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Praise Worthy Prize

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Synthesis of Electrical Quantities Applied to Squirrel Cage Induction Motor Bearing Faults Detection

Mohammed Ferradj, Noureddine Benouzza, Azzedine Bendiabdellah, Benyounes Mazari

Abstract – *Electric motors play a very important role for safe and efficient running of any industrial or power plant. Early detection of abnormalities in the motor will help and avoid expensive failures. Bearing faults create asymmetries and result in abnormal amplitude of the harmonics around the fundamental supply frequency and its harmonics. It has been shown that bearing faults can be detected by several methods. Frequency estimation techniques have been developed and used to detect bearing faults. In this paper an overview of the Concordia vectors technique (namely the α and β components) is applied to the detection of bearing faults. Our main objective is to investigate which of the two components is most sensitive to bearing faults. Experimental tests performed on a number of faulty bearings show that the β- quadrature component is more sensitive to these types of faults.*

Keywords: *Bearing Faults, Concordia Vectors, Diagnosis, Spectral Analysis, Squirrel Cage Motor*

Nomenclature

D_c	Cage diameter
D_b	Ball daimeter
$f_{ring,out}$	Frequency of the outer ring
$f_{ring,in}$	Frequency of the inner ring
f_{cage}	Frequency of the cage
f_{balls}	Frequency of the ball ring
f	Power supply frequency
fr	Rotating frequency
f_{sh}	Rotor slots harmonics frequencies
i_{sa}, i_{sb}, i_{sc}	Three-phase currents.
i_m	Maximum value of the phase current
i_α , i_β	Direct and quadrature Concordia components
k	Positive integers
n_b	Number of rotor bars
N_b	Number of ball ring
p	Number of pole pairs
s	Slip
v	Time order harmonics
β_1	Contact angle

I. Introduction

Electrical machines real-time monitoring is well recommended for faults and overloads detection, especially in power generation and high power drives.

The measured signals that contain significant information on faults are generally voltage, current, speed, vibration and noise [1]-[3].

The development of modern diagnosis methods has widely increased due to advances in micro-electronics and signal processing [4]-[7]. Bearings are among the most important and sensitive elements in electrical machines. They in fact play the role of electromechanical interface between stator and rotor. It should be noted that, most of the bearing faults will affect directly the bearing geometrical shape by either: rolling elements surface corrugations, inner and outer rings cracks or cage damage. This last fault is found to be the most common in bearing faults [8]-[10].

There are various types of faults which can be classified as follows [1], [11]-[13]: Wear/ Fingerprints deformation/ Seizure/ Fissure surfaces/ Corrosion/ Scaling/ Cracks. There are also several diagnosis techniques for bearing faults detection [29]-[31]:

- Diagnosis by vibration measurement;
- Diagnosis by chemical analysis;
- Diagnosis by temperature measurement;
- Diagnosis by acoustic emission;
- Diagnostic by sound pressure;
- Diagnosis by laser displacement measurement;
- Diagnosis by stator currents analysis.

The technique used in this paper for squirrel cage induction machines online faults detection and location is based on the spectral analysis of currents Concordia vectors. This technique is based on the detection of harmonic frequency components generated on the α-β components current spectrum.

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These harmonic frequencies result from imbalance produced by fault presence in different parts of the machine [14]-[16].

Other harmonic frequencies produced due to machine geometry are known as space or rotor slots harmonics and they appear both in the current Concordia vectors spectrum and also in the LISSAJOU form of currents Concordia vectors.

II. Spectral Content of Electrical Quantities with and without Faults

The Ball type bearings are widely used in electrical machinery. They are composed mainly of the outer ring, the inner ring, the balls and the cage providing equidistance between the balls. Fig. 1 shows the geometry of the bearing radial ball.

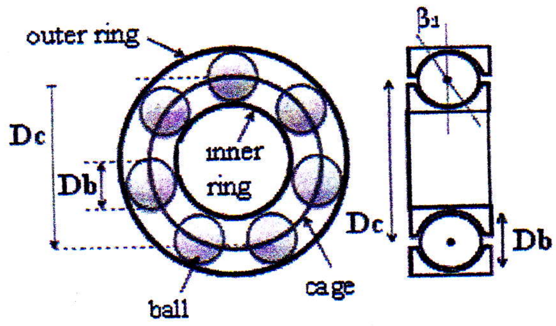


Fig. 1. Geometry of the ball bearing

The characteristic frequencies of the bearing faults are obtained experimentally using vibration monitoring and analysis [11], [17].

