.5	31	0.85	6.1	3.8
Total	-	-	-	18.4	11.1

Table 5.6: North Tower - BF1 motor steady-state measurements.

Line	$V_{in}[V]$	$I_{in}[A]$	PF	$P_{in}[kW]$	$Q_{in}[kVAr]$
L1	231.8	28	0.81	5.1	4.0
L2	232.1	29	0.80	5.1	3.9
L3	231.2	29	0.80	5.1	3.9
Total	-	-	-	15.3	11.8

Table 5.7: North Tower - BF1(R) motor steady-state measurements.

Line	$V_{in}[V]$	$I_{in}[A]$	PF	$P_{in}[kW]$	$Q_{in}[kVAr]$
L1	230.5	26	0.74	4.5	3.9
L2	230.9	25	0.77	4.0	3.2
L3	230.3	25	0.73	4.0	3.3
Total	-	-	-	12.5	10.4

Table 5.8: North Tower - BPC2 motor steady-state measurements.

Line	$V_{in}[V]$	$I_{in}[A]$	PF	$P_{in}[kW]$	$Q_{in}[kVAr]$
L1	231.5	10	0.65	1.5	1.9
L2	232.0	11	0.64	1.7	2.0
L3	231.5	11	0.64	1.7	1.8
Total	-	-	-	4.9	5.7

Table 5.9: North Tower - BPC2(R) motor steady-state measurements.

Line	$V_{in}[V]$	$I_{in}[A]$	PF	$P_{in}[kW]$	$Q_{in}[kVAr]$
L1	230.3	10	0.57	1.3	2.0
L2	230.5	11	0.60	1.5	2.0
L3	230.0	11	0.55	1.3	2.1
Total	-	-	-	4.1	6.1

Table 5.10: North Tower - BPF1 motor steady-state measurements.

Line	$V_{in}[V]$	$I_{in}[A]$	PF	$P_{in}[kW]$	$Q_{in}[kVAr]$
L1	230.7	15	0.81	2.6	2.0
L2	230.8	15	0.78	2.7	2.2
L3	230.3	15	0.79	2.5	2.3
Total	-	-	-	7.8	6.5

Table 5.11: North Tower - BPF1(R) motor steady-state measurements.

Line	$V_{in}[V]$	$I_{in}[A]$	PF	$P_{in}[kW]$	$Q_{in}[kVAr]$
L1	231.9	15	0.78	2.8	2.3
L2	232.2	15	0.81	2.9	2.1
L3	231.7	15	0.78	2.8	2.1
Total	-	-	-	8.5	6.5

Table 5.12: North Tower - BQ1 motor steady-state measurements.

Line	$V_{in}[V]$	$I_{in}[A]$	PF	$P_{in}[kW]$	$Q_{in}[kVAr]$
L1	228.5	12	0.75	1.9	1.9
L2	229.2	13	0.77	2.0	2.0
L3	228.5	12	0.73	1.9	2.1
Total	-	-	-	5.8	6.0

Table 5.13: North Tower - BQ1(R) motor steady-state measurements.

Line	$V_{in}[V]$	$I_{in}[A]$	PF	$P_{in}[kW]$	$Q_{in}[kVAr]$
L1	228.5	12	0.75	2.0	1.8
L2	228.9	12	0.76	2.0	2.0
L3	228.5	12	0.76	2.0	2.0
Total	-	-	-	6.0	5.8

Table 5.14: North Tower - motors steady-state speed values measured and comparison with the rated speeds.

Motor ID	$N[rpm]$	$N_r[rpm]$	$\Delta N[\%]$
BPC1	1474	1470	0.27
BPC1(R)	1474	1470	0.27
BF1	1475	1452	1.58
BF1(R)	1479	1452	1.86
BPC2	1490	1464	1.78
BPC2(R)	1490	1464	1.78
BPF1	1478	1464	0.96
BPF1(R)	1482	1464	1.23
BQ1	1486	1464	1.50
BQ1(R)	1485	1464	1.43

From all the data collected, it can be verified that no motor presents a strong imbalance between the phases, and so the study can proceed for all motors.

A data analysis can be conducted comparing the measured speed value with the rated speed value, using Equation 5.11 to quantify that difference:

$$\Delta N[\%] = \frac{N - N_r}{N_r} \cdot 100\% \tag{5.11}$$

This is a common and simple analysis that allows to investigate if the motor is operating more or less near the rated point. Table 5.14 allows the comparison. All measured speeds are above the rated speed, and it can be inferred that all motors are operating with less load than the rated one. The only motors where this is irrelevant are BPC1 and BPC1(R).

It can be verified that the motors BPC2 and BPC2(R) present power factors below 0.65 on all phases, and an input reactive power value above the input active power. This means that these motors are oversized, and that is contributing to an increase in the reactive power consumed. BQ1 and BQ1(R) present the same pattern, with values of input active and reactive powers very close to each other.

Civil Engineering Building Pumps Motors

The results of the steady-state analysis for the Civil Engineering Building motors are presented in Tables 5.15 to 5.17.

Table 5.15: Civil Engineering Building - B4 motor steady-state measurements.

Line	$V_{in}[V]$	$I_{in}[A]$	PF	$P_{in}[kW]$	$Q_{in}[kVAr]$
L1	234.1	12	0.79	2.3	1.8
L2	235.6	14	0.71	2.4	2.3
L3	234.8	15	0.75	2.6	2.3
Total	-	-	-	7.3	6.4

Table 5.16: Civil Engineering Building - B3 motor steady-state measurements.

Line	$V_{in}[V]$	$I_{in}[A]$	PF	$P_{in}[kW]$	$Q_{in}[kVAr]$
L1	235.5	7	0.74	1.3	1.1
L2	232.5	7	0.76	1.3	1.1
L3	234.6	8	0.77	1.5	1.2
Total	-	-	-	4.1	3.4

Table 5.17: Civil Engineering Building - motors steady-state speed values measured and comparison with the rated speeds.

Motor ID	$N[rpm]$	$N_r[rpm]$	$\Delta N[\%]$
B4	2960	2915	1.54
B3	2959	2890	2.39

From all the data collected, it can be verified that no motor presents a strong imbalance between the phases, and so the study can proceed for all motors.

A data analysis can be conducted comparing the measured speed value with the rated speed value, using Equation 5.11 to quantify that difference, like happened in the North Tower motors' analysis conducted before. Table 5.17 allows the comparison. All measured speeds are above the rated speed, and it can be inferred that all motors are operating with less load than the rated one.

B3 motor presents a low power factor when compared with the rated value. The maximum power factor measured has the value of 0.77, which can be compared with the 0.9 rated power factor value. This means that this motor is oversized, and that is contributing to an increase in the reactive power consumed.

5.4 Operating Point and Efficiency

In this section, the induction motors are analysed one by one, in order to obtain the operating point and efficiency of each one of them.

None of the analysed motors has ever been rewounded. The load is considered constant, meaning that the water flow variation through the pumps is considered small and is not taken into account.

5.4.1 North Tower Pumps Motors

The results of the operating point and efficiency analysis for the North Tower motors are presented in Table 5.18. Each induction motor actual load, relative to the rated load, actual output power, measured total input active power and actual efficiency are presented.

Table 5.18: North Tower - motors operating points and efficiencies.

