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Title:

Spectral analysis of the eccentricity defect in a synchronous motor

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First praise is to Allah, the Almighty, on whom ultimately, we depend for sustenance and guidance

To my parents Houcine and Latefa
To my sisters Nor El Houda and Narimene
To my nephew Yazen
To my friends Chalabi Meriem, Boudjema Asma and Razika Bouziani
To the most patient supervisor Mr Nekrouf Djilali
To all my beloved ones

List of symbols and abbreviation

List of symbols:

NS: the synchronous speed of the stator magnetic field in RPM

P: the number of poles on the stator

f: the supply frequency in Hertz

fs: nominal frequency

List of abbreviation:

RPM: Rotation Per Minute

ARM: Amplitude Recovery Method

FFT: Fast Fourier Transform

PMSM: permanent magnetic synchronous Motor

IGBT: In Saluted-Gate Bipolar Transistor

PSD: Power Spectral Density

FD: Fault Diagnosis

CMFD: Condition Monitoring and Fault Diagnosis

DFT: Discrete Fourier Transform

DSP: Digital Signal Processing

AC: Alternating Current

DC: Direct Current

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Chapter IV: Bench Test

Introduction:

Multiple studies on failures in the electrical system exist long time ago developed with the implementation of technologies, and also based on the experiences gathered from the industry. Maintenance of electrical systems was the main reason to be aware and launch investigation to know the source of divert breakdown. Once that is figured out it will be much easier to solve the problem or fix the failure and lessen the impact on the whole machine and eventually the system. Maintenance is a way of keeping system afloat and avoid unnecessary costs. But within the said failures there's two critical ones which are: eccentricity and demagnetization, they have significant impacts on the performance of the machine and can lead to decreased efficiency, increased maintenance costs, and even equipment failure.

The methods of diagnostics of electric machines are gaining immense popularity and significance. Not all enterprises can continuously upgrade their equipment due to lack of funds. They are forced to reduce the budget for re-equipment and use the machines that long ago need repair. Any electric machine, even with proper care, requires repair. If you do not perform repairs on time, then there may be emergencies that are life-threatening for maintenance personnel. Solving this problem, they resort to a constant assessment of the technical condition of the machine. Our work deals with the implementation of one of the methods of such the estimation, carried out by spectral analysis of the stator current of a synchronous machine. The instantaneous values of the stator currents are decomposed into a harmonic series by means of the coefficients of the Fourier series. Analysis of the spectrum allows us to state that any additional harmonic causes a clear fault in the machine. This approach is as much more objective than other methods.

Spectrum analysis is a powerful tool used in the analysis of PMSM (Permanent Magnet

Synchronous Motor). It helps to identify the motor's frequency components in different stages of operation. Owing to the harmonic content of the motor's magnetic field, there exists a variety of spectrum components related to the fundamental frequency of the motor. Hence, the major aim of spectrum analysis is to identify these harmonic frequencies within the motor through a frequency spectrum.

In this dissertation we’re going to use spectral analysis which involves FFT operated on ‘MATLAB’ but before that let’s get a better knowledge of a common defect to get a closer look of what we’re dealing with here.

Chapter I:
Diagnosis and electrical machine defects

Chapter I: Diagnosis and electrical machine defects

I.1. Generalities:

Electrical machines are widely used in many industrial applications, and their unexpected failures could lead to a temporary shutdown or disruption of the production process, thus resulting in economic losses. Therefore, it is of great significance to evaluate the overall health status of industrial machines as early as possible and in particular to detect, diagnose, and prognosticate developing faults on the sub-systems components of machines. The development of effective and reliable machine fault detection, diagnostics, and prognostics tools has attracted extensive attention in academia and industry. The goal of this topic is to bring researchers and industrial practitioners together to share their research findings and present ideas that are relevant in the field of industrial machine faults detection, diagnosis, and prognosis.[5]

Many mechanical failures in electromechanical machines are related to their bearings. The origin of bearing-centred failures includes vibration, misalignment and shaft distortion. Also, other faults related rotor problems appear with cracked or broken rotor bars, broken end rings, demagnetized rotor magnets or broken rotor magnets.

The early detection of anomalies in the electrical or mechanical parts of electric motors is important to the safe and economic operation of an industrial process. Early fault detection techniques, which are defined for these motors, can significantly reduce the maintenance costs. Thus, condition monitoring studies are proposed for fault diagnosis in electric motors, among which spectral analysis is accepted as one of the outstanding techniques in the literature condition monitoring of rotor problems such as demagnetization and eccentricity in permanent-magnet synchronous motors (PMSMs) are essential for guaranteeing high motor performance, efficiency, and reliability. However, there are many limitations to the offline and online methods currently used for PMSM rotor quality assessment [8].

I.2. Basic Principles of Motor Fault Diagnosis:

During the operation of the motor, some structures and components will gradually deteriorate, causing the motor to appear abnormal; parameters are measured through various detection techniques; in order to identify faults, a large amount of experience must be accumulated to form a database or expert system, so as to achieve predictive maintenance without affecting production. At present, the common faults of motors include two categories: mechanical faults and electrical faults.[9]

At present, the signals collected during the operation of the motor are mostly current signals. Correspondingly, the stator current analysis method is relatively mature as a method of motor fault signal analysis. Normally, the ideal frequency of the stator current of the synchronous motor should be the same as the frequency of the power supply, which is a single frequency. The theory of some scholars has confirmed that when the rotor circuit fails, the stator current spectrum is at a position that is twice the slip frequency (±2sf) from the power frequency.

However, the eccentricity of the air gap may cause uneven magnetic permeability along the circumferential direction of the air gap and will lead to asymmetric distribution of the magnetic field in the air gap; this asymmetric magnetic field distribution will be reflected as harmonics in the stator current. Cameron, Thomson, and Dow’s research also proved that the stator current spectrum, which represents the eccentricity of the air gap, can identify this unique spectral component, and the frequency of these components is:

$$f_{ag} = \{(n_{rt}Z_2 \pm n_d)\frac{1-s}{p} \pm n_{\omega}\} f_0 \quad (\mathrm{Hz})$$

Among them, f_0 is the power frequency, n is any integer, z_2 is the number of rotor slots, s is the slip, p is the number of pole pairs, *nw* is an odd integer, and *na* is an arbitrary integer (*na*=0, for static eccentricity; *na*=1, 2, … for dynamic eccentricity).[9]

Nowadays, the motor structure is gradually becoming more complex, and a non-invasive signal acquisition method is required for the special determination of motor fault characteristics; in this context, the acquisition of vibration signals of motor faults gradually replaces the acquisition of current and voltage. Motor faults are often reflected in abnormal vibration, and sometimes the type of fault can be preliminarily determined by the frequency of its vibration; the following are some typical fault vibration characteristics:

- Electromagnetic vibration of the stator is abnormally generated: under normal conditions, the electromagnetic vibration frequency of the stator should be the product of the rotating magnetic field frequency (*f/p*) multiplied by the electrodynamic series (2p), that is, twice the power frequency. When the three-phase magnetic field of the stator is asymmetrical, the magnetic field of the stator is asymmetrical, resulting in abnormal vibration; The stator core and coil are loose, which increases the electromagnetic vibration and electromagnetic noise of the stator; in addition to the 2f basic component in the vibration spectrum, there are also, harmonic components of 4f, 6f, and 8f; the foot screws of the motor become loose, the stiffness of the frame is reduced, the motor will generate resonance in the vicinity of the frequency close to 2f, and the vibration of the stator will increase, resulting in abnormal vibration.[9]

- Electromagnetic vibration caused by the static eccentricity of the air gap: the static eccentricity of the air gap will often generate a large unilateral magnetic pulling force in the air gap of the motor, resulting in a smaller distance between the stator and the rotor or even friction with each other. The electromagnetic vibration generated by the eccentricity of the static air gap is twice the frequency of the power supply, which is indistinguishable from the electromagnetic vibration generated by the abnormal stator. [9]

- Electromagnetic vibration caused by air gap dynamic eccentricity: when the rotating shaft is deflected or the iron core of the motor is not round, the air gap dynamic eccentricity will occur, and the position of the eccentricity is not fixed relative to the stator and fixed relative to the rotor. For the eccentric point, the speed of the rotating magnetic field exceeding the rotor speed is $[f/p - (1 - s)\ f/p] \ * 2p = 2sf,$ so the electromagnetic vibration generated is f/p frequency vibration, and 1/2sf is the periodic beat pulsation.[9]

- Vibration caused by abnormal rotor conductor: the cage bar is broken, the electrical imbalance of the rotor circuit of the wound asynchronous motor is caused, and its properties are the same as the eccentricity of the dynamic air gap; the vibration waveforms are also similar and difficult to distinguish. When the load exceeds 50%, the phenomenon is obvious; in the spectrum diagram, the side frequency of +2sf will appear on both sides of the fundamental frequency; according to the relationship between the side frequency and the fundamental frequency amplitude, the degree of the fault can be effectively judged.

Fault diagnosis (FD) is called condition monitoring and fault diagnosis (CMFD); it can lead to system malfunction, and this degraded state of the system is called failure. The purpose of fault diagnosis technology is to judge the system state according to the monitoring characteristic information, guide production, improve production efficiency, and stabilize production operation status. In a complex system, if a key device cannot continue to operate due to failure, it often affects the entire system and causes huge losses. Therefore, fault diagnosis technology is one of the key technologies for the safe and reliable operation of complex industrial processes and equipment and has extremely important research significance. [9]

The current fault diagnosis methods mainly include the following three categories:

- fault diagnosis methods based on mathematical models.
- fault diagnosis methods based on signal processing.
- fault diagnosis methods based on artificial intelligence.
- Method of strong tracking filter**:** This method is mainly developed on the basis of the theory of strong tracking filter and is a highly systematic parameter deviation fault diagnosis method. The method can diagnose step-type, slow-drift-type, and even pulse-type faults. This method can even be combined with nonlinear suboptimal Gaussian filtering, realize the online estimation of the fault amplitude of the nonlinear system, and it creates conditions for further realizing fault-tolerant control. [9]
- The method of parameter tracking adaptive observer**:** this method abstracts the state equation of the dynamic system and observes it and obtains the corresponding state deviation equation and system deviation equation. This method designs an adaptive parameter tracking observer, which makes the observer tracking insensitive to noise; the state of the actual object can be well estimated, and the system fault diagnosis can be carried out by generating the state and system residuals.[9]

I.3. Fault of eccentricity:

Fault of eccentricity occurs when the rotor part of the motor is not in its ideal position with respect to the stator. This displacement can be due to various reasons such as manufacturing errors or wear and tear of the bearings over time.

Rotor eccentricity commonly exists in permanent magnet synchronous machines (PMSMs) due to improper assembly, excessive vibration, and continuous operation. Consequently, the unbalanced magnetic pull, introduced by rotor eccentricity, may lead to unfavourable noise, vibration, and even bear damage, which makes the detection of eccentricity meaningful.

Although motor current signal analysis is the most popular method to diagnose eccentricity based on the amplitudes of sideband component, it is a big challenge to classify different types of centricities and quantify the eccentric ratio due to the spatiotemporal coupling effect [1]. In other words, eccentricity is the result of manufacturing imperfections like unbalanced mass, poor alignment and excessive tolerances. 60% of the faults that appear in electrical machines are mechanical and 80% of them can create eccentricity [4]. Eccentricity can also be caused by several factors including manufacturing defects, improper installation, or wear and tear over time.

