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Gradutate in Computer Science

Induction Motors' Predictive Maintenance

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UNIVERSIDADE NOVA DE LISBOA

DRAFT: June 5, 2016

Abstract

The dissertation must contain two versions of the abstract, one in the same language as the main text, another in a different language. The package assumes that the two languages under consideration are always Portuguese and English.

The package will sort the abstracts in the appropriate order. This means that the first abstract will be in the same language as the main text, followed by the abstract in the other language, and then followed by the main text. For example, if the dissertation is written in Portuguese, first will come the summary in Portuguese and then in English, followed by the main text in Portuguese. If the dissertation is written in English, first will come the summary in English and then in Portuguese, followed by the main text in English.

The abstract shoul not exceed one page and should answer the following questions:

- What's the problem?
- Why is it interesting?
- What's the solution?
- What follows from the solution?

Keywords: Keywords (in English) . . .

Resumo

Independentemente da língua em que está escrita a dissertação, é necessário um resumo na língua do texto principal e um resumo noutra língua. Assume-se que as duas línguas em questão serão sempre o Português e o Inglês.

O *template* colocará automaticamente em primeiro lugar o resumo na língua do texto principal e depois o resumo na outra língua. Por exemplo, se a dissertação está escrita em Português, primeiro aparecerá o resumo em Português, depois em Inglês, seguido do texto principal em Português. Se a dissertação está escrita em Inglês, primeiro aparecerá o resumo em Inglês, depois em Português, seguido do texto principal em Inglês.

O resumo não deve exceder uma página e deve responder às seguintes questões:

- Qual é o problema?
- Porque é que ele é interessante?
- Qual é a solução?
- O que resulta (implicações) da solução?

Palavras-chave: Palavras-chave (em Português) ...

Contents

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Listings

Acronyms

AC Alternate Current.

DS Data Science.

EMFS Electromotive Force Systems.

IM three phase induction motor.

IMs three-phase induction motor with squirrel-cage rotor.

IoT Internet of Things.

LCC Life Cycle Cost.

rms root mean square.

TPS Three Phase System.

CHAPTER 1

Introduction

This is the introductory chapter of this dissertation. You will be presented the context in which this work is included, as well as the motivation that lead to the development of this thesis in section 1.1. Section 1.2 will describe the problem this thesis is approaching and disclose its main goals. Furthermore, section 1.3 will present the *as is* proposed solution, following the contributions of this thesis in section 1.4. At last, section 1.5 presents the remaining chapters of this dissertation.

1.1 Context and Motivation

Electric Motors are part of the industrial equipments' great majority. They are electrical machines that convert electrical energy into mechanical energy and they can be found in applications as diverse as industrial fans, blowers, pumps, compressors, conveyors, lifts, households appliances, power tools, etc. These motors are integrated in Electromotive Force Systems (EMFS), which are also composed by a power supply, electric controller, mechanical transmitter and a load. In terms of electrical energy consumed in Industry, electric motors are responsible for the consumption of 30-40% of that energy word-wide, 50-60% of that energy in Developed Countries and 70-75% of that energy in European Union [FC] - making them one of the most important electrical charges. Therefore, even small increases in the efficiency of EMFS will have a very significant impact in the reduction of energy consumption.

Looking to the landscape of electric motor types in the Industry, the most used is the three-phase induction motor with squirrel-cage rotor (IMs) due to its relative low cost, good efficiency and high availability - representing about 85-90% of the motors installed in the industry [FC]. These motors have a life expectancy of 12 to 20 years, in which they are repaired typically 2 to 4 times and consume energy in such a way that its energy consumption can cost up to 200 times their startup cost - being this energy consumption the exploration cost of an electric motor. Both startup cost and exploration cost are part of the Life Cycle Cost (LCC), being the maintenance cost and the exploration cost the most expensive ones in the LCC [FC] (this subject is further discussed in section 2.4). One aspect that is related to both costs is the quality of the maintenance, which is directly related to the motor's efficiency and availability. In the production sector, if an electric motor fails unexpectedly, not only is that failure a cost, it can provoke another failure elsewhere in the EMFS - or in the systems that depends of its mechanical work - and it can also mean that the whole production line will be stopped. The costs associated to these unexpected failures are called the outage costs. Then again, one aspect that can minimize these occurrences is the quality of the maintenance. Therefore, the investment in maintenance practices that improve the efficiency and availability of electric motors is very attractive to the Industry.