Motor ID	$Load[\%]$	$P_{mec}[kW]$	$P_{in}[kW]$	$\eta[\%]$
BPC1	86.7	16.0	17.4	91.6
BPC1(R)	86.7	16.0	18.4	87.0
BF1	52.1	7.8	15.3	51.0
BF1(R)	43.8	6.6	12.5	52.8
BPC2	27.8	2.1	4.9	42.9
BPC2(R)	27.8	2.1	4.1	51.2
BPF1	61.1	4.6	7.8	59.0
BPF1(R)	50.0	3.8	8.5	44.7
BQ1	38.9	2.9	5.8	50.0
BQ1(R)	41.7	3.1	6.0	51.7

The values presented on Table 5.18 are obtained using Equations 4.3, 4.4 and 4.5 defined on the methodology presented in Chapter 4. As an example, calculations are performed for motor BPC1: the total input power measured for this motor is $P_{in} = 17.4\,kW$. Operating point and efficiency are now estimated according to the methodology defined. Calculations are presented in Equations 5.12, 5.13 and 5.14:

$$Load = \frac{N_{synch} - N}{N_{synch} - N_r} \cdot 100\% = \frac{1500 - 1474}{1500 - 1470} \cdot 100\% = 86.7\% \tag{5.12}$$

$$P_{mec} = Load \cdot P_{mec_r} = 0.867 \cdot 18.5 = 16\,kW \tag{5.13}$$

$$\eta = \frac{P_{mec}}{P_{in}} \cdot 100\% = \frac{16}{17.4} \cdot 100\% = 91.6\% \tag{5.14}$$

Analysing the results, it can be concluded that from all the induction motors monitored in the North Tower, only BPC1 and BPC1(R) present a good efficiency value, around 90%. The third more efficient motor - BPF1 - presents a 59% efficiency, which is low, and half of the motors analysed present even lower efficiencies, around 50%. The worst cases are BPC2 and BPF1(R), which present efficiency values below 50%.

The obtained results for all motors are consistent with the speed analysis performed in the measurements section, summarized in Table 5.14. All motors, except for BPC1 and BPC1(R), are oversized, and that is influencing efficiency and is promoting reactive power consumption. Only BPC1 and BPC1(R) are operating at a load between 75 and 100% of the rated load, which was presented in Chapter 3 as the more efficient load interval for induction motors. The worst cases of oversize are BPC2 and BPC2(R), which are operating at 27.8% of the rated load.

All North Tower motors, except BPC1 and BPC1(R), are thus flagged for intervention.

5.4.2 Civil Engineering Building Pumps Motors

The results of the operating point and efficiency analysis for the Civil Engineering Building motors are presented in Table 5.19. Each induction motor actual load, relative to the rated load, actual output power, measured total input active power and actual efficiency are presented.

Table 5.19: Civil Engineering Building - motors operating points and efficiencies.

Motor ID	$Load[\%]$	$P_{mec}[kW]$	$P_{in}[kW]$	$\eta[\%]$
B4	47.1	5.2	7.3	71.2
B3	37.3	2.8	4.1	68.3

The values presented on Table 5.19 are obtained using Equations 4.3, 4.4 and 4.5 defined on the methodology presented in Chapter 4. As an example, calculations are performed for motor B4: the total input power measured for this motor is $P_{in} = 7.3\,kW$. Operating point and efficiency are now estimated according to the methodology defined. Calculations are presented in Equations 5.15, 5.16 and 5.17:

$$Load = \frac{N_{synch} - N}{N_{synch} - N_r} \cdot 100\% = \frac{3000 - 2960}{3000 - 2915} \cdot 100\% = 47.1\% \tag{5.15}$$

$$P_{mec} = Load \cdot P_{mec_r} = 0.471 \cdot 11 = 5.2\,kW \tag{5.16}$$

$$\eta = \frac{P_{mec}}{P_{in}} \cdot 100\% = \frac{5.2}{7.3} \cdot 100\% = 71.2\% \tag{5.17}$$

Analysing the results, it can be concluded that from the two induction motors monitored in the Civil Engineering Building, both present efficiency values around 70%, which is low. B4 is the only high-efficiency motor studied, and, as it can be seen, even when it is operating at less than 50% of the rated load, the efficiency level is not so deteriorated as it is on other motors.

The obtained results for the two motors are consistent with the speed analysis performed in the measurements section, summarized in Table 5.17. Both motors are oversized, and that is influencing efficiency and is promoting reactive power consumption. None of these motors is operating at a load between 75 and 100% of the rated load, which was presented in Chapter 3 as the more efficient load interval for induction motors. The worst case of oversize is B3, which is operating at 37.3% of the rated load.

Both Civil Engineering Building motors are thus flagged for intervention.

5.5 Electric Energy Consumption and Costs

In this section, each induction motor is analysed in order to obtain its electric energy consumption and associated costs.

Data retrieved using energy analysers regarding motors' load profiles is presented. Data could only be measured within a relatively small interval of time, since the access to technical areas is restricted, and a member of the IST maintenance staff has to attend each visit, for safety reasons. Knowledge about each pump operating pattern has to be obtained, in order to extrapolate the results. Calculations must be performed to retrieve motors' consumption costs over a year.

This methodology process requires some assumptions. Since the studied motors are integrated into HVAC systems, their operating patterns depend on climate, as well as on building occupation. At the IST campi, four operating periods are defined over the year:

- Winter: from November to March.
- Summer: from April to October.
- Weekends: over the entire year.
- Holidays: from July to August (two months of the Summer period).

For each case studied, calculations for cost analysis are performed, considering each one of these four periods, and combining them in order to obtain a full year analysis. It is considered that a month has 22 working days, and weekends are 8 days per month.

Other important factor is the energy tariff that has been contacted by IST. The tariff contracted is analysed and the cost of electricity is presented in Table 5.20:

Table 5.20: IST Energy Tariff - electricity costs.

Daily Period	Price [$€/kWh$]	Winter Period	Summer Period
Peak	0.123	9:30 - 12:00 18:30 - 21:00	09:15 - 12:15
Half-Peak	0.1107	07:00 - 09:30 12:00 - 18:30 21:00 - 24:00	07:00 - 09:15 12:15 - 24:00
Normal Off-Peak	0.0861	00:00 - 02:00 06:00 - 07:00	00:00 - 02:00 06:00 - 07:00
Super Off-Peak	0.0738	02:00 - 06:00	02:00 - 06:00

5.5.1 North Tower Pumps Motors

These pump systems are composed by two motors each. Both motors alternate between each other over the day, so one motor does half a day of operation. Electrical energy consumption and costs are calculated for each system, including both motors that belong to it. To obtain the electricity cost associated with each motor, the cost calculated for the system must be divided by two. The same applies to the electrical energy consumed.

The total input powers of the motors were measured over several hours of the day. Measurements were taken during the Summer period. Due to restrictions on time to retrieve data, only the pumps main motors' load profiles were measured. The load profiles obtained are presented in Figures 5.5, 5.6 and 5.7.

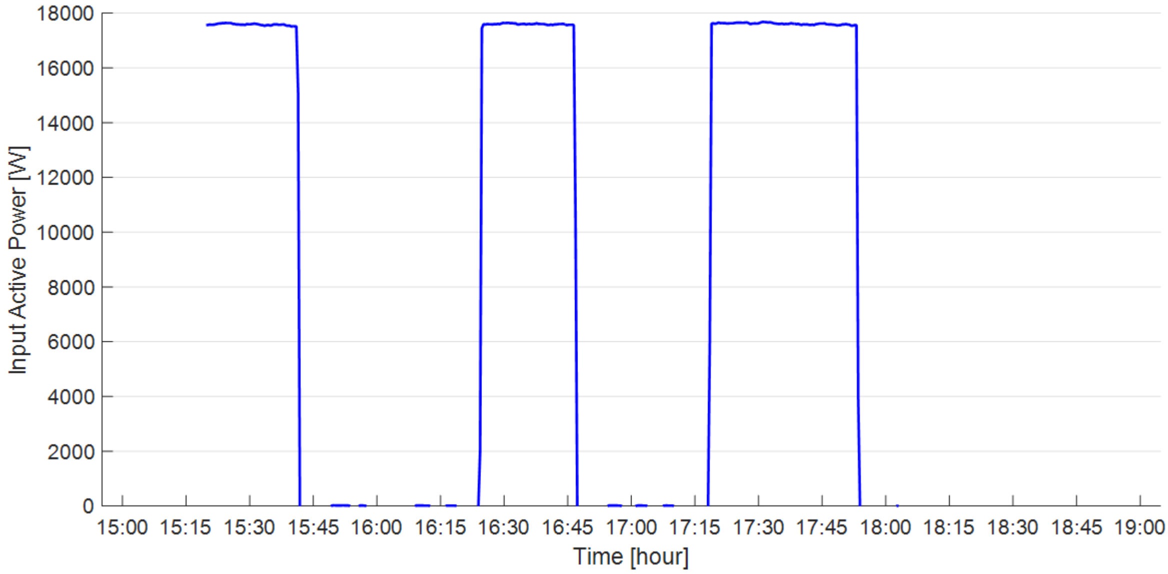


Figure 5.5: BPC1 load profile.