I.3.1. Effects of Eccentricity in Synchronous Motor:

1. **Uneven Air Gap:** As the rotor is not aligned to the rcente of the stator, there is an uneven air gap between the two. This results in variations in the magnetic field and causes the rotor to vibrate.
2. **Increase in Noise and Vibration:** Due to the uneven air gap, the synchronous motor produces more noise and vibration than a properly aligned motor.
3. **Reduction in Efficiency:** The eccentricity in synchronous motor increases the losses due to friction and windage, which ultimately reduces the efficiency.
4. **Increased Heating:** The uneven air gap can cause the rotor to rub against the stator, leading to increased temperature and accelerated aging of the motor.
5. **Risk of Rotor Failure:** The eccentricity can cause the rotor to be unbalanced, which can lead to premature failure of the motor. In a healthy motor, the rotor is center-aligned with the stator bore, and the rotor’s center of rotation is the same as the geometric center of the stator bore, as illustrated in Figure I.1.

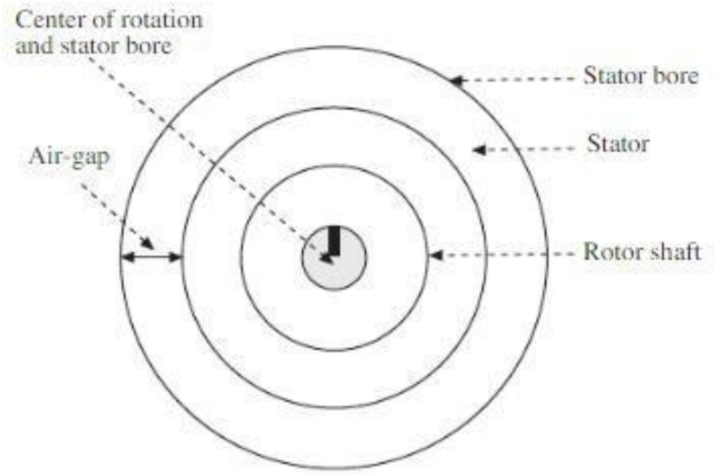


Figure I.1. Healthy motor

I.3.2. Types of eccentricity in synchronous motor:

1-**Static Eccentricity:** It is the condition where the center of the rotor and stator do not coincide, and the air gap is non-uniform. This can be caused by incorrect assembly, faulty bearing, incorrect machining, or shrinkage of the rotor due to high temperature.

2-**Dynamic Eccentricity:** It occurs when the rotor shaft is not straight, and it bends while rotating due to unbalanced magnetic forces, misaligned bearings, or shaft deflection. In such a condition, the air gap varies with the rotation, causing pulsating torque and causing additional heat in the rotor.

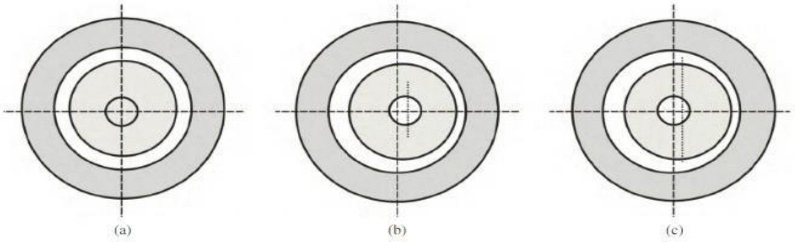


Figure I.2. Types of eccentricity faults: (a) centric rotor, (b) static eccentricity, (c) dynamic eccentricity

To highlight that there is Techniques such as current signature analysis and vibration analysis that can be used to detect and diagnose eccentricity in synchronous motors.

I.4. Different diagnosis techniques:

The history of fault diagnosis, condition monitoring and protection is also old than electrical appliances. Typically, monitoring and diagnosis require detection and analysis of signals containing specific information (symptoms) that characterize the degradation of the machine. Thorsen et al mainly classify these parameters such as: Mechanics (vibrations, acoustics, speed fluctuations, ...), Electromechanical (currents, torque, electromagnetic leakage flow, ...), Thermal and chemical (monitoring of insulating oil particles gas analysis). In the following paragraphs, a brief description of the principles of some of these Techniques is presented:

I.4.1. Diagnosis by vibration analysis:

Vibration analysis is the most widely used diagnostic technique in the industry. This technique is based on vibration signal analysis to provide information on the state of the machine. These signals can be picked up by vibration sensors such as accelerometers placed on the motor bearings in axial, vertical and radial directions as shown in the following figure

Figure I.5. Triaxial accelerometer and its location on a synchronous motor

Unfortunately, the cost of these sensors is relatively high, as well as their installation requires competent personnel to have reliable measurements. Moreover, this technique can't be used only to diagnose large units that work on processes Critical and sensitive given the cost of this type of sensor.[10]

I.4.2. Diagnosis by magnetic flux analysis:

Monitoring the air gap flow of electrical machines can also give accurate and reliable information on the condition of the machine. Any change of air gap, winding, of voltage and current, is reflected in the frequency spectra of the air gap. So, the signature of each defect regardless of its type is manifested in the air flow of the importance of flow analysis as a diagnostic technique. Measuring air gap flow can be made by coils placed either outside or inside. The external coils are used when the machine is already in service. The use of inner coils is very difficult to set up. In addition, for machines with a small air gap, the installation of this type of coils may require significant modifications, difficult to put in place and expensive.[10]

I.4.3. Diagnosis by stator current analysis:

Stator current analysis has been the most promising technique in recent years, and this is due to several advantages; among these advantages we can mention:

- It does not require expensive and bulky equipment but only a current (hall effect probe or current transformer);
- It does not require a specific location of the current sensors. Indeed, it can be placed at any position between the power supply and the motor;
- It has a spectrum rich in harmonics. The frequency position of some of these harmonics provides us with useful information about the condition of the machine and the type of defect;
- It also makes it possible to monitor the severity of the defect detected by monitoring the amplitude of the characteristic harmonic.[10]

Chapter II:
Signal processing methods (FFT)

Chapter II: Signal processing methods (FFT)

II.1. Introduction to FFT:

This chapter discusses the fast Fourier transform (FFT), named after Jean Baptiste Joseph Fourier, the famous French mathematician and physicist, focuses on discrete Fourier transform (DFT), and presents Fourier transforms of “real” signals. It illustrates various experiments based on Fourier's theory and other formulae, using ‘MATLAB’, a numerical calculation tool that works under any operating system and is supplied with plenty of compatible toolboxes for signal processing and graphics. It provides us with some simple formulae that can be used to calculate a full DFT of an N-point vector and shows how each time the number of points is doubled calculation time of a DFT is multiplied by four. An attempt to differentiate between the algorithm of FFT and DFT has been made. FFT is not a new concept but a common and efficient way of calculating a DFT on a computer or microprocessor. How FFT offers a great advantage when N starts to increase is illustrated. Windowing functions relating to FFT—which will slowly reduce the amplitude of the signal to zeros on both ends and other direct or indirect applications of the FFT and how it allows us to get signals out of the noise are discussed.[18]

Fast Fourier transform — FFT — is a speed-up technique for calculating the discrete Fourier transform — DFT, which in turn is the discrete version of the continuous Fourier transform, which indeed is an origin for all its versions. So, historically the continuous form of the transform was discovered, then the discrete form was created for sampled signals and then an algorithm for fast calculation of the discrete version was invented.[16]

The fast Fourier transform is a computational tool which facilitates signal analysis such as power spectrum analysis and filter simulation by means of digital computers. It is a method for efficiently computing the discrete Fourier transform of a series of data samples (referred to as a time series). In this work, the discrete Fourier transform of a time series is defined, some of its properties are discussed, the associated fast method (fast Fourier transform) for computing this transform is derived, and some of the computational aspects of the method are presented. Examples are included to demonstrate the concepts involved.[13]

The fast Fourier transform (FFT) is a discrete Fourier transform algorithm which reduces the number of computations needed for N points from $2N^2$ to 2NlgN, where lg is the base-2 logarithm.

FFTs were first discussed by Cooley and Tukey (1965), although Gauss had actually described the critical factorization step as early as 1805 (Bergland 1969, Strang 1993). A discrete Fourier transform can be computed using an FFT by means of the Danielson-Lanczos lemma if the number of points N is a power of two. If the number of points N is not a power of two, a transform can be performed on sets of points corresponding to the prime factors of N which is slightly degraded in speed. An efficient real Fourier transform algorithm or a fast Hartley transform (Bracewell 1999) gives a further increase in speed by approximately a factor of two. Base-4 and base-8 fast Fourier transforms use optimized code, and can be 20-30% faster than base-2 fast Fourier transforms. prime factorization is slow when the factors are large, but discrete Fourier transforms can be made fast for N=2, 3, 4, 5, 7, 8, 11, 13, and 16 using the Winograd transform algorithm (Press et al. 1992, pp. 412-413, Arndt).

Fast Fourier transform algorithms generally fall into two classes: decimation in time, and decimation in frequency. The Cooley-Tukey FFT algorithm first rearranges the input elements in bit-reversed order, then builds the output transform (decimation in time). The basic idea is to break up a transform of length N into two transforms of length N/2 using the identity

$$\sum_{n=0}^{N-1} a_n\, e^{-2\pi i n k/N} = \sum_{n=}^{\frac{N}{2}-1} a_{2n}\, e^{-2\pi i\,(2n)\,k/N} + \sum_{n=}^{\frac{N}{2}-1} a_{2n+1}\, e^{-2\pi i(2n+1)k/N}$$

$$= \sum_{n=0}^{\frac{N}{2}-1} a_n^{even}\, e^{-2\pi i n k/(\frac{N}{2})} + e^{-2\pi i k/N} \sum_{n=}^{\frac{N}{2}-1} a_n^{odd}\, e^{-2\pi i n k/(\frac{N}{2})}$$

sometimes called the Danielson-Lanczos lemma. The easiest way to visualize this procedure is perhaps via the Fourier matrix.

The Sande-Tukey algorithm (Stoer and Bulirsch 1980) first transforms, then rearranges the output values (decimation in frequency).[23]

Signal processing methods refer to a set of techniques and algorithms used to manipulate and extract information from signals. Signals can be any form of useful information such as sound, images, and data. Signal processing methods are used in a wide range of applications including communications, image processing, speech recognition, and control systems among others.

Some of the common signal processing methods include Fourier analysis, filter design and implementation, statistical signal processing, wavelet analysis, and digital signal processing.

Fourier analysis is used to transform signals from the time domain to the frequency domain, allowing for analysis of the signal's spectrum.

Filter design and implementation involves designing filters that can modify a signal by amplifying or attenuating certain frequencies while leaving others unchanged.

Statistical signal processing involves using statistical tools to extract information from signals, including estimation and detection of signals in noisy environments.

Wavelet analysis is used for analysis and compression of signals in both time and frequency domains.

Digital signal processing involves processing signals using digital hardware or software, typically, through mathematical operations and algorithms

FFT stands for Fast Fourier Transform, which is an algorithm used to transform a time-domain signal into its corresponding frequency-domain representation. It is widely used in signal processing applications such as audio processing, image processing, and data analysis.

The FFT algorithm reduces the computation time required to perform a Fourier transform, which is a mathematical technique used to analyse signals. It works by breaking down the signal into smaller components of different frequencies and performing calculations on those components. The output of an FFT algorithm includes the magnitude and phase of each frequency component in the input signal.

The main advantages of FFT are its speed and efficiency in performing signal analysis. It is also used in many scientific and engineering fields such as astronomy, geology, and physics, to analyse and interpret complex data.