They are based both on the geometry of the bearing and the rotation frequency.

In general, to describe the operation of a squirrel cage motor, the two-dimensional representation is used. One of these representations is the currents Concordia vectors given as [18]-[21]:

$$\begin{cases} i_\alpha = \sqrt{\frac{2}{3}} i_{sa} - \frac{1}{\sqrt{6}} i_{sb} - \frac{1}{\sqrt{6}} i_{sc} = \frac{\sqrt{6}}{2} i_m \sin(2\pi f t) \\ i_\beta = \frac{1}{\sqrt{2}} i_{sb} - \frac{1}{\sqrt{2}} i_{sc} = \frac{\sqrt{6}}{2} i_m \sin\left(2\pi f t + \frac{\pi}{2}\right) \end{cases} \quad (1)$$

i_{sa}, i_{sb}, i_{sc} : Three-phase currents;

i_m : Maximum value of the phase current;

f : Power supply frequency.

The harmonic frequencies of the different faults in a bearing are given by, [11], [22]-[24]:

- *Outer ring fault:*

$$f_{ring,out} = \frac{N_b}{2} fr\left(1 - \frac{D_b}{D_c}\cos\beta_1\right) \quad (2)$$

- *Inner ring fault:*

$$f_{ring,in} = \frac{N_b}{2} fr\left(1 + \frac{D_b}{D_c}\cos\beta_1\right) \quad (3)$$

- *Cage fault:*

$$f_{cage} = \frac{1}{2} fr\left(1 - \frac{D_b}{D_c}\cos\beta\right) \quad (4)$$

- *Balls bearing fault:*

$$f_{balls} = \frac{D_c}{D_b} fr\left(1 - \frac{D_b^2}{D_c^2}\cos^2\beta_1\right) \quad (5)$$

Schoen and co-authors [11] have shown that the bearing faults can manifest themselves as faults in the asymmetric rotor. These are generally classified as harmonics characterizing the eccentricity faults on rotation, which leads to periodic changes of inductances in the machine. This should produce additional frequencies in the stator current and therefore on the α-β components current spectrum.

II.1. Without Faults

For a healthy functioning of the cage induction motor, in addition to the fundamental frequency, appears in the current spectrum, the rotor slots harmonics at frequencies (f_{sh}) given by the following expression:

$$f_{sh} = f\left[\frac{k \cdot n_b}{p}(1-s) \pm \nu\right] \quad (6)$$

with f as the power supply frequency, s as the slip, p as the number of pole pairs, ν as the time order harmonics (harmonics generated by the power supply), nb as the number of rotor bars and k = 1,2 ... positive integers.

II.2. With Bearing Faults

The presence of bearing faults is manifested by the generation of harmonics in the stator current spectrum leading to the production of harmonic components of currents Concordia vectors in the spectrum.

The fault in the bearing outer ring affects the components of the Concordia vectors by producing new harmonics at the frequency [3], [25]-[27]:

$$f_{bearing} = \left| f \pm k \cdot f_{ring,out} \right| \quad (7)$$

where $f = 50$ Hz. Replacing the geometrical data cited in equation (2) (Appendix B), gives the frequency of the cage as follows:

$$f_{ring,out} = 89.27 - 89.27 \cdot s \quad (8)$$

where s is the slip.

By cons, the fault in the inner ring of the bearing is manifested by the production of harmonic in the currents Concordia vectors spectrum:

$$f_{bearing} = \left| f \pm k \cdot f_{ring,in} \right| \quad (9)$$

Replacing the geometrical data cited in Eq. (3) (Appendix B), we obtain the frequency of the outer ring as:

$$f_{ring,in} = 135 - 135 \cdot s \quad (10)$$

By cons, fault in the bearing cage is manifested by the production of harmonic in the currents Concordia vectors spectrum:

$$f_{bearing} = \left| f \pm k \cdot f_{cage} \right| \quad (11)$$

Replacing the geometrical data cited in Eq. (4) (Appendix B), we obtain the frequency of the cage as:

$$f_{cage} = 10 - 10 \cdot s \quad (12)$$

and the fault of the ball bearing is manifested by the production of harmonic in the currents Concordia vectors spectrum:

$$f_{bearing} = \left| f \pm k \cdot f_{balls} \right| \quad (13)$$

Replacing the geometric data cited in equation (5) (Appendix B), we obtain the frequency of the ball bearing as:

$$f_{bearing} = \left| f \pm k \cdot f_{ball} \right| \quad (14)$$

III. Experimental Results of Faults Diagnosis of Bearings

The main experimental tests illustrated in this article are performed by ''the diagnosis group'' in the Laboratory of the Development of Electrical Drives (LDEE) USTO university.