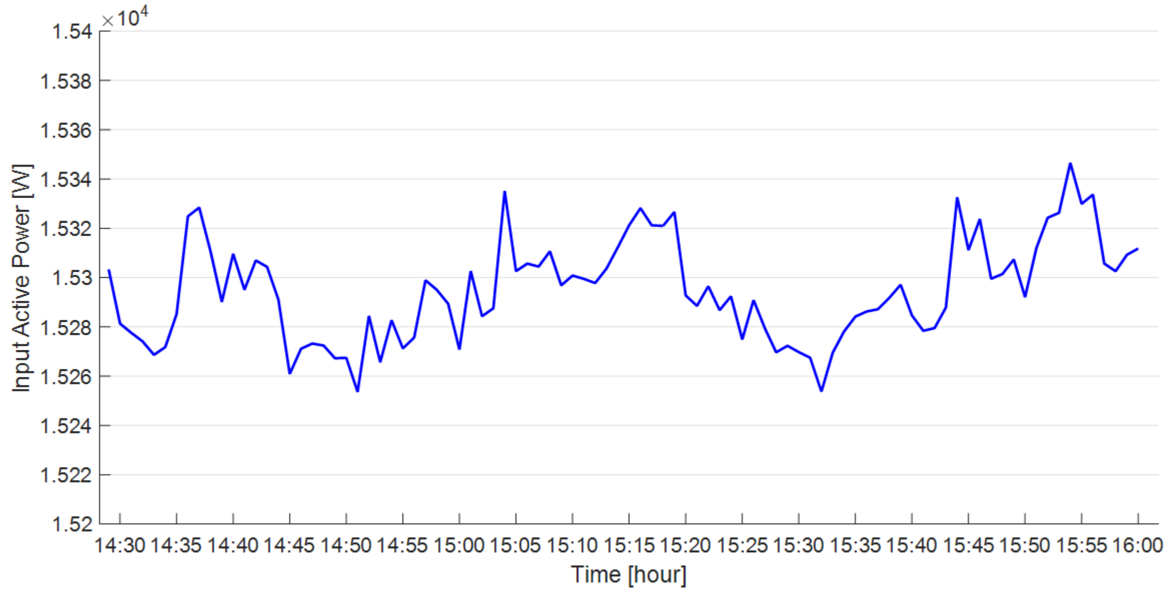


Figure 5.6: BF1 load profile.

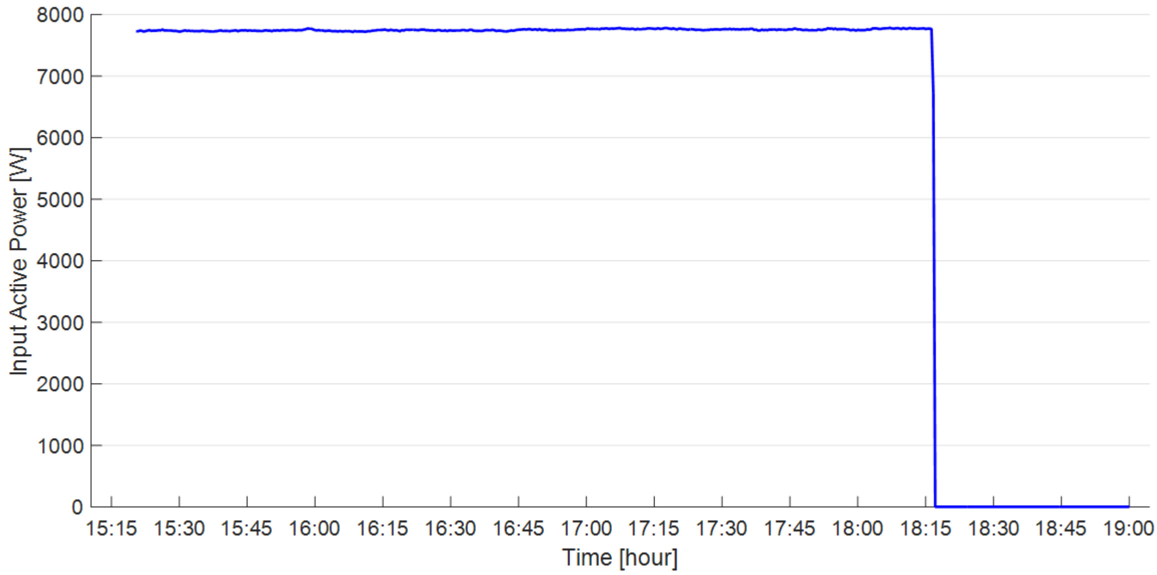


Figure 5.7: BPF1 load profile.

Note that only the BPC1, BF1 and BPF1 motors' load profiles could be retrieved. BPC2 motor load profile could not be obtained, since this system did not operate during the time of the measurement. This pump is responsible for pumping water into the Small Chiller, which is a backup unit that only operates when needed. BQ1 motor load profile also could not be obtained, since measurements were performed during Summer, and this pump is part of the HVAC heating system, which does not operate on Summer.

As stated before, there are restrictions regarding the access to the technical areas to perform measurements, and so the motors' load profiles that could be obtained only represent a period of hours of a week day, which is not sufficient to extrapolate to an entire year period. There are also motors for which a load profile could not even be retrieved. That said, the knowledge that was obtained from the technical personnel regarding the operation of the analysed systems played an important role on the definition of the operating pattern of each one of the pumps. These operating patterns are now developed.

The HVAC cooling system operates the entire year. Two separate operating patterns are defined for this HVAC sub-system:

- Big Chiller and cold water circulation operating pattern:

  This includes the system that pumps water into the main chiller unit, the Big Chiller - composed by motors BPC1 and BPC1(R) - as well as the two systems analysed responsible for pumping water into the cold water circulation system - motors BF1 and BF1(R) and motors BPF1 and BPF1(R). The operating hours are defined for each period:

  - Winter: system operates from 8:00 AM till 8:00 PM.
  - Summer: system operates from 8:00 AM till 8:00 PM.
  - Weekends: does not operate.
  - Holidays: system operates from 8:00 AM till 8:00 PM.