FFT, or Fast Fourier Transform, is a widely used signal processing method for analysing and manipulating signals in a frequency domain. It is based on the mathematical concept of Fourier series and can decompose a complex signal into its constituent sine and cosine waves, which can then be processed and analysed individually.

FFT is particularly useful in applications such as audio and image processing, where signals are often represented as a series of discrete samples. By performing an FFT on such signals, one can analyse the frequency content of the signal, identify specific frequencies and their amplitudes, and manipulate the signal to enhance or filter out certain frequency components.

Aside from its application in signal processing, FFT is also useful in other areas such as cryptography, data transmission, and even weather forecasting. Its efficiency and accuracy have made it a popular tool in many different fields.

II.2. understanding FFT:

Fourier transform is an integral of the form:

$$F(u) = \int_{-\infty}^{\infty} f(x) e^{-i2\pi ux}\, dx \qquad (1)$$

The transform operates in complex domain. Recall, that imaginary exponent could be written as:

$$e^{i\varphi} = \cos\varphi + i\sin\varphi \qquad (2)$$

For sampled function continuous transform (1) turns into discrete one:

$$F_n = \sum_{k=0}^{N-1} f_k e^{-i\left(\frac{2\pi}{N}\right)kn} \qquad (3)$$

Expression (3) is discrete Fourier transform — DFT. Here $\{f_0, f_1, \ldots, f_{N-1}\}$ is input discrete function and $\{F_0, F_1, \ldots, F_{N-1}\}$is result of Fourier transform.

It is easily could be seen that to program DFT it is enough to write double loop and just calculate sums of products of input samples and imaginary exponents. The number of operations required is obviously of O(N2) order. But due to transform properties it is possible to reduce the number of operations to the order of O(N log2 N). Now, let us explore tricks we can use to speed-up calculations.

Let us put N = 8 and write down our DFT:

$$F_n = f_0 + f_1 e^{-i\left(\frac{2\pi}{8}\right)n} + f_2 e^{-i\left(\frac{2\pi}{8}\right)2n} + f_3 e^{-i\left(\frac{2\pi}{8}\right)3n} + f_4 e^{-i\left(\frac{2\pi}{8}\right)4n} + f_5 e^{-i\left(\frac{2\pi}{8}\right)5n} + f_6 e^{-i\left(\frac{2\pi}{8}\right)6n} + f_7 e^{-i\left(\frac{2\pi}{8}\right)7n} \qquad (4)$$

Easily could be seen we can split the sum into two similar sums separating odd and even terms and factoring out the latter sum:

$$F_n = \left[f_0 + f_2 e^{-i\left(\frac{2\pi}{8}\right)2n} + f_4 e^{-i\left(\frac{2\pi}{8}\right)4n} + f_6 e^{-i\left(\frac{2\pi}{8}\right)6n}\right] + e^{-i\left(\frac{2\pi}{8}\right)n}\left[f_1 + f_3 e^{-i\left(\frac{2\pi}{8}\right)2n} + f_5 e^{-i\left(\frac{2\pi}{8}\right)4n} + f_7 e^{-i\left(\frac{2\pi}{8}\right)6n}\right] \qquad (5)$$

Now we can split the sums in brackets again:

$$F_n = [(f_0 + f_4 e^{-i(\frac{2\pi}{8})4n}) + e^{-i(\frac{2\pi}{8})2n}(f_2 + f_6 e^{-i(\frac{2\pi}{8})4n})] + e^{-i(\frac{2\pi}{8})n}[(f_1 + f_5 e^{-i(\frac{2\pi}{8})4n}) + e^{-i(\frac{2\pi}{8})2n}(f_3 + f_7 e^{-i(\frac{2\pi}{8})4n})] \qquad (6)$$

Thus, we have 3 — log2 8 — levels of summation. The deepest one in parenthesis, the middle one in brackets and the outer one. For every level exponent multiplier for the second term is the same.

$$F_n = [(f_0 + f_4 e^{-i\pi n}) + e^{-i(\frac{\pi}{2})n}(f_2 + f_6 e^{-i\pi n})] + e^{-i(\frac{\pi}{4})n}[(f_1 + f_5 e^{-i\pi n}) + e^{-i(\frac{\pi}{2})n}(f_3 + f_7 e^{-i\pi n})] \qquad (7)$$

And now the most important observation one can make to get speed-up: periodicity of the exponent multipliers.

$$e^{i(\varphi+2\pi)} = e^{i\varphi} \qquad (8)$$

For the exponent multiplier $e^{-i\pi n}$ in parenthesis period is n = 2, which means sums in parenthesis are exactly the same for n = 0, 2, 4, 6 and for n = 1, 3, 5, 7. It means on deepest level in parenthesis we need 4 × 2 = 8 — number of sums times period — sums in total. And note, since n = 1, 3, 5, 7 corresponds to the half of the period π, exponent multiplier is the same as for n = 0, 2, 4, 6 but with the opposite sign

$$e^{i(\varphi+\pi)} = -e^{i\varphi} \qquad (9)$$

Indeed, they are 1 for n = 0, 2, 4, 6 and −1 for n = 1, 3, 5, 7:

For the exponent multiplier $e^{-i(\pi/2)n}$ in brackets the period is n = 4, which means we have

$$e^{-i\pi n} = \begin{cases} 1 \ for\, n = 0,2,4,6 \\ -1\, for\, n = 1,3,5,7 \end{cases} \tag{10}$$

the same sums for pairs n = 0, 4; n = 1, 5; n = 2, 6 and n = 3, 7. It means on the middle level in brackets we have 2 × 4 = 8 sums and the second half of them could be received again by changing sign in the first half of them — due to the fact distance between n and n + 2 is π. Thus, for n = 0, 4 the factor is 1 and for n = 2, 6 it is −1; for n = 1, 5 it equals −i and for n = 3,7 it is i.

$$e^{-i\left(\frac{\pi}{2}\right)n} = \begin{cases} 1 \; for \; n = 0,4 \\ -i \; for \; n = 1,5 \\ -1 \; for \; n = 2,6 \\ i \quad for \; n = 3,7 \end{cases} \qquad (11)$$

On the outer level we have just one sum for every transform component, and the period of the exponent multiplier $e^{-i(\pi/4)n}$ is 8. Which gives us 1 × 8 = 8 sums and the second half of them could be received by changing sign in the first half.

$$e^{-i\frac{\pi}{4}n} = \begin{cases} 1 & \text{for } n = 0 \\ \frac{1}{\sqrt{2}} - i\frac{1}{\sqrt{2}} & \text{for } n = 1 \\ -i & \text{for } n = 2 \\ -\frac{1}{\sqrt{2}} - i\frac{1}{\sqrt{2}} & \text{for } n = 3 \\ -1 & \text{for } n = 4 \\ -\frac{1}{\sqrt{2}} + i\frac{1}{\sqrt{2}} & \text{for } n = 5 \\ i & \text{for } n = 6 \\ \frac{1}{\sqrt{2}} + i\frac{1}{\sqrt{2}} & \text{for } n = 7 \end{cases} \qquad (12)$$

So, on every calculation level we have 8 sums. In terms of N it means we have log2 N levels and N sums on every level, which gives us O(N log2 N) order of number of operations. On the other hand, having the constant number of sums on every level means we can process data in-place.

In summary, we have got fast Fourier transform — FFT. Now it is time to develop step-by-step instruction list to be carved in code. [16]

II.3. *Simplified Explanation of Fourier Analysis:*

In general terms, the foundation of the frequency domain is made up of sine and cosine waveforms. The Fourier series works on the principle that we can construct any signal by the sum of a series of sine and cosine waves.

Algorithms can analyse (or separate) time data into components by projecting it onto these sine and cosine waveforms. The set of these components for the given signal is a transform.

The Fourier transform takes apart data using projections. In practice, it digitizes the signal, x, into a sequence of N numbers (x_n, n=1 to N) with a time interval of Δt between samples. The resulting set of components is the Fourier transform of x(t). [24]

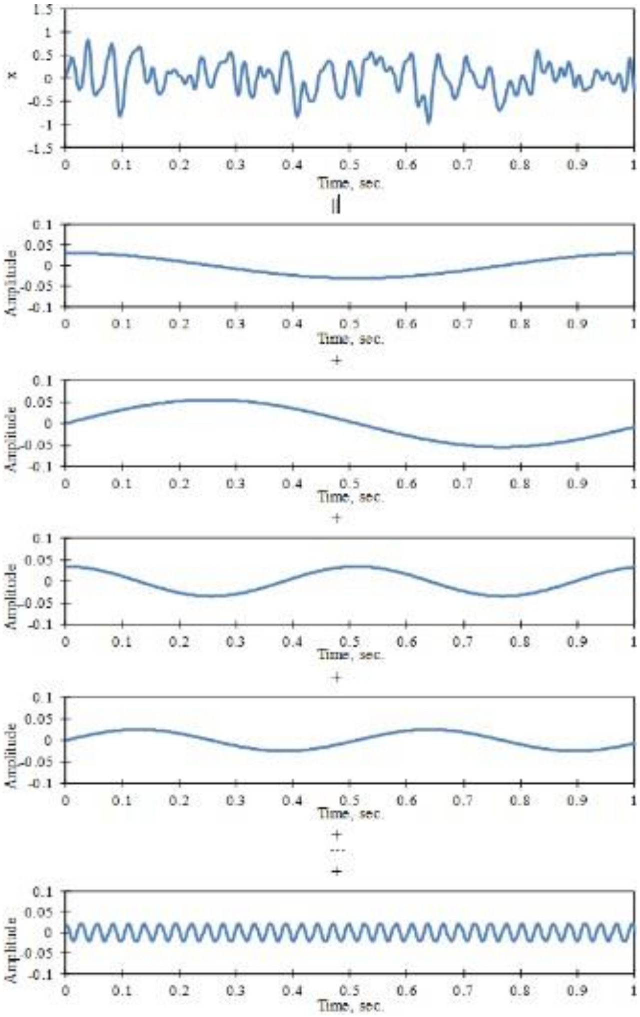


Figure II.1. Fourier series construction of a time signal

II.4. Importance of FFT:

FFT is important because it allows us to analyse signals in the frequency domain, which can reveal important information about the signal. For example, we can use FFT to analyse the spectrum of an audio signal to determine which frequencies are present, and to apply filters to remove unwanted frequencies.[21]

II.5. some applications of FFT:

FFT is used in a wide range of applications some of them are the following:

- **Image Processing:** FFT is used extensively in image processing applications such as image filtering, deconvolution, compression and enhancement. FFT can be used to decompose an image into its frequency components and reconstitute it back again from its frequency domain representation.
- **Audio Processing:** FFT can be used to analyse and manipulate audio signals. In particular, it can be used to convert time domain audio signals to frequency domain representation, which facilitates spectral audio analysis or equalization.
- **Communications:** FFT is employed in a number of communication systems and applications such as modulation and encoding of digital signals. It is also used in speech recognition systems, which process the frequency representation of speech signals.
- **Medical Imaging:** FFT is employed in medical imaging applications to analyse MRI, CT scans and other medical imaging data. This allows for a more detailed view of the internal structures of the human body.
- **Spectroscopy:** FFT is used in spectroscopy to analyse the frequency distribution of light emitted from various sources. It helps in identifying the components of a substance and determining its chemical composition.
- **Financial Analysis:** FFT is employed in Financial Analysis to analyse the frequency distribution of stock prices and other financial data. It is often used to detect

underlying trends in the data and develop trading models.

- **Machine Learning:** FFT is employed in Machine Learning applications for feature extraction and signal analysis. It is used to break down complex signals into simpler components, which can then be processed by machine learning algorithms.