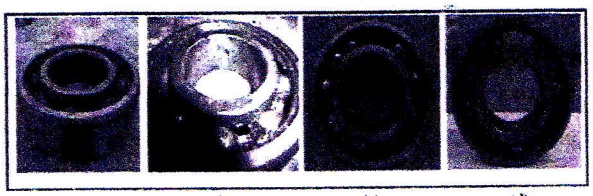
The motor used in these tests is a three-phase squirrel cage induction motor coupled to a DC generator. The motor parameters are given in Appendix A.

Our motor bearings are of ball type, with the reference 6206-ZZ (coupling side) and with the reference 6205-ZZ (opposite coupling side), whose geometrical parameters are given in Appendix B.

The faults dealt with in this paper are listed below:

- Fault of the bearing outer ring,
- Fault of the bearing inner ring,
- Fault of the bearing cage,
- Fault of the ball bearing.

These faults are produced artificially by drilling in the bearing in order to create the same situation as real faults, (see Figs. 2).



Figs. 2. Faults created in the bearings used in our experiments (a) outer ring fault, (b) inner ring fault, (c) cage fault, (d) ball fault

The measurement equipments consists of two current Hall Effect sensors and an acquisition card connected to a computer for viewing the processing of the signals picked up as shown in Fig. 3.

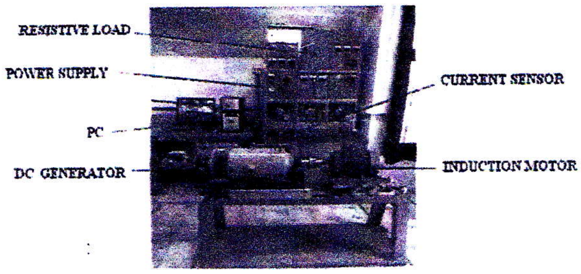


Fig. 3. Motor experimental setup

The different experimental tests focused on the following operating cases:

- Operation of the healthy motor,
- Operation of the motor with outer ring fault,
- Operation of the motor with inner ring fault,
- Operation of the motor with ball fault,
- Operation of the motor with cage fault.

The non-sinusoidal stator windings distribution generates space harmonics. These harmonics manifest themselves as ripples in the time domain of the current harmonics and high frequency harmonics also known as slot rotor harmonics in the stator current frequency spectrum. These harmonics occur in pairs at regular intervals. Harmonic frequencies of the rotor slots are given by Eq. (6). The procedure adopted in this paper for the bearing faults diagnosis is presented by various steps as follows [28]:

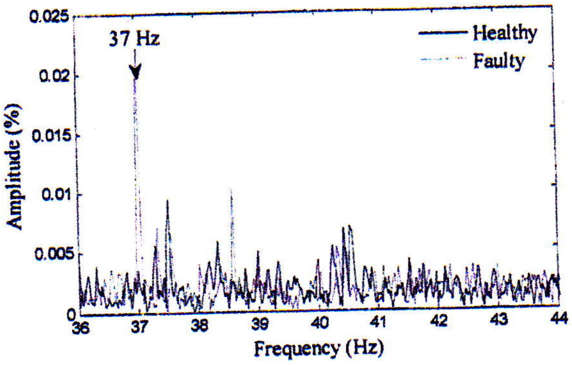
- Estimating of slip by determining the first rotor slot harmonic,
- Predicting of harmonic frequencies characterizing bearing faults deduced from the various theoretical formulas given above,
- Checking of the presence of the predicted harmonic frequencies with those occurring (captured) in the real stator current spectrum.

For the study of each bearing fault, the spectral analysis of the following electrical quantities will be considered:

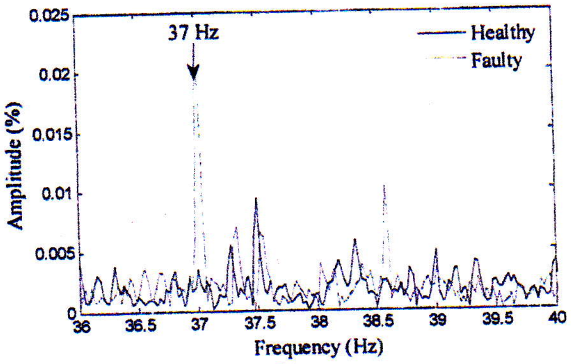
- The stator current,
- The α Concordia component,
- The β Concordia component.