Calculations are now performed in order to obtain the number of hours per year in which these motors are operating on IST tariff's peak and half-peak times. These calculations are presented in Equations 5.18 to 5.25:

$$\begin{aligned} time_{Winter\_Peak} &= Winter\,Months \cdot Working\,Days \cdot Peak\,WorkHours = \\ &= 5 \cdot 22 \cdot 4 = 440\,hours \end{aligned} \tag{5.18}$$

$$\begin{aligned} time_{Winter\_Half-Peak} &= Winter\,Months \cdot Working\,Days \cdot Half-Peak\,WorkHours = \\ &= 5 \cdot 22 \cdot 8 = 880\,hours \end{aligned} \tag{5.19}$$

$$\begin{aligned} time_{Summer\_Peak} &= Summer\,Months \cdot Working\,Days \cdot Peak\,WorkHours = \\ &= 5 \cdot 22 \cdot 3 = 330\,hours \end{aligned} \tag{5.20}$$

$$\begin{aligned} time_{Summer\_Half-Peak} &= Summer\,Months \cdot Working\,Days \cdot Half-Peak\,WorkHours = \\ &= 5 \cdot 22 \cdot 9 = 990\,hours \end{aligned} \tag{5.21}$$

$$\begin{aligned} time_{Holidays\_Peak} &= Holidays\,Months \cdot Working\,Days \cdot Peak\,WorkHours = \\ &= 2 \cdot 22 \cdot 3 = 132\,hours \end{aligned} \tag{5.22}$$

$$\begin{aligned} time_{Holidays\_Half-Peak} &= Holidays\,Months \cdot Working\,Days \cdot Half-Peak\,WorkHours = \\ &= 2 \cdot 22 \cdot 9 = 396\,hours \end{aligned} \tag{5.23}$$

$$\begin{aligned} time_{Peak} &= time_{Winter\_Peak} + time_{Summer\_Peak} + time_{Holidays\_Peak} = \\ &= 440 + 330 + 132 = 902\,hours \end{aligned} \tag{5.24}$$

$$\begin{aligned} time_{Half-Peak} &= time_{Winter\_Half-Peak} + time_{Summer\_Half-Peak} + time_{Holidays\_Half-Peak} = \\ &= 880 + 990 + 396 = 2266\,hours \end{aligned} \tag{5.25}$$

where $time_{Winter\_Peak}$ is the number of hours per year in which a motor is operating on tariff's peak hours during the Winter period, $time_{Winter\_Half-Peak}$ is the number of hours per year in which a motor is operating on tariff's half-peak hours during the Winter period, $time_{Summer\_Peak}$ is the number of hours per year in which a motor is operating on tariff's peak hours during the Summer period, $time_{Summer\_Half-Peak}$ is the number of hours per year in which a motor is operating on tariff's half-peak hours during the Summer period, $time_{Holidays\_Peak}$ is the number of hours per year in which a motor is operating on tariff's peak hours during the Holidays period, $time_{Holidays\_Half-Peak}$ is the number of hours per year in which a motor is operating on tariff's half-peak hours during the Holidays period, $time_{Peak}$ is the number of hours per year in which a motor is operating on tariff's peak hours and $time_{Half-Peak}$ is the number of hours per year in which a motor is operating on tariff's half-peak hours.

- Small Chiller operating pattern:

  This includes the system that pumps water into the backup chiller unit, the Small Chiller - composed by motors BPC2 and BPC2(R). The Small Chiller is a backup of the Big Chiller, which means that it only operates when the demand justifies the need. Since this demand is not linear and totally known, it is considered that these motors operate mainly during the hours when the heat is heavier. The operating hours are defined for each period:

  – Winter: does not operate.

  – Summer: system operates from 11:00 AM till 17:00 PM.

  – Weekends: does not operate.

  – Holidays: system operates from 11:00 AM till 17:00 PM.

  Calculations are now performed in order to obtain the number of hours per year in which these motors are operating on IST tariff's peak and half-peak times. These calculations are presented in Equations 5.26 to 5.31:

$$\begin{aligned} time_{Summer\_Peak} &= Summer\,Months \cdot Working\,Days \cdot Peak\,WorkHours = \\ &= 5 \cdot 22 \cdot 1.25 = 137.5\,hours \end{aligned} \tag{5.26}$$

$$\begin{aligned} time_{Summer\_Half-Peak} &= Summer\,Months \cdot Working\,Days \cdot Half-Peak\,WorkHours = \\ &= 5 \cdot 22 \cdot 4.75 = 522.5\,hours \end{aligned} \tag{5.27}$$

$$\begin{aligned} time_{Holidays\_Peak} &= Holidays\,Months \cdot Working\,Days \cdot Peak\,WorkHours = \\ &= 2 \cdot 22 \cdot 1.25 = 55\,hours \end{aligned} \tag{5.28}$$

$$\begin{aligned} time_{Holydays\_Half-Peak} &= Holidays\,Months \cdot Working\,Days \cdot Half-Peak\,WorkHours = \\ &= 2 \cdot 22 \cdot 4.75 = 209\,hours \end{aligned} \tag{5.29}$$

$$\begin{aligned} time_{Peak} &= time_{Summer\_Peak} + time_{Holidays\_Peak} = \\ &= 137.5 + 55 = 192.5\,hours \end{aligned} \tag{5.30}$$

$$\begin{aligned} time_{Half-Peak} &= time_{Summer\_Half-Peak} + time_{Holidays\_Half-Peak} = \\ &= 522.5 + 209 = 731.5\,hours \end{aligned} \tag{5.31}$$

The HVAC heating system only operates during Winter, when the cold justifies the need. The operating pattern is defined for this HVAC sub-system, that includes the system analysed responsible for pumping water into the hot water circulation system - motors BQ1 and BQ1(R). The operating hours are defined for each period:

- Winter: system operates from 8:00 AM till 8:00 PM.
- Summer: does not operate.

- Weekends: does not operate.
- Holidays: does not operate.

Calculations are now performed in order to obtain the number of hours per year in which these motors are operating on IST tariff's peak and half-peak times. These calculations are presented in Equations 5.32 to 5.35:

$$\begin{aligned} time_{Winter\_Peak} &= Winter\,Months \cdot Working\,Days \cdot Peak\,WorkHours = \\ &= 5 \cdot 22 \cdot 4 = 440\,hours \end{aligned} \tag{5.32}$$

$$\begin{aligned} time_{Winter\_Half-Peak} &= Winter\,Months \cdot Working\,Days \cdot Half-Peak\,WorkHours = \\ &= 5 \cdot 22 \cdot 8 = 880\,hours \end{aligned} \tag{5.33}$$

$$time_{Peak} = time_{Winter\_Peak} = 440\,hours \tag{5.34}$$

$$time_{Half-Peak} = time_{Winter\_Half-Peak} = 880\,hours \tag{5.35}$$

With the operating patterns defined, calculations have now to be performed in order to retrieve the electrical energy consumption and costs that each pump system represents over a year, applying Equations 5.36 to 5.39:

$$Energy_{Peak}[MWh/year] = P_{in} \cdot time_{Peak} \tag{5.36}$$

$$Energy_{Half-Peak}[MWh/year] = P_{in} \cdot time_{Half-Peak} \tag{5.37}$$

$$Energy_{Total}[MWh/year] = Energy_{Peak} + Energy_{Half-Peak} \tag{5.38}$$

$$Cost[€/year] = (Energy_{Peak} \cdot Price_{Peak}/kWh) + (Energy_{Half-Peak} \cdot Price_{Half-Peak}/kWh) \tag{5.39}$$

where $Energy_{Peak}$ is the electrical energy consumed by a system per year on tariff's peak hours, $Energy_{Half-Peak}$ is the electrical energy consumed by a system per year on tariff's half-peak hours, $Energy_{Total}$ is the total electrical energy consumed by a system per year, $Cost$ is the electricity cost associated with a system per year and P_{in} represents the system input active power, which is considered the average input active power between the two motors that are part the system.

As an example, electrical energy consumption and associated costs are calculated for BPC1 and BPC1(R) motor system, as depicted in Equations 5.40 to 5.43:

$$Energy_{Peak} = P_{in} \cdot time_{Peak} = 17.9 \cdot 902 = 16.15\,MWh/year \tag{5.40}$$

$$Energy_{Half-Peak} = P_{in} \cdot time_{Half-Peak} = 17.9 \cdot 2266 = 40.56\,MWh/year \tag{5.41}$$

$$Energy_{Total} = Energy_{Peak} + Energy_{Half-Peak} = 16.15 + 40.56 = 56.71\,MWh/year \tag{5.42}$$

$$\begin{aligned} Cost &= (Energy_{Peak} \cdot Price_{Peak}/kWh) + (Energy_{Half-Peak} \cdot Price_{Half-Peak}/kWh) = \\ &= (16150 \cdot 0.123) + (40560 \cdot 0.1107) = €6476\,/year \end{aligned} \tag{5.43}$$

The results obtained for electric energy consumption and associated costs for all North Tower systems are presented in Tables 5.21 and 5.22.