II.6. software can be used to perform FFT:

There are many software packages available for performing FFT, including MATLAB, Python's scipy module, and GNU Octave. Many digital signal processing tools also include FFT functionality.[22]

II.7. Digital Signal Processing using MATLAB:

MATLAB is a popular software platform for digital signal processing (DSP). It offers a wide range of tools and functions for analysing, designing, and simulating DSP systems.[27] Some of the features of MATLAB that are useful for DSP include:

Signal processing and communications toolboxes: These toolboxes provide a range of functions for processing and analysing signals, designing and analysing filters, and simulating communication systems. They include functions for tasks such as filtering, spectral analysis, and modulating and demodulating signals.[27]

Matrix operations: MATLAB is designed for working with matrices, which are fundamental to many DSP techniques. It provides a range of functions for matrix manipulation and linear algebra, as well as functions for generating common types of matrices. For example, you can use MATLAB to perform matrix multiplication, invert a matrix, or solve a system of linear equations.[27]

Plotting and visualization: MATLAB has powerful functions for visualizing and plotting data, which is often helpful for understanding and analysing signals and systems. You can use MATLAB to create line plots, scatter plots, bar plots, and many other types of plots, and you can customize the appearance of the plots using a variety of options.[27]

Code generation: MATLAB can generate C code from MATLAB algorithms, which can be used to deploy DSP systems on hardware platforms. This can be useful for optimizing the performance of DSP systems or for running them on platforms that do not have MATLAB installed.[27]

User-defined functions: MATLAB allows users to define their own functions, which can be used to encapsulate and reuse code. This is particularly useful for organizing and modularizing DSP algorithms. By defining a function, you can define a set of operations that can be called with a single function call, rather than writing out the individual steps each time you want to perform them. This can make your code more readable and easier to maintain. [27]

Chapter III:
Synchronous motors

Chapter III: Synchronous motors

III.1. Generalities on synchronous motors

Synchronous motors are a type of AC motor that operate at a constant speed determined by the frequency of the power supply. The rotor spins at the same speed as the stator's magnetic field, making it synchronous. PMSMs are increasingly used in many commercial and industrial applications because of their high-power density, wide constant-power speed range, excellent efficiency, high air-gap flux density and high torque to inertia ratio. The PMSMs are most convenient components for the applications of packaging, glass wood, robotics, handling, etc.

Synchronous motor Just like any other motor, it consists of a stator and a rotor. The stator core is constructed with thin silicon lamination and insulated by a surface coating, to minimize the eddy current and hysteresis losses. The stator has axial slots inside, in which three phase stator winding is placed. The stator is wound with a three-phase winding for a specific number of poles equal to the rotor poles.

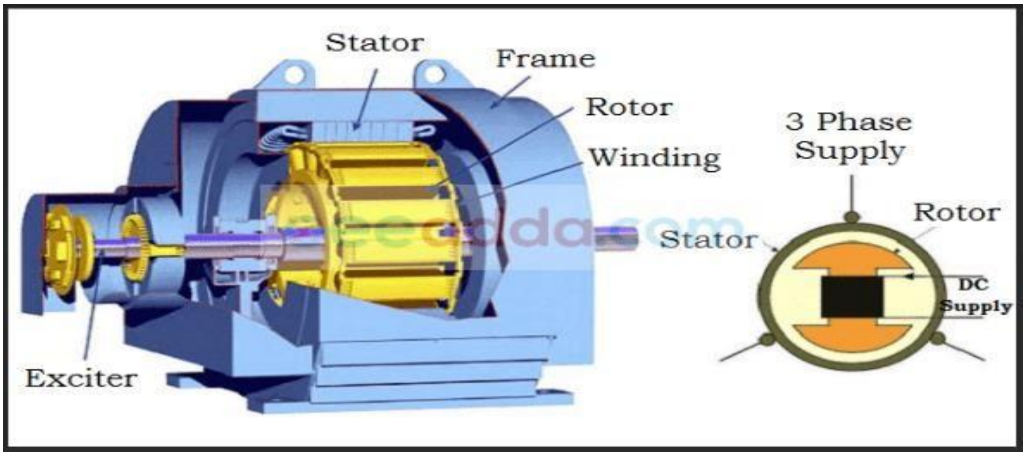


Figure III.1. Synchronous motor

The rotor in synchronous motors is mostly of salient pole type. DC supply is given to the rotor winding via slip-rings. The direct current excites the rotor winding and creates electromagnetic poles. In some cases, permanent magnets can also be used.[7]

The stator is wound for the similar number of poles as that of rotor, and fed with three phases AC supply. The 3 phases AC supply produces rotating magnetic field in stator. The rotor winding is fed with DC supply which magnetizes the rotor. Consider a two-pole synchronous machine as shown in figure below.[7]

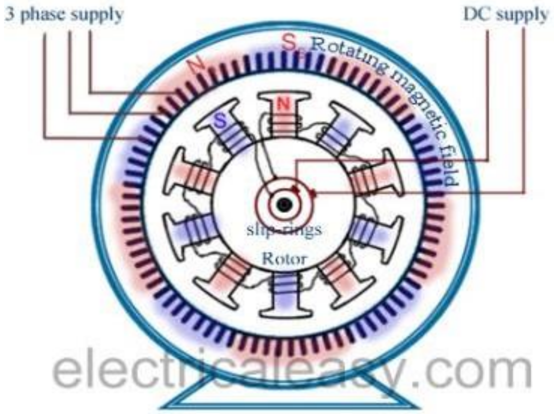


Figure III.2. Construction of synchronous motor

Now, the stator poles are revolving with synchronous speed (let’s say clockwise). If the rotor position is such that, N pole of the rotor is near the N pole of the stator (as shown in first schematic of above figure), then the poles of the stator and rotor will repel each other, and the torque produced will be anticlockwise.[7]

The stator poles are rotating with synchronous speed, and they rotate around very fast and interchange their position. But at this very soon, rotor cannot rotate with the same angle (due to inertia), and the next position will be likely the second schematic in above figure. In this case, poles of the stator will attract the poles of rotor, and the torque produced will be clockwise. Hence, the rotor will undergo to a rapidly reversing torque, and the motor will not start.[7]

But if the rotor is rotated up to the synchronous speed of the stator by means of an external force (in the direction of revolving field of the stator), and the rotor field is excited near the synchronous speed, the poles of stator will keep attracting the opposite poles of the rotor (as the rotor is also, now, rotating with it and the position of the poles will be similar throughout the cycle). Now, the rotor will undergo unidirectional torque. The opposite poles of the stator and rotor will get locked with each other, and the rotor will rotate at the synchronous speed.[7]

When the rotor and stator both have the same pole on the same side, they repel each other. If they have opposite poles, they attract each other. This can easily be understood with the help of the figure shown below:

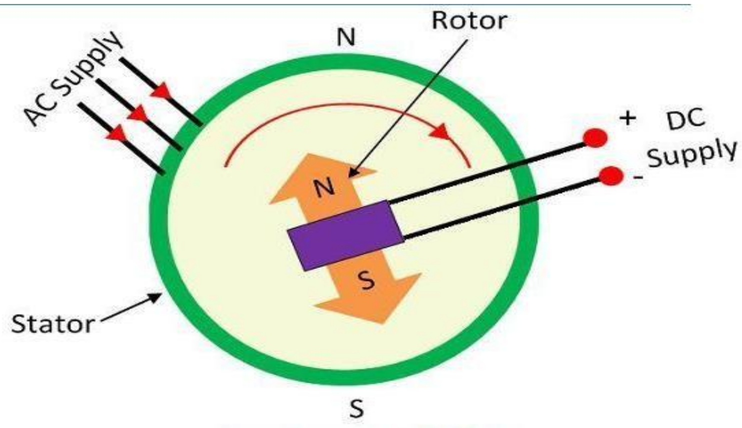


Figure III.3. Synchronous motor

The rotor attracts towards the pole of the stator for the first half cycle of the supply and repels for the second half cycle. Thus, the rotor becomes pulsated only at one place.

III.2. Characteristic Features of a Synchronous Motor:

Synchronous motor will run either at synchronous speed or will not run at all.[7]

The only way to change its speed is to change its supply frequency. (As Ns = 120f / P) Synchronous motors are not self-starting. They need some external force to bring them near to the synchronous speed.[7]

They can operate under any power factor, lagging as well as leading. Hence, synchronous motors can be used for power factor improvement.[7]

These innovations have allowed the PMSM to acquire many advantages such as:

- High volume torque and power density allowing the use of PMSMs

with a more compact design: highly sought-after features for embedded applications;

- Higher efficiency due to the use of permanent magnets to replace rotor windings.

Thus, the rotor does not need to be powered which reduces losses (absence of joule losses).

- Simplicity and reliability of the machine due to the absence of bushings and brushes;
- High dynamic performance thanks to high flux density in the air gap.

In order to take advantage of the benefits of PMSMs, many industries use this Type of machine for various applications. Recently, we can quote:

- **Petrochemical industry**: PMSMs are intended for high-power operations

(Several MW) and high speed (> 10,000 rpm).

- **Renewable energy industry**: specifically in the energy sector wind turbine.

PMSMs are intended for high power operations (several MW) and low speed (around 1,000 rpm).

- **Automotive industry**: for the design of hybrid or fully electric vehicles.

PMSMs are intended for low-power operations (limited to a few tens of kW).

- **Aeronautical industry**: for the development of the more electric aircraft that

constitutes one of the main lines of research in this field. The powers involved can reach 175kW.

- **Railway industry:** PMSMs are intended for medium power traction operations,

where a permanent magnet generator has been sized for a rated power of 250kW.[10]

III.3. Application Of Synchronous Motor:

As synchronous motor is capable of operating under either leading and lagging power factor, it can be used for power factor improvement. A synchronous motor under no-load with leading power factor is connected in power system where static capacitors cannot be used.[7]

It is used where high power at low speed is required. Such as rolling mills, chippers, mixers, pumps, compressors etc. [7]

Synchronous motor and induction motor are the most widely used types of AC motor. Construction of a synchronous motor is similar to an alternator (AC generator). A same synchronous machine can be used as a synchronous motor or as an alternator. Synchronous motors are available in a wide range, generally rated between 150kW to 15MW with speeds ranging from 150 to 1800 rpm.[7]

Synchronous motors are usually used where there is a need for precise and constant speed. Low power applications of these motors include positioning machines. This kind of electric motors is also applied in robot actuators. Some other applications make use of synchronous motors such as ball mills, clocks, and record player turntables. Besides, these motors are also used as servomotors and timing machines.

Three-phases synchronous motors find their major application in industrial situations where there is a large, reasonably steady mechanical load, usually in excess of 300 kilowatts, and where the ability to operate at leading power factor is of value. Below this power level, synchronous machines are generally more expensive than induction machines.

The field current may be supplied from an externally controlled rectifier through slip rings, or in larger motors, it may be provided by a shaft-mounted rectifier with a rotating transformer or generator.

