Efficiency Assessment of Induction Motors Drives Operating Under Shaft Misalignment Conditions

Carlos VERUCCHI[1], *Esteban GIRALDO*[1], *Matias MEIRA*[1], *Cristian RUSCHETTI*[1], *Jose BOSSIO*[2] and *Guillermo BOSSIO*[2]

[1] Physics and Engineering Research Center of the Center of the Province of Buenos Aires (UNCPBA-CICPBA-CONICET), Av. Del Valle 5737, B7400JWI Olavarria, Argentina
[2]Applied Electronics Group-Research Institute for Energy Technologies and Advanced Materials (UNRC-CONICET), Ruta Nac. 36, X5804BYA Rio Cuarto, Argentina

verucchi@fio.unicen.edu.ar, esteban.giraldo@fio.unicen.edu.ar, matias.meira@fio.unicen.edu.ar, cruschet@fio.unicen.edu.ar, jmbossio@ing.unrc.edu.ar, gbossio@ing.unrc.edu.ar

DOI: 10.15598/aeee.v18i3.3596

Abstract. *Historically, the negative effects of misalignment between the motor shaft and the load on the electric drives are well known. Vibrations, loss of life of couplings and deterioration of efficiency are some of these effects. Regarding this last point, the literature offers contradictory opinions. Some studies consider that the loss of efficiency in cases of misalignment is undesirable; while others consider that it has significant importance. In this paper, experimental results show in which cases the misalignment has a significant effect on efficiency and in which cases it can be neglected. For this, radial and angular misalignment cases are studied with four of the most used flexible couplings in the industry. The obtained results are analysed in relation to the actual regulations on energy efficiency in induction motors. The reached conclusions offer new tools for the correct selection of flexible couplings tending to the improvement of energy efficiency.*

Keywords

Couplings, energy efficiency, induction motors.

1. Introduction

Induction Motors (IMs) have become an almost exclusive alternative for developing mechanical power for industrial applications. It is estimated that between 43 % and 46 % of the generated electric power in the world is currently destined to power electric motors, which are mostly IMs [1]. Current normative have established the minimum efficiency allowed for this type of machine. Premium Efficiency Motors (IE3) and Super Premium Efficiency Motors (IE4) have replaced the Standard Efficiency Motors (IE1) and the High Efficiency Motors (IE2). Besides, the tendency to continue raising the minimum efficiency levels allowed is expected in the future [2]. IEC 600340 [3] standardizes the classification, the measurement procedure and the indication of the efficiency data on motors. These higher efficiencies are obtained by modifications in the manufacturing process such as: shorter air-gap lengths, use of cores with reduced losses, special designs in the rotor bars and end ring, optimization and better quality of the stator winding, improved of the external cooling fan design, etc. [4].

To reduce the consumption of electrical energy, it is not only necessary to increase the efficiency levels of the motors, but also to guarantee adequate operating conditions. When an IM operates with low load levels (over-sizing), its efficiency is significantly reduced. Similarly, below-rated supply voltages or unbalanced supply voltages affect the efficiency of the IM [5], [6] and [7]. The presence of voltage harmonics is another efficiency derating factor of IMs [8]. Good maintenance practices require periodic control of all these conditions in order to ensure high levels of efficiency.

Recently, research has shown that faults in IMs can also reduce their efficiency. The most common cases of faults are cracked or broken rotor bar and wear of rolling bearings [9]. In addition to these cases, other faults such as deterioration of the magnetic core, fan defects or short- circuited turns of the windings increase the losses of an electrical machine.

Another operating condition that increases the losses in electric drives is the misalignment between the motor and the driven load. Flexible couplings are currently used for power transmission through which they can be easily coupled between the motor and the load. Besides, these couplings can operate with certain levels of misalignment. Misalignment produces losses due to heating of the flexible element and additional stress in the IM and load bearings [10]. In [11], a mathematical model is presented to find the variations that occur in the torque transmitted from the motor to the load when the shafts are not perfectly aligned. Such variations consist of torque fluctuations at the coupling rotation frequency and its multiples. Torque fluctuations, in turn, cause harmonic components in the stator current. These components are not linked to the mechanical power transmitted to the load, although they generate losses in the windings. On the other hand, [12] and [13] analyse the temperature increase that occurs in the coupling and bearings in cases of misalignment. This temperature rise involves greater losses of energy.