Table 5.21: North Tower - systems electric energy consumption.

Motors IDs	$Energy_{Peak}[MWh/year]$	$Energy_{Half-Peak}[MWh/year]$	$Energy_{Total}[MWh/year]$
BPC1/BPC1(R)	16.15	40.56	56.71
BF1/BF1(R)	12.54	31.50	44.04
BPC2/BPC2(R)	0.87	3.29	4.16
BPF1/BPF1(R)	7.35	18.47	25.82
BQ1/BQ1(R)	2.60	5.19	7.79

Table 5.22: North Tower - systems electricity costs.

Motors IDs	$Cost[€/year]$
BPC1/BPC1(R)	6476
BF1/BF1(R)	5029
BPC2/BPC2(R)	471
BPF1/BPF1(R)	2949
BQ1/BQ1(R)	894

As it can be verified, BPC1/BPC1(R) and BF1/BF1(R) are the systems that represent a higher electricity cost, followed by the BPF1/BPF1(R) system.

5.5.2 Civil Engineering Building Pumps Motors

Electrical energy consumption and costs are calculated for each motor.

The total input powers of the motors were measured over several hours of the day. Measurements were taken during the Summer period. The load profiles obtained are presented in Figures 5.8 and 5.9.

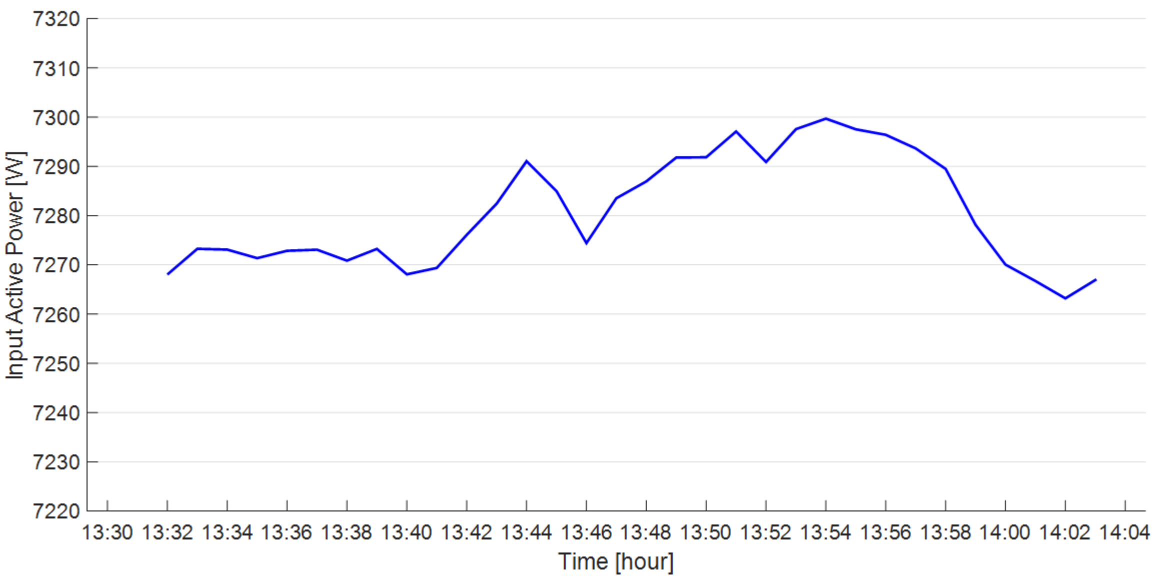


Figure 5.8: B4 load profile.

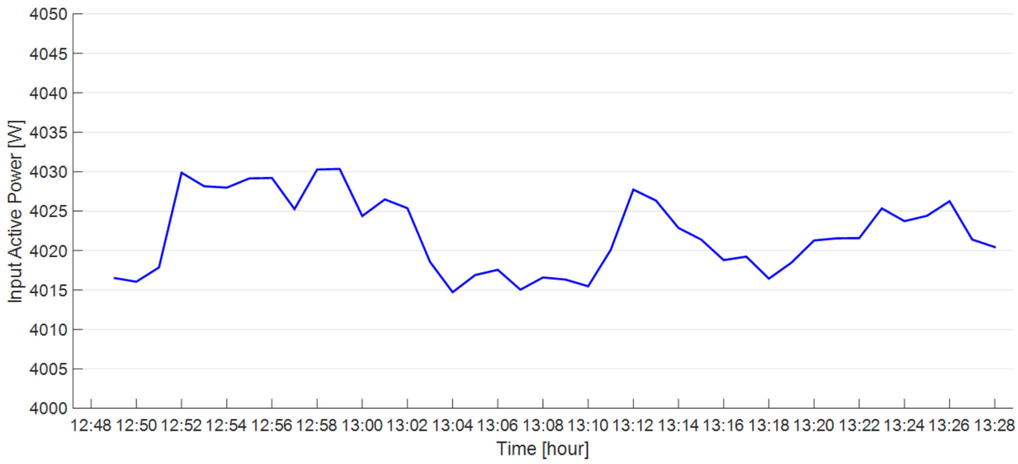


Figure 5.9: B3 load profile.

As stated before, there are restrictions regarding the access to the technical areas to perform measurements, and so the motors' load profiles that could be obtained only represent a period of hours of a week day, which is not sufficient to extrapolate to an entire year period. That said, the knowledge that was obtained from the technical personnel regarding the operation of the analysed systems played an important role on the definition of the operating pattern of each one of the pumps. These operating patterns are now developed.

These motors are part of pumps that are responsible for the air conditioning water circulation. The operating hours are defined for each period:

- Winter: motors operate from 8:00 AM till 8:00 PM.
- Summer: motors operate from 8:00 AM till 8:00 PM.
- Weekends: motors do not operate.
- Holidays: motors operate from 8:00 AM till 8:00 PM.

Calculations are now performed in order to obtain the number of hours per year in which these motors are operating on IST tariff's peak and half-peak times. These calculations are presented in Equations 5.44 to 5.51:

$$\begin{aligned} time_{Winter\_Peak} &= Winter\,Months \cdot Working\,Days \cdot Peak\,WorkHours = \\ &= 5 \cdot 22 \cdot 4 = 440\,hours \end{aligned} \tag{5.44}$$

$$\begin{aligned} time_{Winter\_Half-Peak} &= Winter\,Months \cdot Working\,Days \cdot Half-Peak\,WorkHours = \\ &= 5 \cdot 22 \cdot 8 = 880\,hours \end{aligned} \tag{5.45}$$

$$\begin{aligned} time_{Summer\_Peak} &= Summer\,Months \cdot Working\,Days \cdot Peak\,WorkHours = \\ &= 5 \cdot 22 \cdot 3 = 330\,hours \end{aligned} \tag{5.46}$$

$$time_{Summer\_Half-Peak} = Summer\,Months \cdot Working\,Days \cdot Half-Peak\,WorkHours = \\ = 5 \cdot 22 \cdot 9 = 990\,hours \tag{5.47}$$

$$time_{Holidays\_Peak} = Holidays\,Months \cdot Working\,Days \cdot Peak\,WorkHours = \\ = 2 \cdot 22 \cdot 3 = 132\,hours \tag{5.48}$$

$$time_{Holidays\_Half-Peak} = Holidays\,Months \cdot Working\,Days \cdot Half-Peak\,WorkHours = \\ = 2 \cdot 22 \cdot 9 = 396\,hours \tag{5.49}$$

$$time_{Peak} = time_{Winter\_Peak} + time_{Summer\_Peak} + time_{Holidays\_Peak} = \\ = 440 + 330 + 132 = 902\,hours \tag{5.50}$$

$$time_{Half-Peak} = time_{Winter\_Half-Peak} + time_{Summer\_Half-Peak} + time_{Holidays\_Half-Peak} = \\ = 880 + 990 + 396 = 2266\,hours \tag{5.51}$$

With the operating pattern defined, calculations have now to be performed in order to retrieve the electrical energy consumption and costs that each pump motor represents over a year, applying Equations 5.36 to 5.39, with the difference that P_{in} here represents each motor input active power.