There are maintenance practices that allow the improvement of the efficiency and availability of electric motors, like preventive maintenance and predictive maintenance. Predictive Maintenance is a type of maintenance whose goal is to provide timely malfunction signals of the motors' status, minimizing the probability of an outage. On the other hand, if the malfunctions are detected in an early stage then the repair actions tend to be less costly, not only because it is possible to timely plan the repair, as well as the malfunction tend to stay contained to its original location, not spreading to other areas of the motor.

In an era where the Internet of Things (IoT) is being massively adopted by the industry and where the term Data Science (DS) is a buzzword, comes up the possibility of having a solution that relies on a proper trained model that uses the online data provided by sensors to provide insights and answers. With an infrastructure of this nature, it would be possible not only to predict failures as well as give real time insights of the electric motors' status. With this insights and predicted failures, it would led to an improvement of efficiency and availability, reduction in exploration costs, reduction in maintenance costs and a greater security in the decision-making process for maintenance.

Há motores que já vêm equipados com sensores, e outros não. Dos sensores que já vêm equipados com sensores, essa info pode ser aproveitada para fazer um modelo. Para aqueles que não vêm equipados com sensores, há a opção de se instalar sensores - podendo as análises destes sensores serem intrusivas ou não intrusivas. Na categoria das análises não intrusivas, existe a Electrical Signature Analysis

Guidelines: - Minimizar outages - Conseguir planear arranjos/paragens por avaria através de um modelo preditivo - conseguir maximixar o tempo de vida de um motor - conseguir aumentar a produtividade e tempo de produção de uma linha

1.2 Problem

It is up to you, the student, to read the FCT and/or UNL regulations on how to format and submit your MSc or PhD dissertation.

This template is endorsed by the FCT-UNL and even linked from its web pages, but it is not an official template. This template exists to make your life easier, but in the end of the line you are accountable for both the looks and the contents of the document you submit as your dissertation.

1.3 Proposed Solution

The proposed solution is a procedure to acquire and analyze electrical signals for condition monitoring of electrical machines through motor current signature analysis in order to get the best possible maintenance results in an industrial environment.

1.4 Contributions

1.5 Outline

Chapter 2

Understanding Three Phase Induction Motors

This chapter introduces the principal concepts that must be known when addressing Three Phase System (TPS). Section 2.1 presents an overview of what is a TPS and its properties. Section 2.2 explains the composition of a three phase electric motor - also known as three phase induction motor (IM) - as well as its working principle and several properties and characteristics. In section 2.3 it's presented the reason why this kind of motor is so important and its landscape. Furthermore, section 2.4 will present the lyfe cycle cost of these motors and approach the current maintenance strategies.

2.1 Three phase systems

A three-phase system is an AC-circuit which contains three voltage power sources. These systems have a power source with three phases and a three phase load that connects its phases to the power source phases. The generation of electric power in a three-phase system is accomplished with an electric generator, which converts mechanical energy to electric energy appropriated to this mode. Each phase has a sinusoidal voltage with a magnitude and frequency. An example of a three phase electric system squematic is reprensented in figure 2.1.

2.1.1 Motivation

A three-phase system has several advantages over a single-phase system - and that's why the three-phase system has been adopted universally for transmission of AC power.

With a three-phase system, we can get an higher power/weight ratio of alternators, since a three-phase alternator is smaller and lighter than a single phase alternator of the

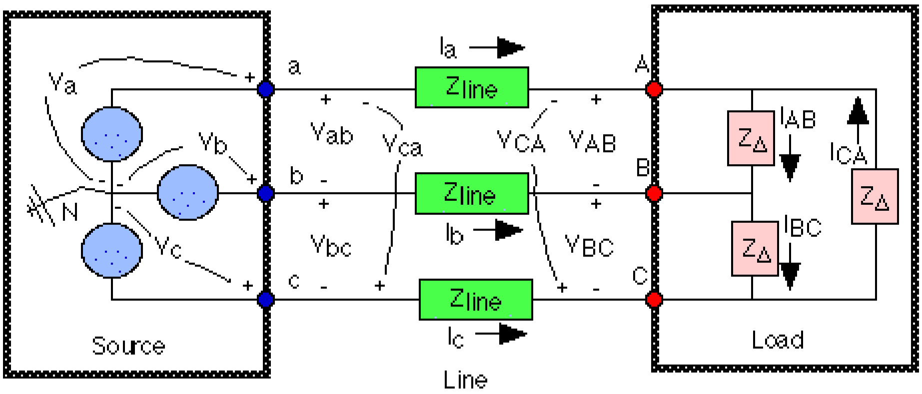

Figure 2.1: A balanced three phase circuit with a load connected in Δ

same power output. Also, the three-phase transmission system requires less copper or aluminium to transmit the same quantity of power of a specific distance than a single phase system.