The literature has extensively dealt with the misalignment problem [10], [11], [12], [13], [14] and [15]. One of its most serious consequences lies in the generation of vibrations. Vibrations can cause damage to the motor or other components of the drive [13]. Furthermore, the couplings' lifetime is significantly reduced as the misalignment increases. This is due to the fact that misalignment causes additional stresses on the couplings in relation to a perfect alignment state.

Some researchers suggest that the efficiency reduction due to the misalignment effects is not significant and can be rejected [10] and [13]. Nevertheless, other authors affirm that for misalignments above to those allowed by the couplings, the losses can reach up to 2.3 % of the rated power of the motor [16]. However, these researches were made in the last century, when energy efficiency issues of electric motors had not gained the current relevance. Nowadays, the reduction of energy consumption and care for the environment is much more demanding than in previous decades. Slight improvements in the efficiency levels of electric motors can be of great importance. Such a situation forces not to discard any possibility that allows the increase of the motor efficiency.

Conclusions presented in [10], on the other hand, only consider misalignments less than or equal to the limits recommended by each manufacturer. So, real situations that occur in the industry where these limits are exceeded are not taken into account. Otherwise, it should be noted that some manufacturers have raised such limits of permissible misalignment through the development of new models of flexible couplings.

For all these reasons, it is interesting to review the relation between misalignment and efficiency loss from a current point of view and taking into account modern flexible coupling models. It is also considered useful to analyse situations where misalignment degree exceeds the allowed ones by the manufacturer. Therefore, it is proposed to analyse the efficiency loss in drives with flexible couplings through experimental studies for cases of radial misalignment and angular misalignment. The growing demands in relation to the energy efficiency justify the study. It is focused on low-power electric motors, which demand a significant fraction of the total electrical energy consumed by electric motors. Likewise, it is considered important the behaviour of each of the flexible couplings currently used in the industry in relation to the efficiency loss due to misalignment. Thus, it is expected to provide useful elements for proper selection.

The problem of misalignment in general terms is described in the following section and lists the different cases that arise in industrial applications. Meanwhile, in Sec. 2. the consequences of misalignment on the motor's electric torque and stator current are analysed. Section 3. shows the experimental results obtained from a 5.5 kW motor and different types of flexible couplings. Finally, in Sec. 4. the obtained results are discussed and the reached conclusions are analysed.

2. General Characteristics of Misaligned Drives

In order to carry out the mechanical power transmission from a motor to a load under ideal conditions, the axes of each machine must coincide. In this case, it is considered that the shafts are aligned with each other. In industrial applications, this condition is very difficult to achieve. Small misalignments usually occur between the shafts of each machine. The elements that are used to couple one shaft with another, such as flexible couplings, are designed to tolerate small deviations in the alignment.

These misalignments can be of two types: angular misalignment and radial misalignment. It is considered that there is angular misalignment when the rotation shafts of each machine are contained in two lines intersecting at the centre of the coupling as shown in Fig. 1(a). In such a case, the misalignment degree is given by the angle α. On the other hand, it is considered that radial misalignment occurs when the shafts of each machine are perfectly parallel but not coincident, as shown in Fig. 1(b). In this case, the misalignment degree is given by the distance between each shaft, indicated as d in Fig. 1(b). This differentiation between angular misalignment and radial misalignment is established mainly for study purposes; in practice, both misalignment types usually occur simultaneously.

Misalignment situations are widespread in industrial applications. They usually arise during an inadequate assembly process, in efforts on the shafts due to faulty operation of gearboxes or belts, looseness of the motor or load fasteners, and in eccentricities of the components of the drive, among many others.

Misalignment problems cause excessive stress on bearings, bending stresses on shafts and vibrations, among other undesirable effects. To reduce these effects, elastic couplings are generally used. This coupling type is able to bear small misalignment levels and dampens disturbances that occur on the power transmission between shafts. With the use of these couplings, it is possible to reduce unwanted vibrations and stresses on other elements of the installation. Flexible couplings of different characteristics are offered in the market. Each of them allows a certain tolerance in both angular and radial misalignment.

Although these couplings significantly improve the behaviour of power transmission, high misalignments cause a significant reduction in their useful life. In addition, the increase in system losses due to stresses on the couplings causes its temperature increase [10] and [14].