As an example, electrical energy consumption and associated costs are calculated for B4 motor, as depicted in Equations 5.52 to 5.55:

$$Energy_{Peak} = P_{in} \cdot time_{Peak} = 7.3 \cdot 902 = 6.58\,MWh/year \tag{5.52}$$

$$Energy_{Half-Peak} = P_{in} \cdot time_{Half-Peak} = 7.3 \cdot 2266 = 16.54\,MWh/year \tag{5.53}$$

$$Energy_{Total} = Energy_{Peak} + Energy_{Half-Peak} = 6.58 + 16.54 = 23.12\,MWh/year \tag{5.54}$$

$$Cost = (Energy_{Peak} \cdot Price_{Peak}/kWh) + (Energy_{Half-Peak} \cdot Price_{Half-Peak}/kWh) = \\ = (6580 \cdot 0.123) + (16540 \cdot 0.1107) = €2640\,/year \tag{5.55}$$

The results obtained for electric energy consumption and associated costs for all Civil Engineering Building pumps are presented in Tables 5.23 and 5.24.

Table 5.23: Civil Engineering Building - motors electric energy consumption.

Motors IDs	$Energy_{Peak}[MWh/year]$	$Energy_{Half-Peak}[MWh/year]$	$Energy_{Total}[MWh/year]$
B4	6.58	16.54	23.12
B3	3.70	9.29	12.99

Table 5.24: Civil Engineering Building - motors electricity costs.

Motors IDs	$Cost[€/year]$
B4	2640
B3	1483

As it can be verified, B4 is the motor that represents a higher electricity cost, which is expected, since this motor has a higher input active power than B3, and both motors have the same operating pattern.

5.6 Motors' Results Analysis and Proposed Solutions

In this section, the results obtained for each one of the induction motors analysed are dissected, with the objective of studying the interventions that can be made in order to improve efficiency.

The proposed interventions have a special focus on motor substitution by a high-efficient one. For new motor acquisition choices regarding this substitution, it is considered that the output power delivered by each motor must remain constant. Investment payback analysis is performed according to the methodology defined in Chapter 4, in Equations 4.7 and 4.8. Calculations are defined in Equations 5.56 to 5.59:

$$Savings_{annual\_Peak}\,[€] = \left(\frac{1}{\eta_{currentmotor}} - \frac{1}{\eta_{newmotor}}\right) \cdot P_{mec}\,[kW] \cdot \\ \cdot Peak\,WorkHours\,[h] \cdot Price_{Peak}\,[€/kWh] \tag{5.56}$$

$$Savings_{annual\_Half-Peak}\,[€] = \left(\frac{1}{\eta_{currentmotor}} - \frac{1}{\eta_{newmotor}}\right) \cdot P_{mec}\,[kW] \cdot \\ \cdot Half - Peak\,WorkHours\,[h] \cdot Price_{Half-Peak}\,[€/kWh] \tag{5.57}$$

$$Savings_{annual}[€] = Savings_{annual\_Peak} + Savings_{annual\_Half-Peak} \tag{5.58}$$

$$Payback\,[years] = \frac{Cost_{newmotor}}{Savings_{annual}} \tag{5.59}$$

where $Savings_{annual\_Peak}$ are the annual savings obtained during IST tariff's peak hours when a high-efficiency motor is operating instead of the existing motor, $Savings_{annual\_Half-Peak}$ are the annual savings obtained during IST tariff's half-peak hours when a high-efficiency motor is operating instead of the existing motor and $Savings_{annual}$ are the total annual savings obtained when a high-efficiency motor is operating instead of the existing motor. $Price_{Peak}$ and $Price_{Half-Peak}$ represent the IST energy tariff on peak and half-peak hours, respectively.

5.6.1 North Tower Pumps Motors

In the analysed systems there is a pair of motors per pump, and they behave in the same manner when it comes to efficiency. When any intervention is considered, both motors are included on it. The economical analysis is performed for each pair of motors, so there is no differentiation when it comes to that.

In the operating point and efficiency analysis performed in Section 5.4, it was concluded that all North Tower motors, except BPC1 and BPC1(R), are flagged for intervention due to oversize and consequent inefficiency. All these cases are analysed. Nevertheless, BPC1 and BPC1(R) motors represent the higher yearly operation cost obtained (€$6476/year$), and so they should be monitored regularly, in order to check if the efficient behaviour continues to be verified over time.

As stated before, it is verified that all North Tower motors alternate between each other during the daily operation cycle, and so starts and stops occur during the day. That said, the installation of a soft-starter for each motor is proposed, in order to prevent inefficiency, as well as current peaks, during motor starts.

BF1 and BF1(R)

From the operating point analysis, it can be verified that these motors deliver a maximum 7.8 kW mechanical power, which can be compared with the rated 15 kW.

The substitution of the existing motors by high-efficiency motors is now considered. The motor suggested for replacement is the OMEC OMT1-IE3, which has the reference number AA384A1151T001. This motor is an IE3 Premium Efficiency motor with 4 poles, has a rated output power of 11 kW, which is closer to the required output power, and costs €$687/unit$. This means that if the new motor is delivering the calculated average mechanical power of 7.2 kW, then it is operating at $\frac{7.2}{11} \cdot 100\% = 66\%$ load. From the motor technical characteristics, it can be inferred that, with this load, the motor is operating with about 90.5% efficiency, which can be compared with the 52.8% maximum efficiency calculated for one of the currently existing motors.

Payback analysis is now applied, according with Equations 5.56 to 5.59. The efficiency of the current motor is the average efficiency of the two motors, as well as is the delivered mechanical power. Calculations are presented in Equations 5.60 to 5.63:

$$Savings_{annual\_Peak} = \left(\frac{1}{0.519} - \frac{1}{0.905}\right) \cdot 7.2 \cdot 902 \cdot 0.123 = €656 \tag{5.60}$$

$$Savings_{annual\_Half-Peak} = \left(\frac{1}{0.519} - \frac{1}{0.905}\right) \cdot 7.2 \cdot 2266 \cdot 0.1107 = €1484 \tag{5.61}$$

$$Savings_{annual} = 656 + 1484 = €2140 \tag{5.62}$$

$$Payback = \frac{2 \cdot 687}{2140} = 0.64\, years \approx 8\, months \tag{5.63}$$

The obtained value proves that the proposed solution is economically viable. After 8 months, the money invested is recovered, and from that point on all the savings can be considered revenue.

BPC2 and BPC2(R)

From the operating point analysis, it can be verified that these motors deliver a maximum 2.1 kW mechanical power, which can be compared with the rated 7.5 kW.

The substitution of the existing motors by high-efficiency motors is now considered. The motor suggested for replacement is the OMEC OMT1-IE3, which has the reference number AA35430051T001. This motor is an IE3 Premium Efficiency motor with 4 poles, has a rated output power of 3 kW, which is closer to the required output power, and costs €$243/unit$. This means that if the new motor is delivering the calculated average mechanical power of 2.1 kW, then it is operating at $\frac{2.1}{3} \cdot 100\% = 70\%$ load. From the motor technical characteristics, it can be inferred that, with this load, the motor is operating with about 88% efficiency, which can be compared with the 51.2% maximum efficiency calculated for one of the currently existing motors.

Payback analysis is now applied, according with Equations 5.56 to 5.59. The efficiency of the current motor is the average efficiency of the two motors, as well as is the delivered mechanical power. Calculations are presented in Equations 5.64 to 5.67:

$$Savings_{annual\_Peak} = \left(\frac{1}{0.471} - \frac{1}{0.88}\right) \cdot 2.1 \cdot 192.5 \cdot 0.123 = €49 \tag{5.64}$$

$$Savings_{annual\_Half-Peak} = \left(\frac{1}{0.471} - \frac{1}{0.88}\right) \cdot 2.1 \cdot 731.5 \cdot 0.1107 = €168 \tag{5.65}$$

$$Savings_{annual} = 49 + 168 = €217 \tag{5.66}$$

$$Payback = \frac{2 \cdot 243}{217} = 2.24\, years \approx 2\, years\, and\, 3\, months \tag{5.67}$$

The obtained value proves that the proposed solution is economically viable. After 2 years and 3 months, the money invested is recovered, and from that point on all the savings can be considered revenue.