In Single phase systems, the instantaneous power power is sinusoidal, therefore not constant, resulting in power vibrations. In a balanced three phase power system, though, the instantaneous power is always the same.

2.1.2 Characteristics

As the name implies, these systems have a three-phase system voltage. If the sinusoidal voltages have the same magnitude and frequency and each voltage is 120º out of phase with the other two, the voltages are said to be balanced. If the loads are such that the currents produced by the voltages are also balanced, the entire circuit is referred to as a *balanced three-phase circuit*.

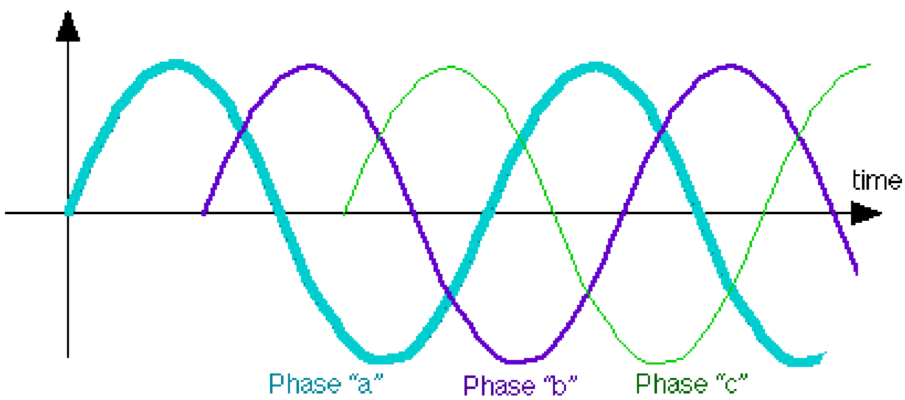

Figure 2.2: Balanced 3-Phase Variables in Time Domain

Each phase is separated by 120º, which means that if phase a has a value of 0 in 0º, then the phase b will have a value of 0 in 0º + 120º and phase c will have a value 0 in 0º + 120º + 120º, as in figure 2.2. Given that the voltages represented in the figure are the difference between each phases' potential energy and neutral's potential energy, each phase can also be noted as phase *an*, *bn* and *cn*.

2.1.3 Line-to-neutral voltage phasors

The voltage phases of figure 2.2 can be expressed in the time domain as:

$$V_{an}(t) = V_m\sqrt{2}\cos\omega t V \tag{2.1.3.1}$$

$$V_{bn}(t) = V_m\sqrt{2}\cos\omega t - 120°V \tag{2.1.3.2}$$

$$V_{cn}(t) = V_m\sqrt{2}\cos\omega t - 240°V \tag{2.1.3.3}$$

where V_{an} represents the voltage between phase a and neutral, V_{bn} represents the voltage between phase b and neutral, V_{cn} represents the voltage between phase c and neutral, V_m denotes the phasors' magnitude, ω represents the angular velocity - which is $2\pi f$, where f is the frequency of the phase.

These voltage phases can also be represented in phasors, where we can note that:

$$V_{an} = V_m\angle_{\phi} \tag{2.1.3.4}$$

$$V_{bn} = V_m\angle_{\phi-120°} \tag{2.1.3.5}$$

$$V_{cn} = V_m\angle_{\phi-240°} = V_m\angle_{\phi+120°} \tag{2.1.3.6}$$

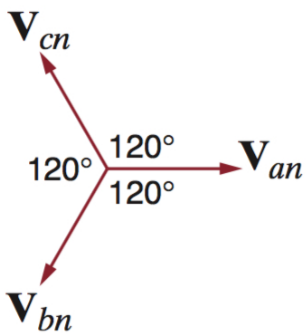

Figure 2.3: Phasor diagram for a balanced three phase voltage source

Since the phasors have the same magnitude and are the same amount of degrees apart of each other, we can also represent them as follow:

$$V_{bn} = V_{an}(1\angle_{-120°}) \tag{2.1.3.7}$$

$$V_{cn} = V_{an}(1\angle_{+120°}) \tag{2.1.3.8}$$

These phasors can be represented on a phasor diagram, as shown in figure 2.3. This differential potential between a given point (a,b or c) and the neutral is called the *line-to-neutral voltage*. An important property of the balanced voltage phasors set is the following