Figure 2 shows some of the most used flexible couplings in the industry [13]. The so-called Jaw couplings (Fig. 2(a)) stand out for their low cost and easy installation. The joining element is constituted by elastomeric materials and goes up to speeds of 5.000 RPM. They allow high levels of angular misalignment and are one of the most used options in industrial applications.

Gear couplings (Fig. 2(b)), on the other hand, show high torque density and are torsion-resistant. The joining element is constituted by synthetic resin and goes up to speeds of 50.000 RPM. Metal Ribbon Couplings (Fig. 2(c)) allow torsion as well as angular and radial misalignment and can be used up to speeds of approximately 6.000 RPM. Unlike other couplings, the flexible element must be grease-lubricated, which determines certain limitations in relation to the working temperature. Finally, the Rubber-type couplings (elastomeric joint) (Fig. 2(d)), which are ideal for damping vibrations and go up to speeds of 5.000 RPM, are one of the most used. In these cases, the lifetime of the flexible element is seriously reduced when the misalignment is greater than the allowed one.

As it is shown in [12] and [17], in the event of misalignment, a cyclical variation in the transmitted torque by the motor to the load is observed. This disturbance is repeated at twice the shaft rotation frequency Eq. (1) and is reflected in its multiples and submultiples.

$$T_k = \left[\frac{1}{\cos\alpha} - \frac{\sin^2\alpha}{2\cos\alpha} - \left(\frac{\sin^2\alpha}{2\cos\alpha}\cdot\cos 2\theta_l\right)\right] T_l, \quad (1)$$

where θ_l is the angular position of load and T_l is the load torque. Equation (1) shows that if the misalignment angle is zero, the transmitted torque coincides with that requested by the load. The fluctuation produced by the misalignment, on the other hand, increases its amplitude as the misalignment level increases. A torque fluctuation is reflected in the motor stator current through sidebands around the mains frequency, as indicated in Eq. (2).

$$f_s = f \pm n f_r, \quad (2)$$

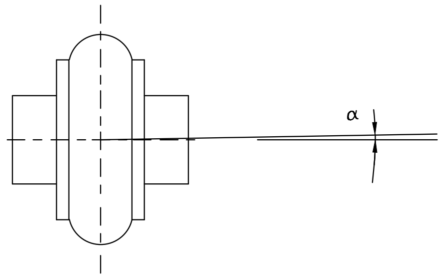
where n are integers greater than zero, f is the supply frequency and f_r the motor rotation frequency. Thus, it is possible to affirm that misalignment cases are observed in the motor stator current and could be detected from its tracing. The mathematical model represented by Eq. (1) and Eq. (2) was obtained considering a universal coupling. Therefore, its application to cases of flexible couplings such as those presented in Fig. 2 is not possible. However, it is useful to understand the nature of the phenomenon and its effect on the transmitted torque and the stator current. Complementary studies [17] have shown that the misalignment phenomenon is also reflected in torque harmonic components at the rotation frequency. In [11], an alternative model for misalignment cases is presented where the same conclusions as those obtained in this work are reached.

3. Experimental Results

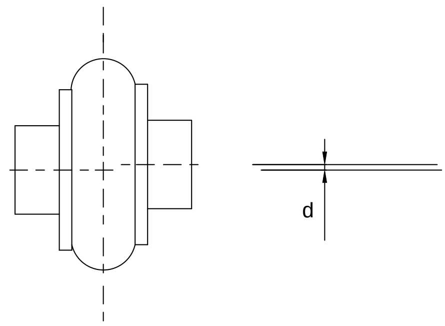
3.1. Misalignment Effects on the Stator Current, Electrical Torque and Coupling Temperature

In the field of preventive maintenance of rotating electrical machines, important advances have been made during the last decades. On-line application techniques have been proposed and tested successfully for both induction machines [18] and synchronous machines [19]. The advantage of these techniques over the traditional ones lies in the possibility of implementing continuous monitoring of a machine without removal from service. Some works even propose to use the electric motor as a sensor, in order to extend the diagnosis to the entire drive. So, it is possible to detect misalignment between shafts [12] and [17] or faults in gearboxes [20], among others.

According to the model presented in the previous section, it can be ensured that a misalignment case could be detected from the tracking of the component at twice the rotation frequency and its multiples in the transmitted electrical torque by the motor or in the sidebands that are observed around the fundamental frequency in the stator current [11], [21] and [22]. In [17], it is shown that the misalignment phenomena can also be detected from the tracking of the rotation frequency component in the electric torque. When the transmitted torque is used as a diagnostic tool, it is not essential to use a torque sensor. On the contrary, it is possible to use an estimated torque based on the measurement of the voltages and currents in the motor terminals. When the motor is at a steady-state, the same components as in the torque are observed in the electrical power input.