III.4. Methods of Starting of Synchronous Motor:

1-Motor starting with an external prime Mover: Synchronous motors are mechanically coupled with another motor. It could be either 3 phase induction motor or a DC shunt motor. Here, we do not apply DC excitation initially. It rotates at speed very close to its synchronous speed, and then we give the DC excitation. After some time when magnetic locking takes place supply to the external motor is cut off.[26]

2- Damper winding in this case, the synchronous motor is of salient pole type, the additional winding is placed in the rotor pole face. Initially, when the rotor is not rotating, the relative speed between damper winding and rotating air gap flux is large and an emf is induced in it which produces the required starting torque. As speed approaches synchronous speed, emf and torque are reduced and finally when magnetic locking takes place; torque also reduces to zero. Hence, in this case, the synchronous motor first runs as three phase induction motor using additional winding and finally it is synchronized with the frequency.[26]

III.5. Different Types of a synchronous motor:

based on the method of magnetization of the rotor, there are two types of synchronous motors which are:

III.5.1. Non-excited Motor:

- In this type of motors, the rotor is magnetized by the external stator magnetic field and the rotor has a constant magnetic field. In this type, to make the rotor, high retentive steel such as cobalt steel is used. This causes three other classifications as a permanent magnet, reluctance, and hysteresis motors.
- For the design of Permanent magnet synchronous motors, a permanent magnet is used along with steel. They have a constant magnetic field in the rotor, so induction winding cannot be used for starting. Being used as gearless elevator motors.
- The rotor of the reluctance motor is made up of steel casting with poles of projecting tooted. The rotor poles are less than the stator poles in order to minimize the torque ripples.
- Hysteresis motors are self-starting motors. in this type of synchronous motors, the rotor is a smooth cylinder made-up of hard cobalt steel. This type of motor is expensive and is usually used where there is a need for precise constant speed.

III.5.2. DC Current Excited Motor:

When the rotor of a synchronous motor is excited using the direct current supplied directly through slip rings, it is called DC current excited motor.

III.6. Parts of synchronous motor:

III.6.1. Stator:

Stator is an immobile part of the electric motor, which includes several windings. Once an alternating current is applied to it, then its polarity will be changed all the time. When the power supply is given to the stator, an AC flows through the stator windings to create an electromagnetic field across the bars of the rotor. The alternating current (AC) makes the magnetic field rotates. This includes thin and stacked laminations, wounded by an insulated wire. The core in the stator includes a number of these laminations.[20]

Figure III.4. Stator in motor

The motor's stator housing is designed with aluminium up to 22 kW, whereas motors with high outputs contain cast-iron stator housings. Stators with different poles are most commonly used in connection with a pump to decide the force & the flow through the speed. The stator is mainly designed for handling different frequencies, voltages, outputs as well as an unstable no. of poles.[20]

There are two types of stators which is defined by the coiling, it is either a distributed coiling (a) or a concentric coiling(b) and it shows in the figure below:

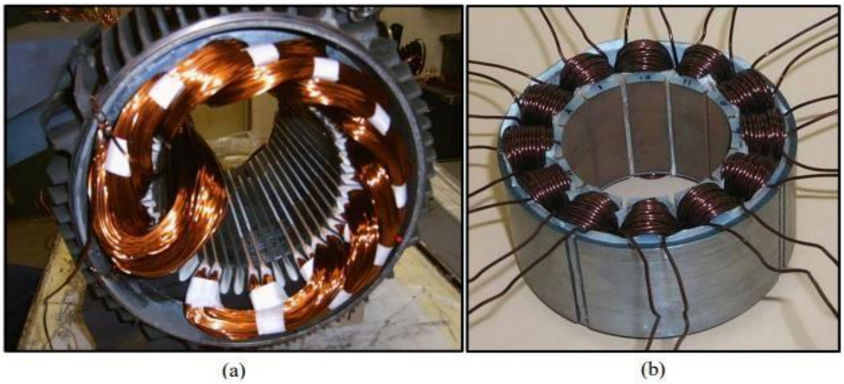


Figure III.5. Two main coiling families: distributed (a) and concentrate (b)

- The distributed coiling is the most widely used technique in the industry. Its major advantage is that it allows a quasi-sinusoidal distribution of the field magnetic in the air gap. Therefore, it increases the ability of the winding to recover the rotor flux and thus reduce magnetic losses.[10]
- On the other hand, distributed winding is well suited in high-speed applications,

where a reduced number of pole pairs is necessary. The main disadvantage of this winding structure is the large volume of copper lost, especially in the heads of coils, during its installation.[10]

III.6.2. Rotor:

The rotor is a moving component of an electromagnetic system in the electric motor, electric generator, or alternator. Its rotation is due to the interaction between the windings and magnetic fields which a torque around the rotor's axis.

The rotor is made up of several thin steel laminations with evenly spaced bars, which are made up of aluminium or copper, along the periphery. In the most popular type of rotor (Squirrel cage rotor), these bars are connected at ends mechanically and electrically by the use of rings. Almost 90% of induction motors have squirrel cage rotors. This is because the squirrel cage rotor has a simple and rugged construction. The rotor consists of a cylindrical laminated core with axially placed parallel slots for carrying the conductors. Each slot carries a copper, aluminium, or alloy bar. These rotor bars are permanently short-circuited at both ends by means of the end rings. The rotor slots are not exactly parallel to the shaft. Instead, they are given a skew for two main reasons.

The first reason is to make the motor run quietly by reducing magnetic hum and to decrease slot harmonics.

The second reason is to help reduce the locking tendency of the rotor. The rotor teeth tend to remain locked under the stator teeth due to direct magnetic attraction between the two. This happens when the number of stator teeth are equal to the number of rotor teeth.

The rotor is mounted on the shaft using bearings on each end; one end of the shaft is normally kept longer than the other for driving the load. Some motors may have an accessory shaft on the non-driving end for mounting speed or position sensing devices. Between the stator and the rotor, there exists an air gap, through which due to induction, the energy is transferred from the stator to the rotor. The generated torque forces the rotor and then the load to rotate. Regardless of the type of rotor used, the principle employed for rotation remains the same.[12]

III.6.2.1. Types of rotors:

1.Salient pole rotor - the individual rotor poles protrude from the center of the rotor, characterized by concentrated windings, non-uniform air gap, larger rotor diameters, used in applications requiring low machine speed and a large number of machine poles (example hydroelectric generation).[11]

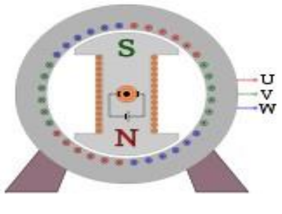


Figure III.6. Salient pole rotor

2. Cylindrical rotor - the individual rotor poles are produced using a slotted cylindrical rotor, characterized by distributed windings, nearly-uniform air gap, smaller rotor diameters, used in applications requiring high machine speed and a small number of machine poles, typically, 2 or 4 poles (example - steam or gas turbine generators).[11]

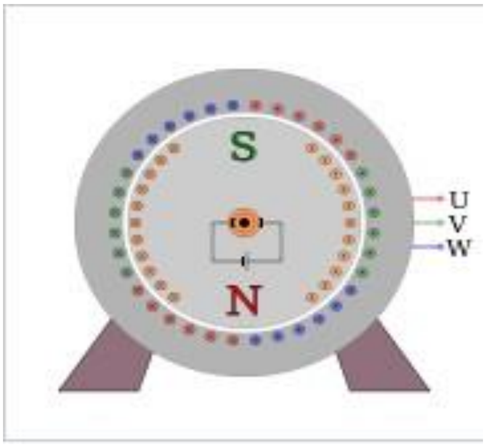


Figure III.7. Cylindrical rotor

3. Wound rotor-the wound rotor is a cylindrical core made of steel lamination with slots to hold the wires for its 3-phase windings which are evenly spaced at 120 electrical degrees apart and connected in a 'Y' configuration [25]. The rotor winding terminals are brought out and attached to the three slips rings with brushes, on the shaft of the rotor [14]. Brushes on the slip rings allow for external three-phase resistors to be connected in series to the rotor windings for providing speed control [15]. The external resistances become a part of the rotor circuit to produce a large torque when starting the motor. As the motor speeds up, the resistances can be reduced to zero [14].

4. Squirrel-cage rotor-The squirrel-cage rotor consists of laminated steel in the core with evenly spaced bars of copper or aluminium placed axially around the periphery, permanently shorted at the ends by the end rings [12]. This simple and rugged construction makes it the favourite for most applications. The assembly has a twist: the bars are slanted, or skewed, to reduce magnetic hum and slot harmonics and to reduce the tendency of locking. Housed in the stator, the rotor and stator teeth can lock when they are in equal number and the magnets position themselves equally apart, opposing rotation in both directions [12]. Bearings at each end mount the rotor in its housing, with one end of the shaft protruding to allow the attachment of the load. In some motors, there is an extension at the non-driving end for speed sensors or other electronic controls. The generated torque forces motion through the rotor to the load.

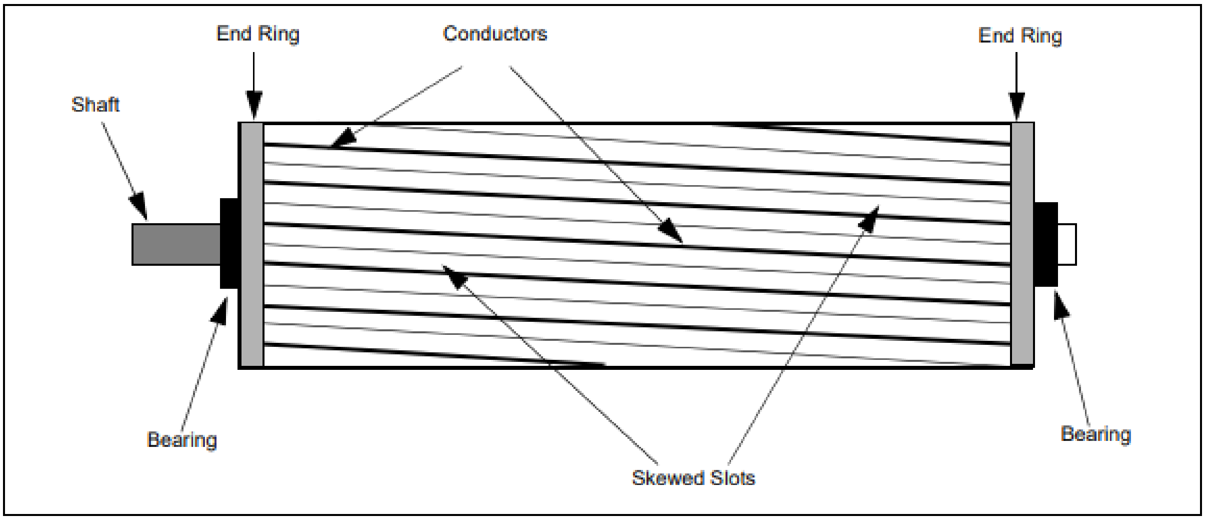


Figure III.8. Squirrel-cage rotor

Figure III.9. a selection of various types of rotors

III.7. Mechanical components:

There are other mechanical components at the PMSM level, among them we can mention:

- **The tree**: the tree in the PMSMs plays the role of the transmission organ. It includes a central part that serves as a support for the rotor body, and connected to the load via a coupling. It is supported by both levels.
- **The bearings**: allow to support and rotate the rotor shaft, they consist of flanges and ball bearings inserted hot on the shaft. The flanges, cast in cast iron, are fixed to the stator housing by bolts or clamping rods.
- **The flanges**: close the engine housing at the ends. They are made from a grey cast iron or injected aluminium. The flanges are centered on the housing and joined together by tie rods or assembly rods.
- **The carcass**: generally, it consists of injected aluminium for small engines and grey cast iron for large engines. It acts as an envelope of the magnetic circuit and ensures its protection from the external environment. The terminal box is usually mounted directly on top or side of the carcass.
- **The fan**: it is placed at the end of the shaft on the rotor for cooling the PMSM, It can be replaced by forced ventilation for cooling at slow speeds.
- **Bearings**: the bearing is a basic component that provides the moving link between two elements of a rotating mechanism relative to each other. Its function is to allow the relative rotation of these elements, under load, with precision and minimal friction.[10]

III.8. Defects affecting permanent magnet synchronous machines:

Throughout their life, permanent magnet synchronous machines are subjected to operational and environmental constraints that lead to the degradation of their components. Declining health can lead to failures that we divide into two categories, electrical failures and mechanical failures. These failures are caused by more or less aggravating factors, We distinguish four main constraints:

- **Mechanics**: mechanical vibrations, unbalanced electromagnetic forces, variation of load, bearing wear;
- **Electrical**: high surges caused by switching power electronics components;
- **Thermal**: heating, losses in copper, cooling problems;
- **Environmental**: temperature, pressure, dust, surrounding humidity;
- **Abnormal operation**: Overload, overspeed;
- **Wrong sizing**: bad installation or misalignment. [10]

Chapter IV:
Bench test

Chapter IV: Bench test

The main objective of this chapter is to validate the results obtained by simulation. Unfortunately, we do not have a test bench for the short circuit fault between stator whorls, this is why we will limit ourselves to the following defects:

- Eccentricity defect
- Demagnetization defect

To do this, we used a test bench, carried out by the diagnostic group within the Electrical Drive Development Laboratory (LDEE) of the University of Sciences and Technology of Oran - Mohamed Boudiaf (USTO-MB).