[Hel00, chapter 11, p. 547]:

$$V_{an} + V_{bn} + V_{cn} = 0 \tag{2.1.3.9}$$

as we can infer from figure 2.3.

The magnitude of these phasors are typically measured in root mean square (rms), which calculated by:

$$X_{rms} = \sqrt{\frac{1}{N}\sum_{i=1}^{N} x_i^2} \tag{2.1.3.10}$$

2.1.4 Line-to-line voltage Phasors

Besides the line-to-neutral voltage, there is also the line-to-line voltage - which is the difference potential between two phase lines. In the phasor diagram, this can be seen as the sum of two phasors representing the phases, as shown in figure 2.4.

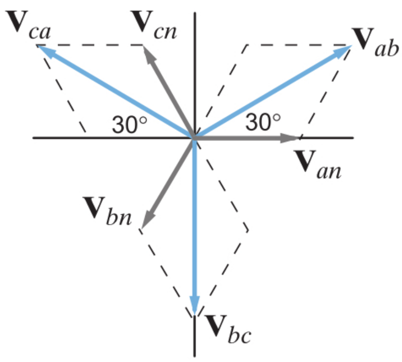

Figure 2.4: Phasor representation of line-to-line voltages

We can obtain the set of line-to-line voltages as the following [Hel00, chapter 11, p. 548]:

$$V_{ab} = \sqrt{3}V_p\angle_{\phi+30^\circ} \tag{2.1.4.1}$$

$$V_{bc} = \sqrt{3}V_p\angle_{\phi-120^\circ+30^\circ} = \sqrt{3}V_p\angle_{\phi-90^\circ} \tag{2.1.4.2}$$

$$V_{ca} = \sqrt{3}V_p\angle_{\phi-240^\circ+30^\circ} = \sqrt{3}V_p\angle_{\phi-210^\circ} \tag{2.1.4.3}$$

where V_p is the phase voltage magnitude (since the system is balanced, it can either be phase a, b or c).

2.1.5 Connection types

From the standpoint of the user who connects a balanced load to the balanced three phase voltage source, there are two possible configurations for the load. The load can be connected in *wye* (Y) - figure 2.5 - or in *delta* (Δ) - figure 2.6.

As you can notice from the figures 2.5 and 2.6, these configurations differ in the way that Y connections are all connected to the line neutral, whereas the Δ connections are connected with each two other phase - being it phase a connected to phase b, phase b connected to phase c and phase c connected to phase a. Thus, connecting the load in Y configuration will create a line impedance of Z_Y, while connecting the load in Δ will create a line impedance of Z_Δ.