The objective of the analysis is to find the most sensitive electrical quantity (among the three quantities listed above) when carrying the various bearing faults diagnosis. Figs. 4(a), 4(b) and 4(c) represent the spectra of the stator current, the α component and the β component in the case of a motor operating with an outer ring fault. It can be noted that in the spectra of the three electrical quantities, the presence of the harmonic characteristic of the outer ring fault frequency is 37Hz.

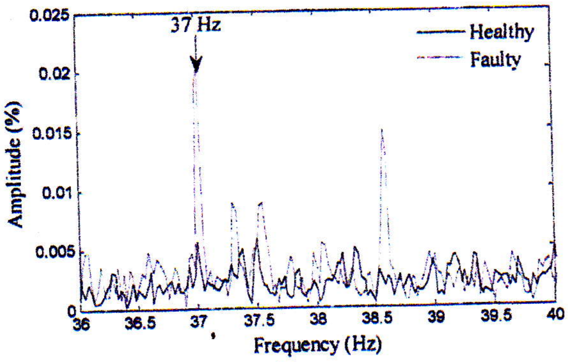
The obtained results validate the theoretical relation (Eq. (10)) which predicts the frequency of the outer ring fault. The amplitude of the harmonic characteristic of the outer ring fault for the stator current, the α component and the β Concordia component is respectively 0.01968, 0.01968 and 0.02022.



(a)



(b)



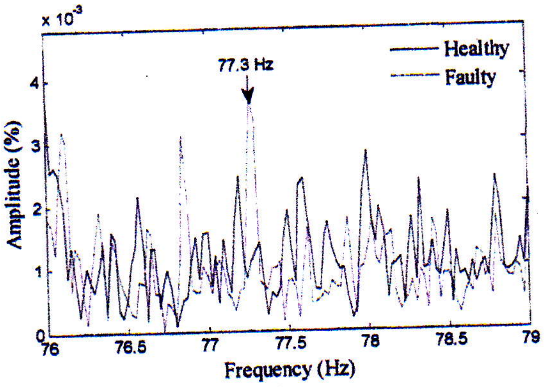
(c)

Figs. 4. Case of operating the motor with the outer ring bearing faults, (a) the stator current spectrum, (b) spectrum of the α Concordia component c: spectrum of the β Concordia component

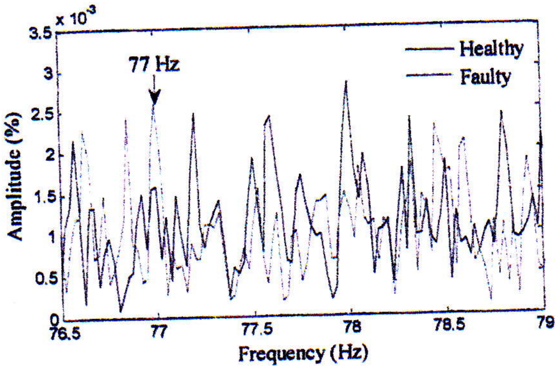
It can be seen that, among the three quantities, the β Concordia component is more sensitive to the presence of the outer ring fault.

Figs. 5(a), 5(b) and 5(c) represent respectively the spectra of the stator current, the α and the β Concordia components in the case of the motor operating with an inner ring fault.

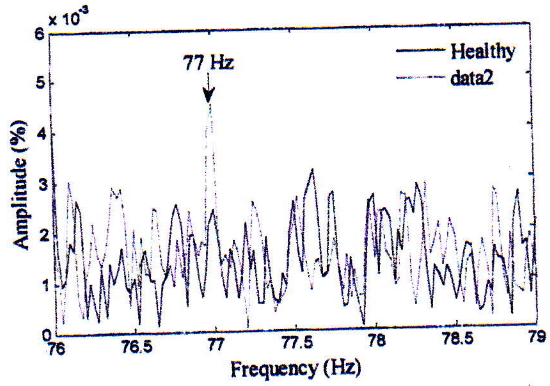
It can be noticed the appearance of the harmonic characteristic of the inner ring fault in the spectrum of the three electrical quantities at frequency 77Hz. It can also be noticed the significant sensitivity of the β Concordia component of this type of fault compared to the other ones.