IV.1. Description of bench test:

The synoptic diagram of the test bench carried out is illustrated by Figure

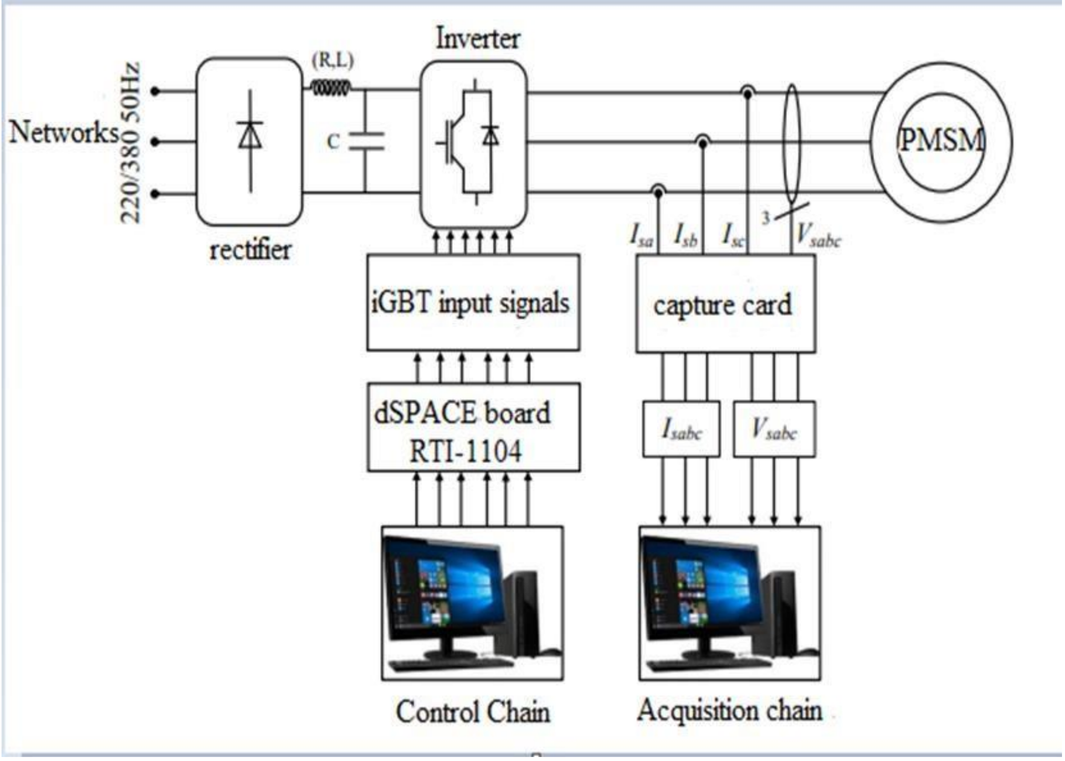


Figure IV.1. Synoptic diagram of the measuring bench made

All the equipment used to carry out the various tests of our work are illustrated by the photo of the Figure

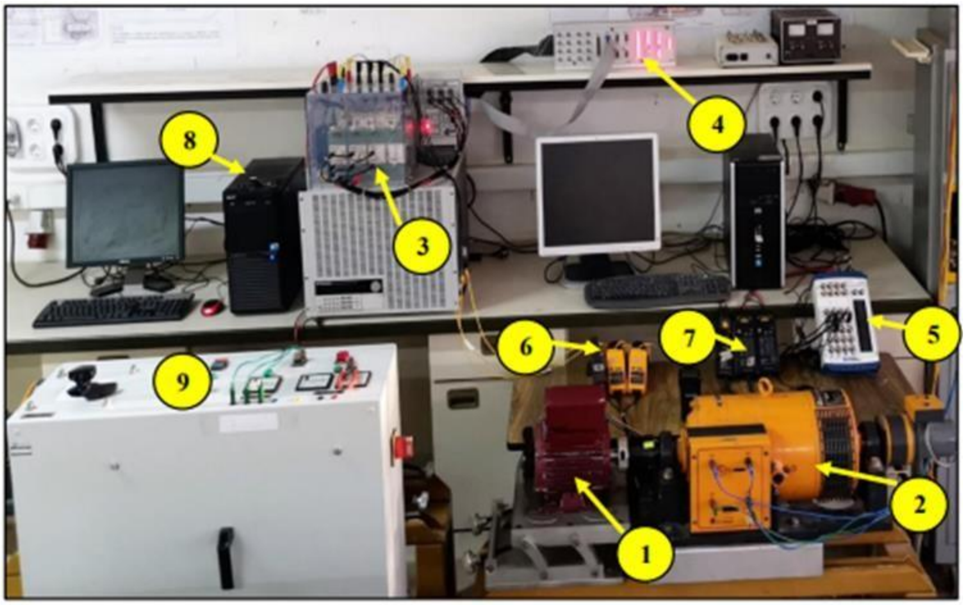


Figure IV.2. Photo of the measuring bench made

① Permanent Magnet Synchronous Motor: The motor used in our experimental tests is type LEROY SOMER LSRPM90SL and 360 V, 100 Hz, 5.9 A, 8 poles, 1500 rpm and 3 kW. The photo of this engine is illustrated by the Figure

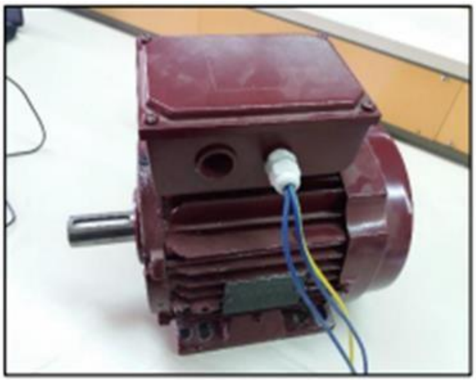


Figure IV.3. photo of PMSM used

② DC generator: The motor used is mechanically coupled to a DC generator. This generator powers a set of resistors playing the role of a mechanical load. The photo of this generator is illustrated by the Figure IV.4.

Figure IV.4. Photo of the generator used

③ Three-phase inverter: the motor used is powered by a three-phase inverter of the type SEMIKRON AN-8005 based on IGBTs, controlled by an RTI-1104 DSPACE board. The IGBT of this inverter are controlled by the MLI-SVM strategy with a frequency of 6 kHz switching. The photo of this inverter is illustrated by the Figure IV.5.

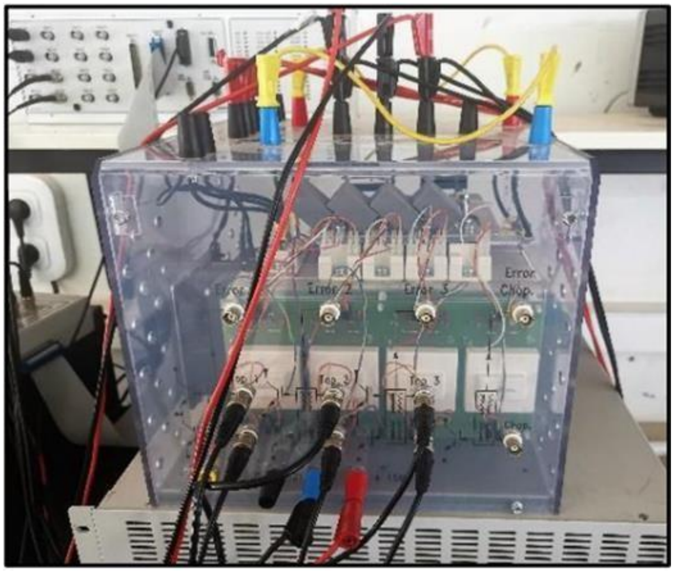


Figure IV.5. Photo of the inverter used

④ dSPACE board: the dSPACE 1104, is a very flexible and powerful digital board with high computing characteristics and I/O devices.

It acts as an interface between the computer and the IGBTs of the inverter. Programming of this map is made using the "Simulink" tool under the MATLAB environment.

The photo of the dSPACE used is given in the following figure (IV.6).

Figure IV.6. Photo of the dSPACE RTI - 1104 used

⑤ Capture card: the capture card used is of type NATIONAL INSTRUMENT USB-622. It has 8 analog inputs. This card is the main element of the chain acquisition because it digitizes analog signals.

Figure IV.7. Photo of the capture card used

⑥ Current sensor: The current sensors used are hall effect sensors of the type FLUCK i30s (AC/DC CURRENT CLAMP). The role of these sensors is to measure and give an image of stator currents. The maximum current that can be measured is ± 20 A. The photo of this sensor is given by the following figure.

Figure IV.8. Photo of the current sensor used

⑦ Voltage sensor: The voltage sensors used are sensors of the type TEKTRONIX P5200. The role of these sensors is to measure and give an image on the tensions between phases of the PMSM. The maximum voltage that can be measured is ± 1000 V. The photo of this sensor is given in the following figure (IV.9).

Figure IV.9. Photo of the voltage sensor used

⑧ Microcomputer: The microcomputer used for the acquisition chain has the

Specifications: 2GB RAM and 3 GHz AMD processor. The role of this computer is to control the capture card. In addition, it also allows you to Visualize, analyse, process and store the different signals captured.

IV.2. Creation of the eccentricity defect:

The creation of the eccentricity defect requires high precision because of the thickness of the gap. There are many ways to create this type of defect. Among them, we know any problem with the inner ring of the bearing causes dynamic eccentricity and any defect related to the outer ring creates a static eccentricity. For this reason, our mechanism is based on modifying the rings (internal and external) of the bearing to create accurately the eccentricity defect in the PMSM. The purpose of this mechanism is to add additional rings that have an oval shape with dimensions precise enough to avoid friction between the stator and the rotor.

To create the static eccentricity defect, we have a ring of an oval shape between the outer ring of the bearing and the flange maintaining the same dimensions of the ring internal. Moreover, the creation of the dynamic eccentricity defect is done in the same way as the previous case, except that we keep the dimensions of the outer ring and we place a ring of an oval shape between the rotation shaft and the inner ring of the bearing. The Figure shows a photo of the bearings with the additional rings of the eccentricity defect mechanism.