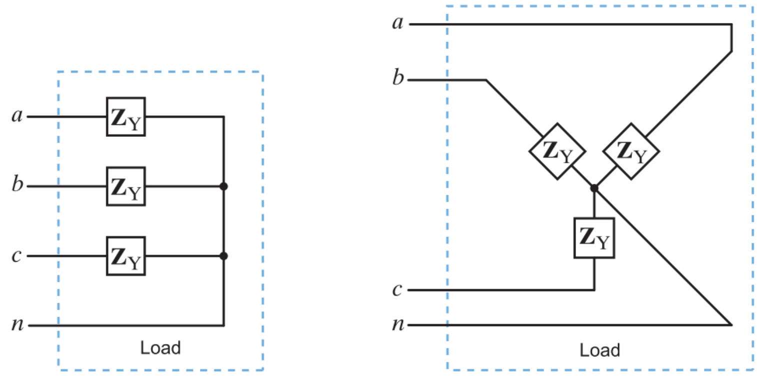

Figure 2.5: Wye connected load

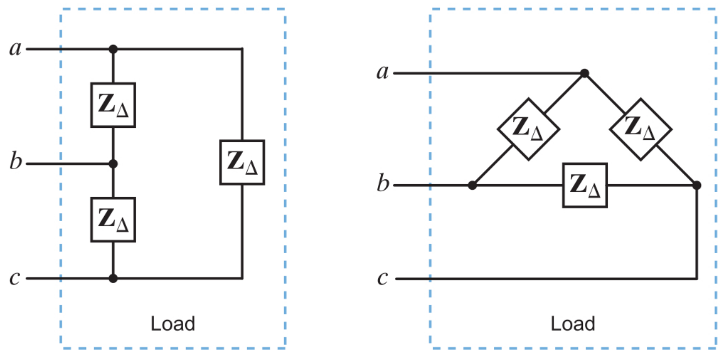

Figure 2.6: Delta connected load

In a Y connected system, the line current for the phase a is:

$$I_a = \frac{V_{an}}{Z_y} = \frac{V_p \angle \phi}{Z_y} \tag{2.1.5.1}$$

where I_b and I_c have the same magnitude but lag I_a by 120°and 240°(respectively), since it is a balanced circuit. We can also denote that the neutral current is 0, since:

$$I_n = (I_a + I_b + I_c) = 0 \tag{2.1.5.2}$$

In a Δ connected system, since the line is connected between two phases, the line voltage that connects phase a to phase b (V_{ab}) depends on the phase voltage (V_p), being the V_{ab} described by the equation 2.1.4.1, on page 8.

The line voltages for V_{bc} and V_{ca} can also be defined the same way, being it described by equation 2.1.4.2 and 2.1.4.3 (page 8), respectively.

The phase current for I_{ab} is:

$$I_{ab} = \frac{V_{ab}}{Z_\Delta} \tag{2.1.5.3}$$

The Δ impedance (Z_Δ) is three times greater than the Y impedance (Z_Y) [Hel00, chapter 11, p. 555].

2.2 Three Phase Induction Motors

A motor is a machine that transforms electric energy in mechanical energy. Such a machine can be implemented with the support of a DC power supply (DC Motor) or with a AC power supply (AC Motor). This motors will have different characteristics, but both classes have the same purpose - to transform electric energy in mechanical movement. In the AC Motor class, there are still two kind of motors - the synchronous motors and the asynchronous motors, being the last one is also known as three phase induction motor (IM).

Then, an IM can be implemented for a specific kind of phase voltage - single-phase, two-phase or three-phase. By two-phases or three-phases (polyphase) we mean that the stator contains multiple distinct windings per motor pole, driven by corresponding time shifted sine waves. Our focus will be on the three phase induction motor (IM).

These motors are globally the most used, since they have several advantages over the single phase motors. For example, a three-phase motor is self starting due to the rotating magnetic field, while a single phase motor requires a capacitator and an auxiliary winding [FC].

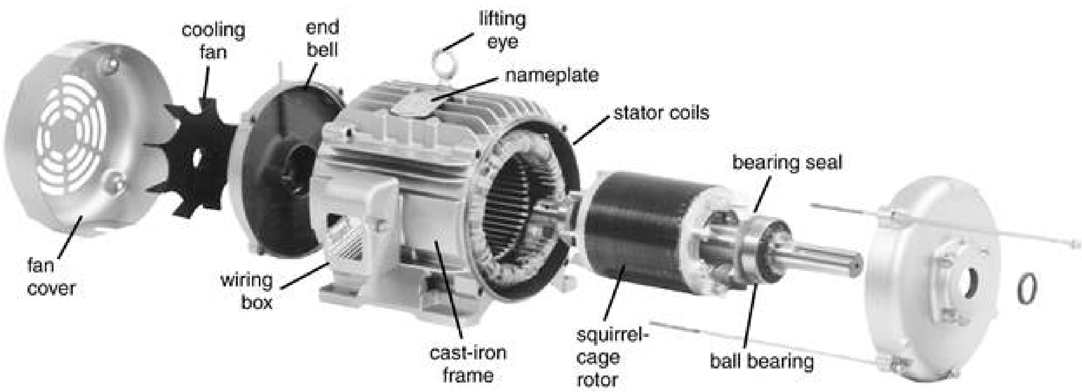

Figure 2.7: three-phase induction motor with squirrel-cage rotor (IMs)

This kind of motors has been used, traditionally, in constant and variable-speed drive applications that do not offer fast dynamic processes. Because of the recent development of several new control techniques, this situation is changing. This is due to the fact that the three-phase induction motor with squirrel-cage rotor (IMs) is much cheaper and more rugged than its competitors.