(a)



(b)

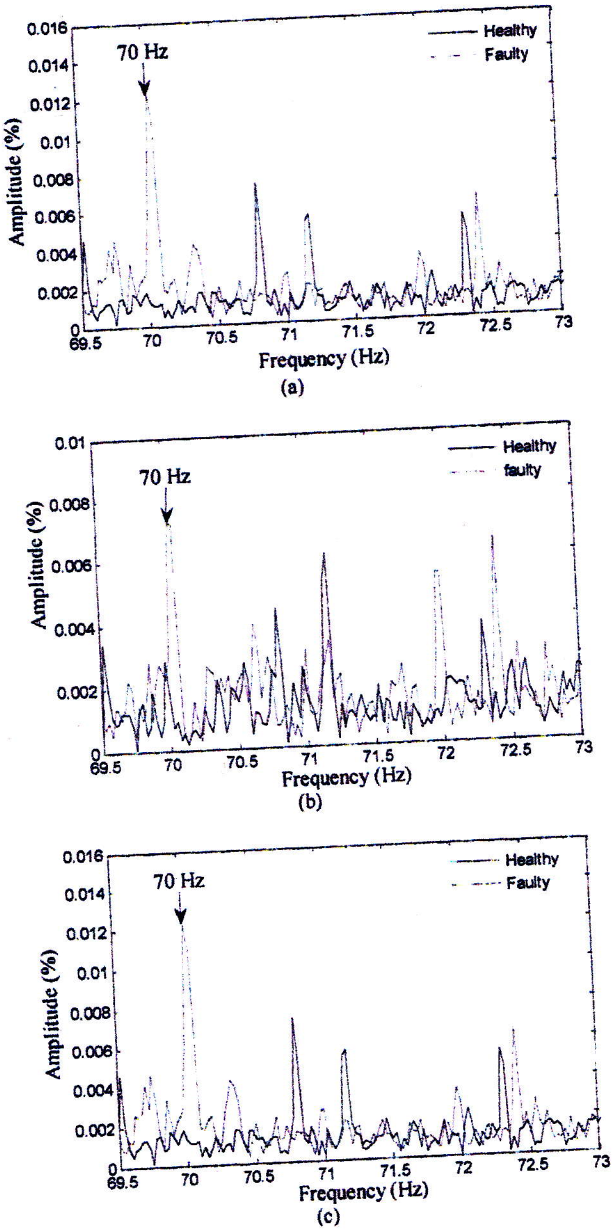


(c)

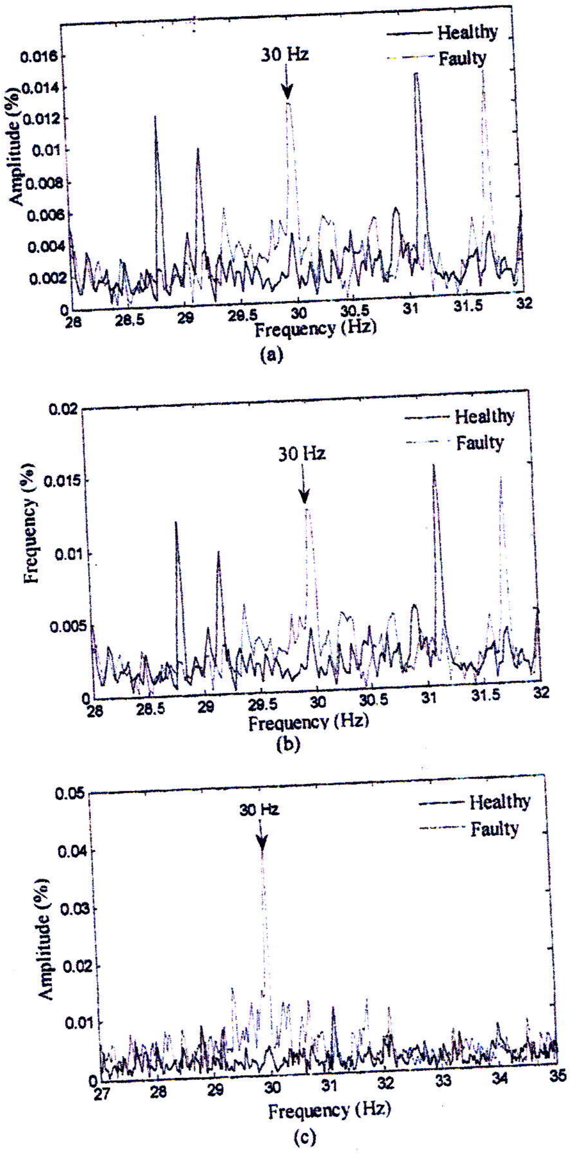
Figs. 5. Case of operating the motor with the inner ring bearing faults, (a) the stator current spectrum, (b) spectrum of the α Concordia component, (c) spectrum of the β Concordia component