Figure IV.10. Mechanism for creating eccentricity defect

All acquisitions are made in steady state with a rotation speed of 1500 rpm. The acquisition parameters chosen are: an acquisition time of 40 s and a sampling frequency of 3 kHz. Under these conditions, we obtain a frequency resolution equal to 0.025 Hz. To have a more reliable analysis and view the character random of the measured signals, several acquisitions were made for each mode of operation. The two modes of operation treated are:

- Healthy engine operation;
- Operation of the engine in the presence of eccentricity defect;

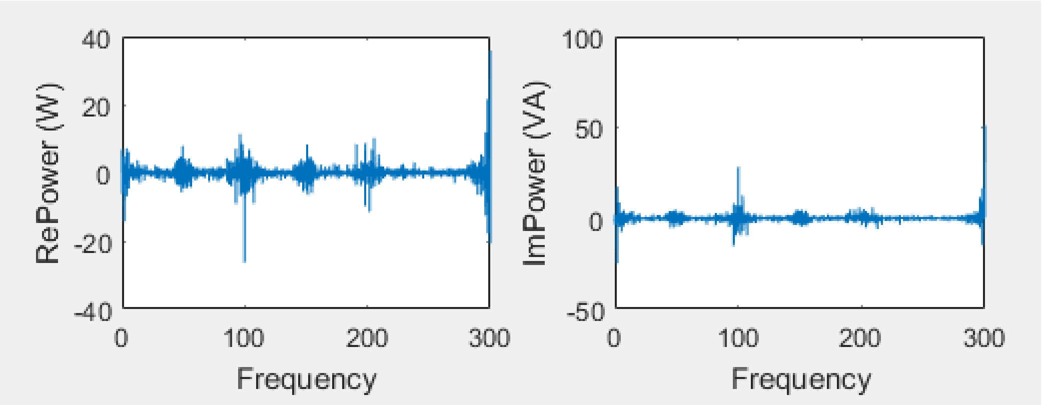
IV.3. *Healthy engine operation:*

To identify the possible presence of a defect in the MSAPs by the technique of analysis Spectral of the stator current, it is necessary to identify the reference spectrum by the analysis of the stator current in the case of a healthy motor. Indeed, a comparison of the amplitude of The characteristic harmonic of the defect with the reference harmonic is often used to detect the presence or absence of a defect and even for monitoring the severity of the defect if it exists.

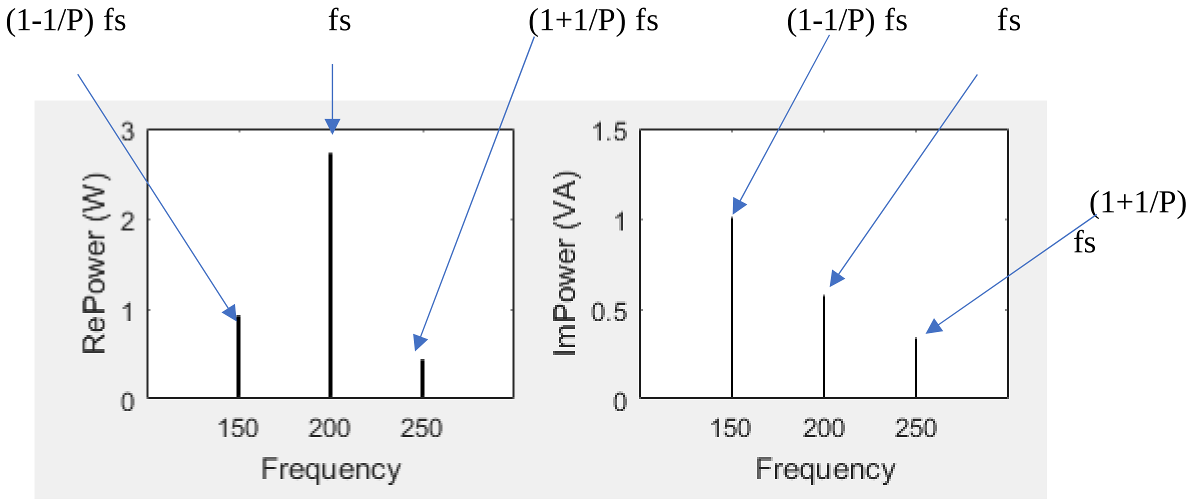
Presents the spectrum of the supply voltage of phase "A", for healthy operation and under a nominal load. We note that the spectral content of this spectrum is not limited to not fundamental (100 Hz). It presents other harmonics at frequencies: 200 Hz, 300 Hz, ...

These harmonics are due to pollution of the power source and switching of IGBTs.

The figures below of a healthy motor:



(a)



(b)

Figure.IV.11. spectral analysis of a healthy motor (a, b)

IV.4. Case of operation in the presence of eccentricity defect:

the presence of eccentricity is manifested by creating a series of harmonics in the stator current spectrum, at frequencies fext defined by equation, with fs the supply frequency, P the number of pole pairs, k a positive integer.

$$f_{ext}=[1\pm(k/p)]\ f_s$$

Thus, the same characteristic signatures can be used to detect this type of defect, thanks to a spectral analysis on stator currents.

The study is realised between the two frequencies 150Hz and 250Hz and by applying 3 different percentage of eccentricity on the healthy motor in the order (10%; 20%; 30%) and we are analysing the power in each Specter.

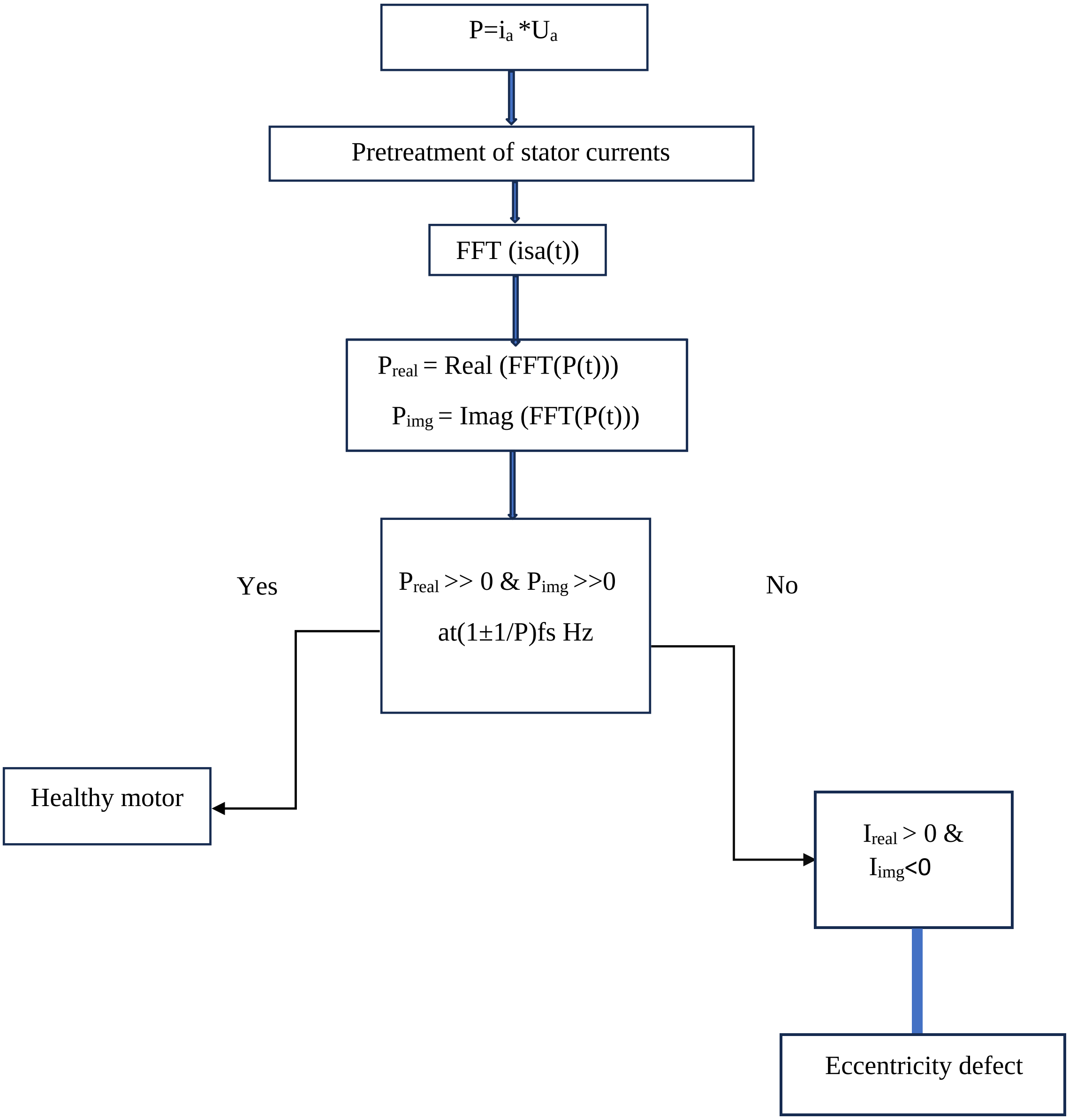
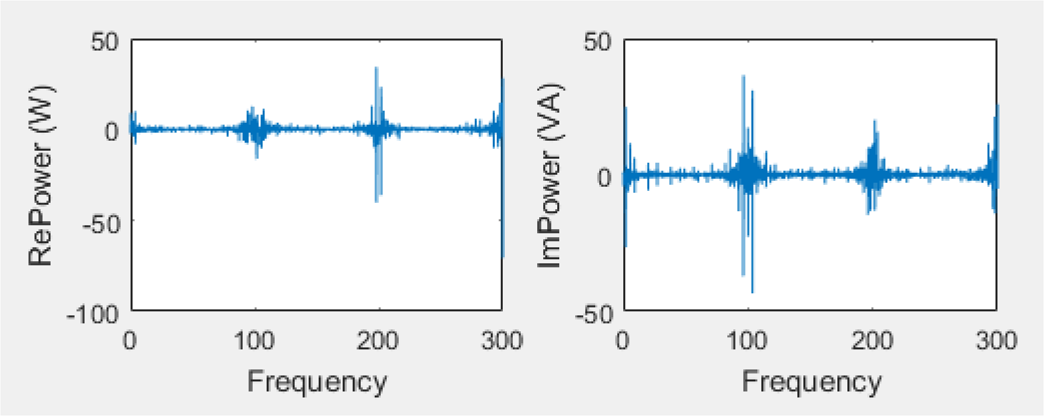


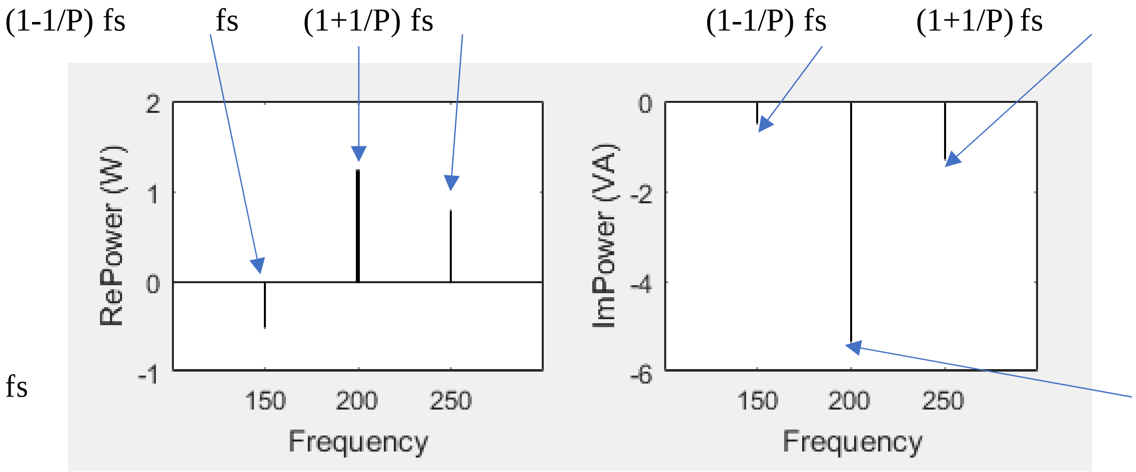
Figure.IV.12. Flowchart of the proposed approach