2.2.1 Main Components

The IMs is also known as asynchronous motor. This term *asynchronous* is used because the speed of the generated magnetic field is not equal to the speed of the rotor. The term *indction* is used because the rotor movements is due to the electromotive forces exerced by the generated magnetic field. In figure 2.7 (page 10) you can see the several components of the IMs. You can see that the motor is composed by a fan, an end bell, a wiring box, a stator (and stator coils), a rotor (a squirrel-cage one) and bearings. The fan will mantain the motor at an appropriated temperature, while the stator will receive current from the power source connected to the motor and the rotor will rotate, supported by the bearings - creating mechanical movement. In this section, we will only cover the stator and the rotor, which are the main components of the motors.

2.2.1.1 Stator

The stator is the static part of the motor, which contains windings connected to a three-phase energy source. The stator represented in the figure 2.8 has six coils, and will generate a magnetic field with 2 poles when connected to a three-phase power source - since it has 6 coils (3 pairs), each pair of coils will connected to each phase of the three-phase power source supply.

These pairs of coils are connected in series for each phase of the power source supply, and corresponde to the opposite poles of an electromagnet. The figure 2.9 is an example of that magnet configuration, where each A, B and C is connected to its own phase of the three phase power supply.

Figure 2.8: A stator

In spite of the stators in the figures 2.8 and 2.9 have only 6 coils and generate a magnetic field with 2 poles, a stator can generate a magnetic field with 2, 4, 6, 8, 10, 12 or more poles - but motors with more than 12 poles are not normally used. For the stator to generate as many poles as needed, it has to have a specific amount of coils configured in such a way so that the stator can generate the needed poles.

Figure 2.9: A stator configuration model

2.2.1.2 Rotor

The rotor is the rotative part of the motor and is inside the stator. In its essence, a rotor is a part of the motor where the magnetic field is induced so that it is pulled against the rotational magnetic field of the stator. Due to that purpose, the rotor has to be a conductor and has to have the hability to rotate. The IMs has a squirrel cage rotor, but there is another type of rotor - the wound rotor.

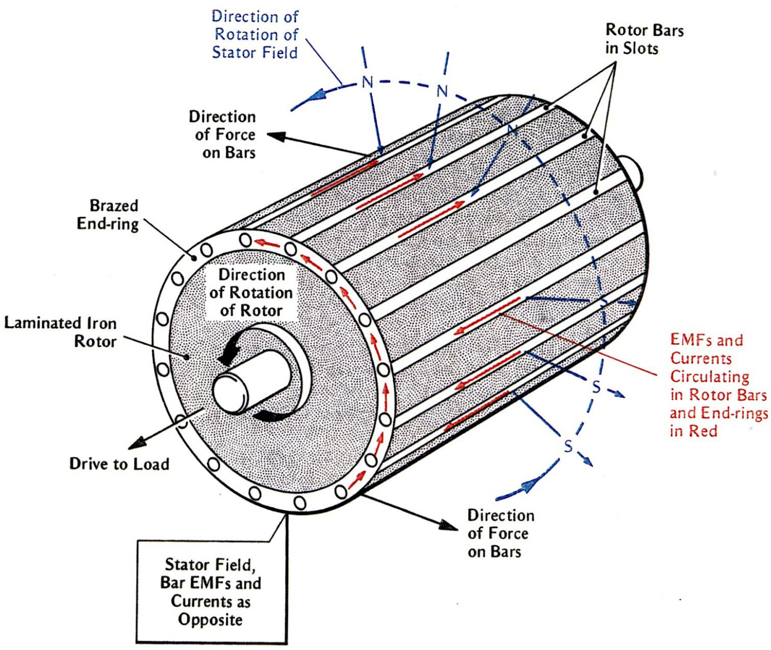

Figure 2.10: A balanced three phase circuit with a load connected in Δ

Most of the IM (up to 90%) are of squirrel cage type. As seen in figure 2.10, this type of rotor consist of a cylindrical laminated core, having parallel slots on it. These parallel slots carry rotor conductors (represented as red arrows in figure 2.10). In this type of rotor, heavy bars of copper, aluminum or alloys are used as rotor conductors instead of wires - as it would be in a wound rotor. The rotor slots are slightly skewed to achieve following advantages:

1. it reduces locking tendency of the rotor, i.e. the tendency of rotor teeth to remain under stator teeth due to magnetic attraction

2. increases the effective transformation ratio between stator and rotor

3. increases rotor resistance due to increased length of the rotor conductor

2.2.2 Working Principle

The three-phase induction motor with squirrel-cage rotor (IMs) - as well as the others three phase induction motor (IM) - working principle is based on the generation of a rotating magnetic field by the stator. The windings that exist in the stator will create several electromagnetic coils, as shown in figure 2.9. These coils are power supplied by a three phase AC source, which have the property of being sinusoidal - changing the value between positive and negative over time. This will generate a rotating magnetic field that will induce and electromotive force on the rotor. This phenomena can also be view as an rotating magnet around the rotor.

Since the rotor has conductive components and the rotating magnetic field will create magnetic flux changes in the rotor, these magnetic flux changes will create a current in the rotor in such a way that it will create a magnetic field in the opposite direction of the magnetic flux change (Faraday-Lenz law). This will create a magnet in the rotor that will try to align itself with the rotating magnetic field. Since the velocity in which the rotor rotates is lower than the rotational velocity of the magnetic field, the rotor will never align with the rotating magnetic field, creating the mechanical movement.

2.2.3 Properties

2.2.3.1 Number of poles and Synchronous Speed

The Synchronous Speed is the speed at which the rotational magnetic field rotates. This speed is constant, and its given by:

$$n_s = \frac{120f}{p}(rpm) \tag{2.2.3.1}$$

where f is the voltage frequency and p is the number of poles in the stator.

From the expression 2.2.3.1 we can see that the greater is the pole quantity (always in pairs), the lower is the rotating magnetic field frequency. Therefore, the max speed of an IM supplied by a 50hz power source is 3000rmp, due to the fact that the minimum value of poles number is 2.

2.2.3.2 Slip

In an induction motor, the rotors rotational speed is not equal to the synchronous speed. This difference between synchronous speed and rotor speed is commonly referred to as the *slip* of the rotor. We can measure this split in rpms by subtracting the rotor speed to the synchronous speed, being it has follow:

$$n_s - n \tag{2.2.3.2}$$

where n_s is the synchronous speed and n is the rotor speed.

However, *slip* is more usually expressed as a fraction of synchronous speed. The *factional slip s* is

$$s = \frac{n_s - n}{n_s} \tag{2.2.3.3}$$

where n_s is the synchronous speed and n is the rotor speed.

The slip will depend of mechanical friction and the load.

2.2.3.3 Efficiency and Losses

2.2.3.4 Torque

2.2.3.5 Motor Start

At the start, the rotor is stationary ($n = 0$), the split (equation 2.2.3.3) is 1. Then, the field produced by the rotor currents revolves at the same speed as the stator field, creating a starting torque. This torque will tend to turn the rotor in the direction of rotation of the stator-inducing field. If this torque is sufficient to overcome the opposition to rotation created by the shaft load, the rotor will come up to its operating speed.

Rever isto, que n tenho a certeza se ao início é preciso mais corrente ou menos corrente, e até acho que é menos corrente

Therefore, the initial torque has to be bigger than the nominal torque - where the nominal torque is the torque under which the motor has been constructed to operate.

To create a start torque, more current is needed than the nominal current. If the motor continues to operate with this higher current, it can have adverse effects to the motor (deteriorating insulation due to overheating) as well as to the electrical installation (triggering the protection device).

Therefore, alternatives methods are needed for starting motors. The two most used are *start-delta* starters and

2.2.3.6 Motor Speed Control

2.3 Relevance and Landscape of Three Phase Induction Motors

Reler a parte dos tipos de motores elétricos industriais para fazer o enquadramento de onde se situa o MIs

Tipos de motor elétricos industriais [FC]

2.4 Three Phase Induction Motors' Maintenance and Life-cycle

2.5 Summary

Chapter 3

State of the Art

3.1 Predictive Maintenance by Electrical Signature Analysis to Induction Motors

3.2 Summary

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Appendix A

A Computer Science's perspective to understand Electric Motors

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