Figs. 6(a), 6(b) and 6(c) represent respectively the spectra of the stator current, the α and β Concordia components in the case of the motor operating with a ball fault. It can be seen the presence of the harmonic characteristic of the ball fault in the spectrum of the three electrical quantities at frequency 70Hz. We also note the sensitivity of the β Concordia component of this type of fault compared to the other electrical quantities.

Figs. 7(a), 7(b) and 7(c) represent respectively the spectra of the stator current, the α component and β component in the case of the motor operating with cage fault. It can be seen the presence of the harmonic characteristic of the cage fault in the spectrum of the electrical quantities at frequency 30Hz.



Figs. 6. Case of operating the motor with ball bearing faults, a: the stator current spectrum, b: spectrum of the α Concordia component, c: spectrum of the β Concordia component



Figs. 7. A case of operating the motor with cage fault, (a) the stator current spectrum, (b) spectrum of the α Concordia component, (c) spectrum of the β Concordia component

It can be noted the sensitivity of the β Concordia component of this type of fault compared to the other quantities. Tables I and II summarize the obtained results for the various faults dealt with in this paper.

TABLE I

AMPLITUDE AND FREQUENCY CHARACTERISTICS OF THE FAULTS OF THE OUTER AND INNER RING FOR THE THREE ELECTRICAL QUANTITIES

	Outer ring fault		Inner ring fault	
	Freq(Hz)	Amp (%)	Freq (Hz)	Amp (%)
Stator current spectrum	37	0.01968	77.3	0.003645
Spectrum of the α Concordia component	37	0.01968	77	0.002591
Spectrum of the β Concordia component	37	0.02022	77	0.004507

TABLE II
AMPLITUDE AND FREQUENCY CHARACTERISTICS OF THE FAULTS OF THE BALLS AND CAGE FOR THE THREE ELECTRICAL QUANTITIES

	Ball fault		Cage fault	
	Freq (Hz)	Amp (%)	Freq (Hz)	Amp (%)
Stator current spectrum	70	0.01223	30	0.01235
Spectrum of the α Concordia component	70	0.00748	30	0.01242
Spectrum of the β Concordia component	70	0.01242	30	0.03722

The results show that the technique of spectral analysis of the β Concordia component is best suited for fault diagnosis of bearing faults.

IV. Conclusion

In this work we have shown the usefulness and merits of the Concordia vectors diagnostic technique for the detection and localization of bearing faults in the squirrel cage machine.

For this, we have presented in this paper the spectral analysis of three electrical quantities namely the stator current, the α Concordia component and the β Concordia component.

The experimental results carried out in our laboratory have shown on the one hand the correspondence between the theoretical frequencies and those occurring in the spectra of the three electrical quantities and on the other hand the sensitivity of the β Concordia component for the case of bearing faults.

Appendix A

Rated Power	3 kW
Supply frequency	50 Hz
Rated voltage	380 V
Rated current	7A
Rotor speed	1440 rev/min
Number of rotor bars	28
Number of stator slots	36
Power factor	0.83
Number of pair of poles	2

Appendix B

Our motor bearings are of ball type reference: 6206-ZZ 6205-ZZ, the data for these bearings are:

Coupling side reference 6206-ZZ:

- Diameter of the outer ring 62 mm,
- Diameter of the inner ring 30mm,
- Cage diameter 46 mm,
- Approximate ball diameter 9.5 mm,
- Number of ball bearings Nb = 9.

The contact angle β_1 is assumed to be equal to zero.

Opposite coupling side reference 6205-ZZ:

- Diameter of the outer ring 52 mm,
- Diameter of the inner ring 25mm,
- Cage diameter 38.5 mm,
- Approximate ball diameter 7.938 mm,
- Number of ball bearings Nb = 9.

The contact angle β_1 is assumed to be equal to zero.

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