IV.4.1. case in the presence of eccentricity defect of 10%:

We get from the simulation the figures which shows the power density spectral:



(a)



(b)

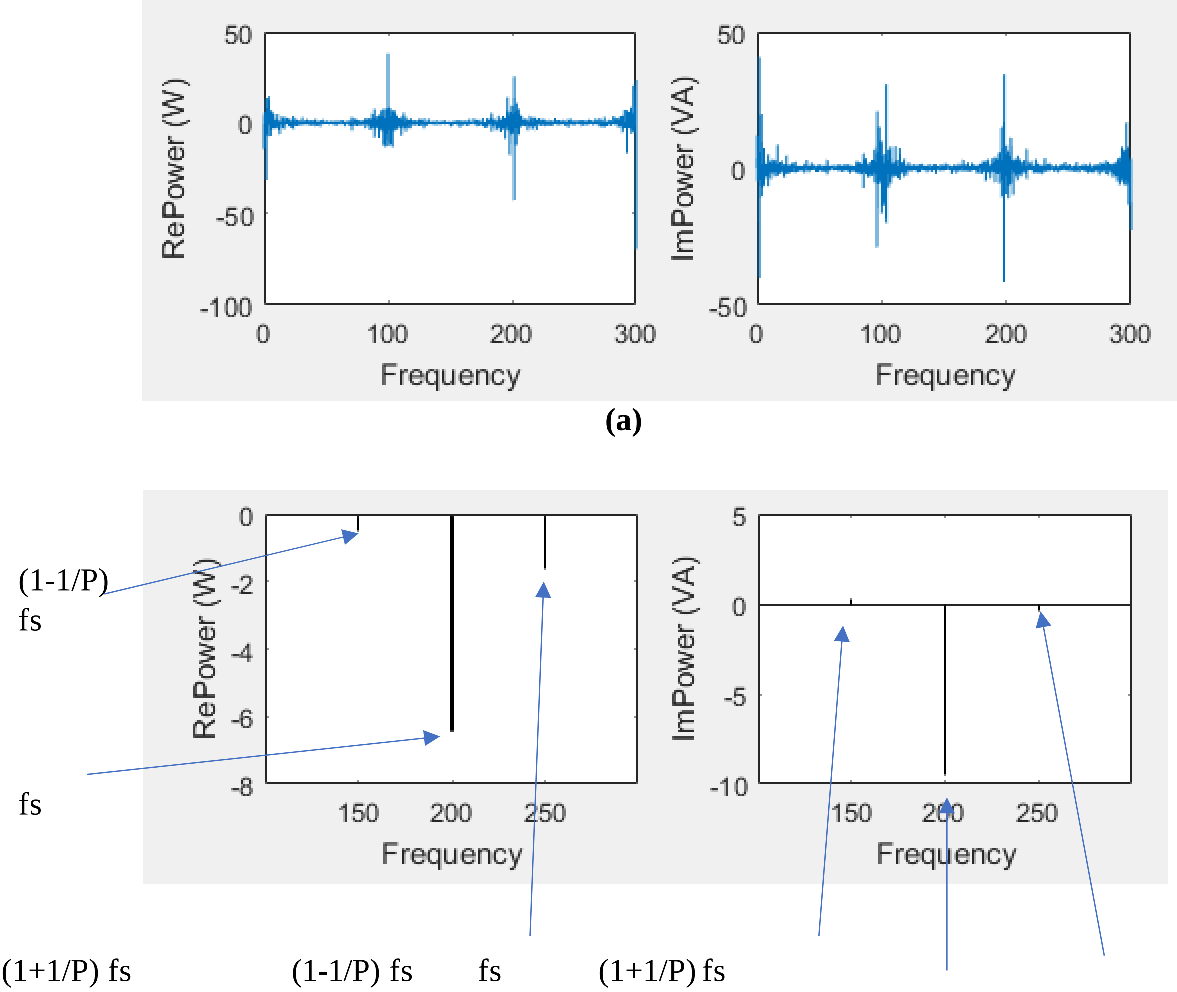
Figure.IV.13. spectral analysis of eccentricity defect of 10% (a, b)

Since power in the normality is positive that is why in the real spectral is positive except for one bar in the left and in the imaginary spectral all of the bars are negative.

	Eccentricity defect	
	Real	Imaginary
(1-1/P) f_s	-	-
(1+1/P) f_s	+	-

Table IV.1. Signs of real and imaginary plots in the case of eccentricity defect (10%)

IV.4.2. A case in the presence of eccentricity defect of 20%:



(a)

(1-1/P) fs

fs

(1+1/P) fs

(1-1/P) fs

fs

(1+1/P) fs

(b)

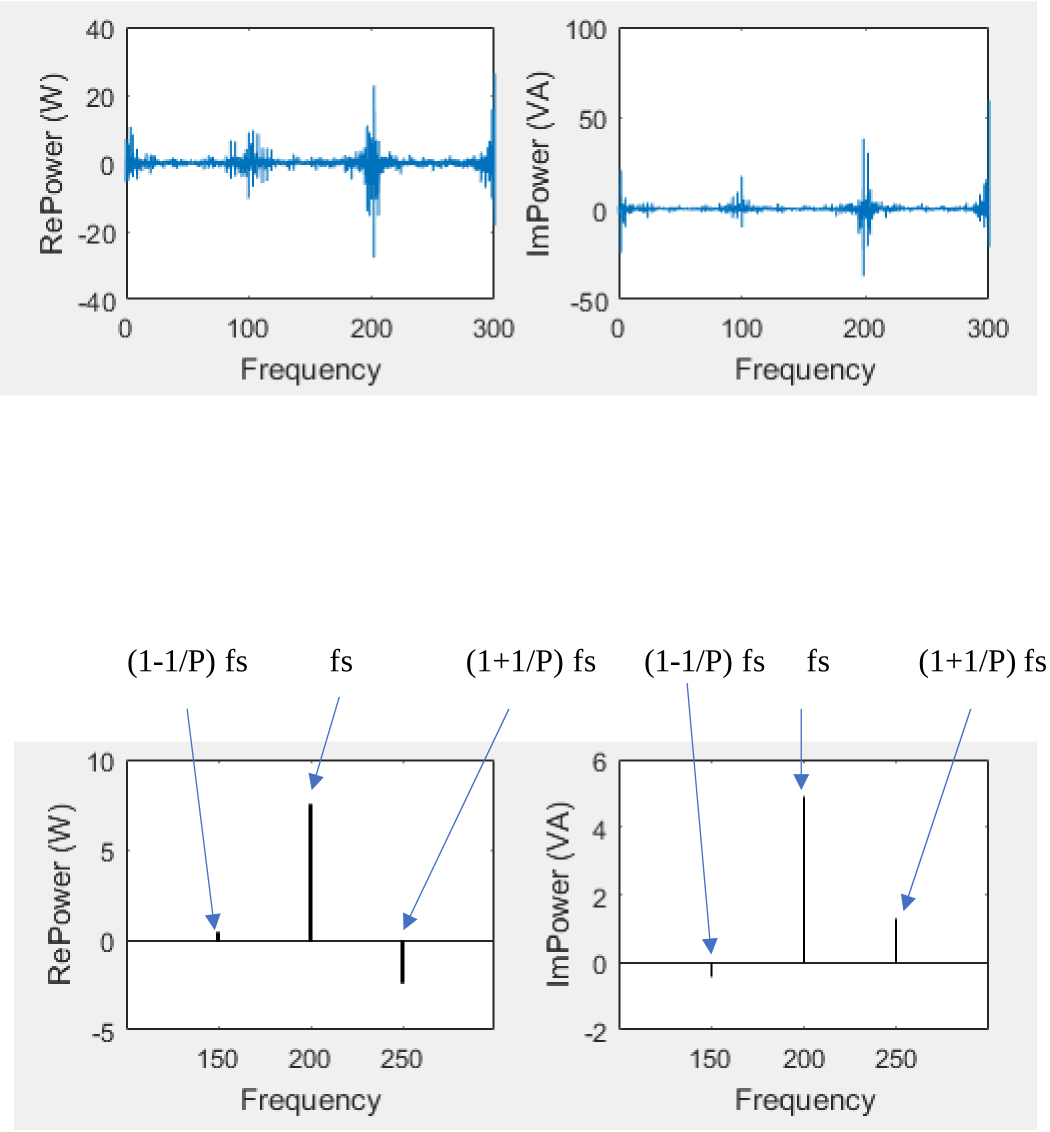
Figure. IV.14. spectral analysis of eccentricity defect of 20% (a, b)

The figure shows that the spectral of power is all negative in the real one and negative in the imaginary one but the bars are shorter then the ones from the previous figure

	Eccentricity defect	
	Real	Imaginary
(1-1/P) fs	-	+
(1+1/P) fs	-	-

Table IV.2. Signs of real and imaginary plots in the case of eccentricity defect (20%)

IV.4.3. A case in the presence of eccentricity defect of 30%:



(a)

(b)

Figure.IV.15. spectral analysis of eccentricity defect of 30% (a, b)

This figure shows the real power spectral is mostly positive except one bar on the right and all positive in the imaginary but one little bar on the left.

	Eccentricity defect	
	Real	Imaginary
(1-1/P) fs	+	-
(1+1/P) fs	-	+

Table IV.3. Signs of real and imaginary plots in the case of eccentricity defect (30%)

IV.4. conclusion:

By analysing the PDS of the eccentricity defect on a healthy synchronous motor we got the idea that this defect is affecting the motor by the loss of energy which is a magnetic type of energy and is shown through the Specters in the shape of the bar below the zero in the case of the real and the contrary in the case of imaginary.

This procedure is based on the analysis of the real and imaginary parts of frequency signatures of the defect treated. Thus, a simple follow-up of the signs of these two signatures (real parts and imaginary), allows a better readability of the spectrum and a speed of decision with regard to the defect of eccentricity.

General Conclusion

General conclusion:

In this work we opted to do a spectral analysis of the eccentricity defect in synchronous motor so, we began with talking of methods of diagnostic and electrical machine defects, then we gave a brief introduction on signal processing methods and precisely FFT and we included digital signal processing using MATLAB which is the software we used in our work. After that we talked in details about synchronous motors and their characteristics, we eventually got to the experiment part of our work by applying Bench test included with the simulation on MATLAB software.

In conclusion, spectral analysis of eccentricity defect in synchronous motor is a valuable diagnostic tool for detecting and identifying faults in the motor. The technique involves analysing the motor's spectral signature to identify specific frequency components associated with the eccentricity defect. Therefore, spectral analysis should be an integral part of the maintenance routine for all synchronous motors to ensure the smooth and efficient operation of equipment.

Since we got good results while doing spectral analysis on eccentricity defect in a synchronous motor, for the foreseeable future we would like to apply spectral analysis on other defects in the said motor such as demagnetization defect.

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