BPF1 and BPF1(R)

From the operating point analysis, it can be verified that these motors deliver a maximum 4.6 kW mechanical power, which can be compared with the rated 7.5 kW.

The substitution of the existing motors by high-efficiency motors is now considered. The motor suggested for replacement is the OMEC OMT1-IE3, which has the reference number AA37455051T001. This motor is an IE3 Premium Efficiency motor with 4 poles, has a rated output power of 5.5 kW, which is closer to the required output power, and costs $€382/unit$. This means that if the new motor is delivering the calculated average mechanical power of 4.2 kW, then it is operating at $\frac{4.2}{5.5} \cdot 100\% = 76\%$ load. From the motor technical characteristics, it can be inferred that, with this load, the motor is operating with about 90% efficiency, which can be compared with the 59% maximum efficiency calculated for one of the currently existing motors.

Payback analysis is now applied, according with Equations 5.56 to 5.59. The efficiency of the current motor is the average efficiency of the two motors, as well as is the delivered mechanical power. Calculations are presented in Equations 5.68 to 5.71:

$$Savings_{annual\_Peak} = \left(\frac{1}{0.519} - \frac{1}{0.9}\right) \cdot 4.2 \cdot 902 \cdot 0.123 = €381 \tag{5.68}$$

$$Savings_{annual\_Half-Peak} = \left(\frac{1}{0.519} - \frac{1}{0.9}\right) \cdot 4.2 \cdot 2266 \cdot 0.1107 = €861 \tag{5.69}$$

$$Savings_{annual} = 381 + 861 = €1242 \tag{5.70}$$

$$Payback = \frac{2 \cdot 382}{1242} = 0.62\, years \approx 7\, months \tag{5.71}$$

The obtained value proves that the proposed solution is economically viable. After 7 months, the money invested is recovered, and from that point on all the savings can be considered revenue.

BQ1 and BQ1(R)

From the operating point analysis, it can be verified that these motors deliver a maximum 3.1 kW mechanical power, which can be compared with the rated 7.5 kW.

The substitution of the existing motors by high-efficiency motors is now considered. The motor suggested for replacement is the OMEC OMT1-IE3, which has the reference number AA36440056T001. This motor is an IE3 Premium Efficiency motor with 4 poles, has a rated output power of 4 kW, which is closer to the required output power, and costs $€294/unit$. This means that if the new motor is delivering the calculated average mechanical power of 3 kW, then it is operating at $\frac{3}{4} \cdot 100\% = 75\%$ load. From the motor technical characteristics, it can be inferred that, with this load, the motor is operating with about 89.3% efficiency, which can be compared with the 51.7% maximum efficiency calculated for one of the currently existing motors.

Payback analysis is now applied, according with Equations 5.56 to 5.59. The efficiency of the current motor is the average efficiency of the two motors, as well as is the delivered mechanical power. Calculations are presented in Equations 5.72 to 5.75:

$$Savings_{annual\_Peak} = \left(\frac{1}{0.509} - \frac{1}{0.893}\right) \cdot 3 \cdot 440 \cdot 0.123 = €137 \tag{5.72}$$

$$Savings_{annual\_Half-Peak} = \left(\frac{1}{0.509} - \frac{1}{0.893}\right) \cdot 3 \cdot 880 \cdot 0.1107 = €247 \tag{5.73}$$

$$Savings_{annual} = 137 + 247 = €384 \tag{5.74}$$

$$Payback = \frac{2 \cdot 294}{384} = 1.53\, years \approx 1\, year\, and\, 6\, months \tag{5.75}$$

The obtained value proves that the proposed solution is economically viable. After 1 year and 6 months, the money invested is recovered, and from that point on all the savings can be considered revenue.

5.6.2 Civil Engineering Building Pumps Motors

In the analysed systems there is one motor per pump. The economical analysis is performed for each motor.

In the operating point and efficiency analysis performed in Section 5.4, it was concluded that both Civil Engineering Building motors are flagged for intervention due to oversize and consequent inefficiency. These cases are analysed.

B4

From the operating point analysis, it can be verified that this motor delivers a maximum 5.2 kW mechanical power, which can be compared with the rated 11 kW.

The substitution of the existing motor by a high-efficiency motor is now considered. The motor suggested for replacement is the OMEC OMT1-IE3, which has the reference number AA37275051T001. This motor is an IE3 Premium Efficiency motor with 2 poles, has a rated output power of 7.5 kW, which is closer to the required output power, and costs €$424/unit$. This means that if the new motor is delivering the calculated mechanical power of 5.2 kW, then it is operating at $\frac{5.2}{7.5} \cdot 100\% = 69\%$ load. From the motor technical characteristics, it can be inferred that, with this load, the motor is operating with about 90% efficiency, which can be compared with the 71.2% efficiency calculated for the currently existing motor.

Payback analysis is now applied, according with Equations 5.56 to 5.59. Calculations are presented in Equations 5.76 to 5.79:

$$Savings_{annual\_Peak} = \left(\frac{1}{0.712} - \frac{1}{0.9}\right) \cdot 5.2 \cdot 902 \cdot 0.123 = €169 \quad (5.76)$$

$$Savings_{annual\_Half-Peak} = \left(\frac{1}{0.712} - \frac{1}{0.9}\right) \cdot 5.2 \cdot 2266 \cdot 0.1107 = €383 \quad (5.77)$$

$$Savings_{annual} = 169 + 383 = €552 \quad (5.78)$$

$$Payback = \frac{424}{552} = 0.77\,years \approx 9\,months \quad (5.79)$$

The obtained value proves that the proposed solution is economically viable. After 9 months, the money invested is recovered, and from that point on all the savings can be considered revenue.

B3

From the operating point analysis, it can be verified that this motor delivers a maximum 2.8 kW mechanical power, which can be compared with the rated 7.5 kW.

The substitution of the existing motor by a high-efficiency motor is now considered. The motor suggested for replacement is the OMEC OMT1-IE3, which has the reference number AA36240051T001. This motor is an IE3 Premium Efficiency motor with 2 poles, has a rated output power of 4 kW, which is closer to the required output power, and costs €$264/unit$. This means that if the new motor is delivering the calculated mechanical power of 2.8 kW, then it is operating at $\frac{2.8}{4} \cdot 100\% = 70\%$ load. From the motor technical characteristics, it can be inferred that, with this load, the motor is operating with about 88% efficiency, which can be compared with the 68.3% efficiency calculated for the currently existing motor.

Payback analysis is now applied, according with Equations 5.56 to 5.59. Calculations are presented in Equations 5.80 to 5.83:

$$Savings_{annual\_Peak} = \left(\frac{1}{0.683} - \frac{1}{0.88}\right) \cdot 2.8 \cdot 902 \cdot 0.123 = €102 \quad (5.80)$$

$$Savings_{annual\_Half-Peak} = \left(\frac{1}{0.683} - \frac{1}{0.88}\right) \cdot 2.8 \cdot 2266 \cdot 0.1107 = €230 \quad (5.81)$$

$$Savings_{annual} = 102 + 230 = €332 \quad (5.82)$$

$$Payback = \frac{264}{332} = 0.80\,years \approx 10\,months \quad (5.83)$$

The obtained value proves that the proposed solution is economically viable. After 10 months, the money invested is recovered, and from that point on all the savings can be considered revenue.

Table 5.25 resumes all the results obtained regarding motors substitution by high-efficient ones:

Table 5.25: Motors substitution: obtained results.

Motor	Annual Savings [€]	Investment Cost [€]	Payback [months]
BPF1/BPF1(R)	1242	764	7
BF1/BF1(R)	2140	1374	8
B4	552	424	9
B3	332	264	10
BQ1/BQ1(R)	384	588	18
BPC2/BPC2(R)	217	486	27
BPC1/BPC1(R)	NA	NA	NA

The sum gives a total annual savings value of €4867, with a total investment of €3900 in new high-efficiency motors.

The paybacks obtained for all motors are very satisfying. The highest payback value obtained is 27 months, corresponding to the system composed by BPC2 and BPC2(R) motors, which is responsible for pumping water into the Small Chiller. All investments are clearly justified, and savings are soon turned into profit.

Soft-starters installation is also proposed for every North Tower pumps motors. As stated before, payback analysis is not performed for power electronics solutions, however, the starts and stops verified during this study reveal that it is important to consider this hypothesis, as it allows to save energy and to reduce current peaks.

As it can be noticed, VSDs are not proposed for any of the cases studied, since these equipments are mainly used when speed variations, associated with load variations, are required, which is not the case in any of the analysed scenarios. There is also the possibility of introducing a VSD on an oversized induction motor and then adapt it to the required load. In this thesis, this solution is not considered. That solution is applicable if motors are new, and so this investment is justified, since it will be explored for years. However, in this study, none of the motors are new. That said, when inefficiency is verified, the solution that is considered is motor substitution, allowing the money invested to be placed on buildings' HVAC systems, and not on old motors that will eventually fail, and then have to be substituted.

Chapter 6

Conclusions

The methodology defined for induction motors' energy efficiency assessment was applied to the selected HVAC systems' pumps motors, which are part of the IST Alameda Campus. The methodology proved to be indeed low-cost and non-invasive, as predicted, but it also proved to be reliable and allowed a quick motor analysis, since measurements do not take long to obtain (except for the load profiles) and calculations can be easily performed. By following the instructions, as long as the applier has some knowledge in electricity, so the electric panel can be safely accessed, this methodology can be indeed applied by anyone.

Motor analysis led to the fact that the current situation, regarding energy efficiency in the selected systems, is not satisfactory. Only one of the analysed systems, the North Tower pump responsible for pumping water into the main chiller, composed by motors BPC1 and BPC1(R), presented an efficiency level around 90%. All the other systems proved to require some intervention in order to enhance electric energy efficiency. The main reason behind this is the fact that motors are oversized.

Solutions were proposed for every system studied. The main focus was on the substitution of the existing motors by a high-efficiency motor, but the introduction of soft-starters was also considered. The introduction of high-efficiency motors proved to be economically feasible for all applicable cases, with paybacks between 7 and 27 months. Soft-starters installation is proposed for every North Tower pumps motors studied, since these pumps are composed by two motors each, which alternate between each other during the daily operation. That said, energy can be saved and current peaks avoided on motor starts.

The development of this thesis not only contributed to provide solutions that target the improvement of the IST Alameda Campus energy efficiency, but also summarized a powerful induction motor efficiency assessment method that can be applied in other scenarios. All objectives were accomplished, bearing in mind the initial motivation of contributing to a better environment.

6.1 Further Works

The introduction of soft-starters on North Tower pumps motors is proposed, but a payback analysis and equipment selection have yet to be performed.

There are other systems on IST that include motors, from HVAC to elevators, that require analysis. The efficiency assessment method developed on this thesis can be applied to all those induction motors.

While analysing the HVAC systems, other problems were identified on the water circulation, such as damaged valves or pipes. This is also a situation that requires attention.

A preventive maintenance plan regarding electric motors is also proposed to be developed. Regular actions, such as motor cleaning and monitoring, allow to prevent premature failures and to span motors' lifetime.

Bibliography

[1] Commission of the European Communities, “Commission Regulation (EC) No 640/2009,” *Official Journal of the European Union*, Jul. 2009.

[2] (2016) Instituto Superior Técnico (IST). [Online]. Available: http://www.tecnico.ulisboa.pt

[3] UNEP and COPPER, “Technical study report - energy efficiency improvements for motors & it’s drive systems,” 2011.

[4] (2016) WEG. [Online]. Available: http://www.weg.net

[5] G. McCoy, “Motor systems assessment training, including use of the motor systems tool suite,” U.S. Department of Energy.

[6] R. Guimarães, “Comportamento elétrico, mecânico e hidráulico de um sistema de bombeamento sob o enfoque da eficiência energética,” Master’s thesis, Faculdade de Engenharia Elétrica - Universidade Federal de Uberlândia, Uberlândia, Brazil, 2008.

[7] (2017) National Aeronautics and Space Administration (NASA). [Online]. Available: http://climate.nasa.gov

[8] (2017) United Nations (UN). [Online]. Available: http://www.un.org

[9] (2017) United Nations - Framework Convention on Climate Change. [Online]. Available: http://www.unfccc.int

[10] A. T. de Almeida, P. Fonseca, and P. Bertoldi, “Energy-efficient motor systems in the industrial and in the services sectors in the European Union: characterisation, potentials, barriers and policies,” in *Elsevier Energy 28*, 2003, pp. 673–690.

[11] J. Bernardo, “Estratégia para a eficiência energética nos edifícios públicos,” Direção Geral de Energia e Geologia, 2015.

[12] Wikipedia. (2016) Instituto Superior Técnico. [Online]. Available: http://pt.wikipedia.org/wiki/Instituto_Superior_Tecnico

[13] (2016) European Council for an Energy Effcient Economy (ECEEE). [Online]. Available: http://www.eceee.net

[14] Commission of the European Communities, “Commission Regulation (EU) No 4/2014,” *Official Journal of the European Union*, Jan. 2014.

[15] Wikipedia. (2016) Portugal. [Online]. Available: http://pt.wikipedia.org/wiki/Portugal

[16] (2017) ADENE - Agência para a Energia. [Online]. Available: http://www.adene.pt

[17] W. C. Turner and S. Doty, *Energy Management Handbook*, 6th ed. Lilburn, GA, USA: The Fairmont Press, Inc., 2007.

[18] A. G. P. Garcia, “Impacto da lei de eficiência energética para motores elétricos no potencial de conservação de energia na indústria,” Master’s thesis, Universidade Federal do Rio de Janeiro, Rio de Janeiro, Brazil, 2003.

[19] J. P. S. Paiva, *Redes de Energia Eléctrica: uma análise sistémica*, 3rd ed. Lisbon, Portugal: IST Press, 2011.

[20] A. Dente, *Máquina Assíncrona*. Lisbon, Portugal: IST/DEEC - Energia, 2007.

[21] A. Zabardast and H. Mokhtari, “Effect of high-efficient electric motors on efficiency improvement and electric energy saving,” in *Third International Conference on Electric Utility Deregulation and Restructuring and Power Technologies*, Nanjing, China, Apr. 6–9, 2008, pp. 533–538.

[22] V. Dlamini, R. Naidoo, and M. Manyage, “A non-intrusive method for estimating motor efficiency using vibration signature analysis,” in *International Journal of Electrical Power & Energy Systems*, vol. 45, no. 1. Elsevier, February 2013, pp. 384–390.

[23] C. F. V. Alves, “Plano de eficiência energética numa unidade industrial,” Master’s thesis, Faculdade de Engenharia da Universidade do Porto, Porto, Portugal, 2009.

[24] V. Dlamini, R. C. Bansal, and R. Naidoo, “An improved motor replacement strategy using non-intrusive motor efficiency estimation,” in *Industrial and Commercial Use of Energy (ICUE), 2014 International Conference on the*. IEEE, August 2014.

[25] A. J. F. Cabral, “Manutenção preditiva de accionamentos electromecânicos: detecção e diagnóstico de condições de funcionamento anómalas em motores de indução trifásicos,” Master’s thesis, Instituto Superior Técnico - Universidade de Lisboa, Lisbon, Portugal, 2016.