(a) Angular misalignment.



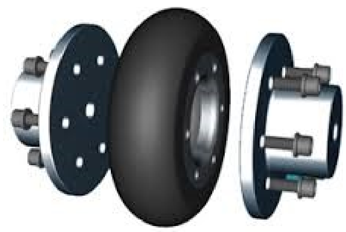
(b) Radial misalignment.

Fig. 1: Different types of misalignment.

(a) Jaw coupling.

(b) Gear coupling.

(c) Metal ribbon coupling.



(d) Rubber tire-type coupling.

Fig. 2: Different types of couplings.

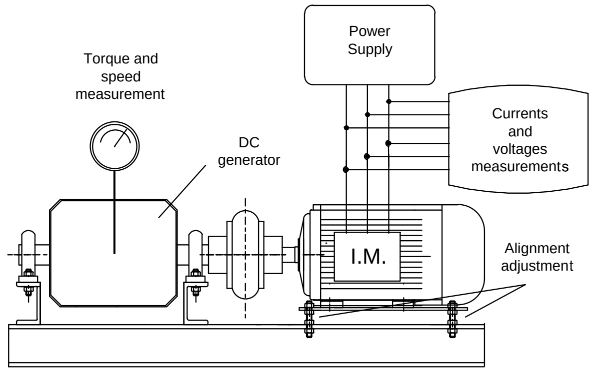


Fig. 3: Schematic laboratory assembly.

In Fig. 3, a schematic of the test bench used for laboratory tests is presented. A motor of 5.5 kW, 36.2 Nm, 4 poles, 11.6 A, 50 Hz and 380 V was used. In all tests, the induction motor was powered from the grid and its speed ranges between 1450 RPM and 1499 RPM, depending on the corresponding load factor. The motor is suspended on a base which can be moved relative to the load base. Thus, through the regulators indicated in Fig. 3 as "alignment adjustment", it is possible to misalign the motor in both angular and radial directions. An analysis of the frequency spectrum of the instantaneous power for a jaw coupling with different load states and misalignment degrees are observed in Fig. 4 and Fig. 5, obtained through the experimental laboratory results. Particularly, Fig. 4 shows the frequency spectrum of the instantaneous power consumed by a motor of 5.5 kW under normal operating conditions (without misalignment). The motor is operating with a 50 % load factor. A small component is observed at the motor rotation frequency (f_r), while no appreciable components are observed at the multiple frequencies of the previous one ($2f_r$ and $3f_r$). The component at f_r can be attributed to a small misalignment or to a mass imbalance in the motor or load. In Fig. 5, the same frequency spectrum is presented but in this case with a 2 mm radial misalignment intentionally caused. In this case, the component at f_r is observed significantly higher than that observed in Fig. 5. Moreover, components at $2f_r$ and $3f_r$ are easily identifiable. These changes are undoubtedly due to the misalignment between the motor and load shafts.

The fluctuations in the instantaneous power absorbed by the motor are reflected in the stator current at the frequencies given by Eq. (2). In Fig. 6 and

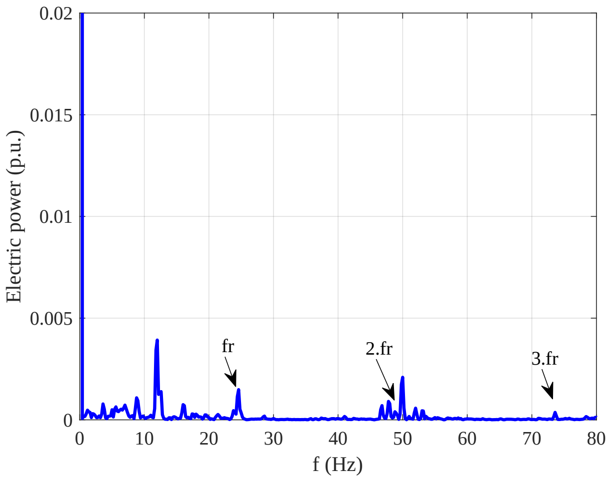


Fig. 4: Electric power frequency spectrum - Jaw coupling - 50 % of load - aligned shafts.

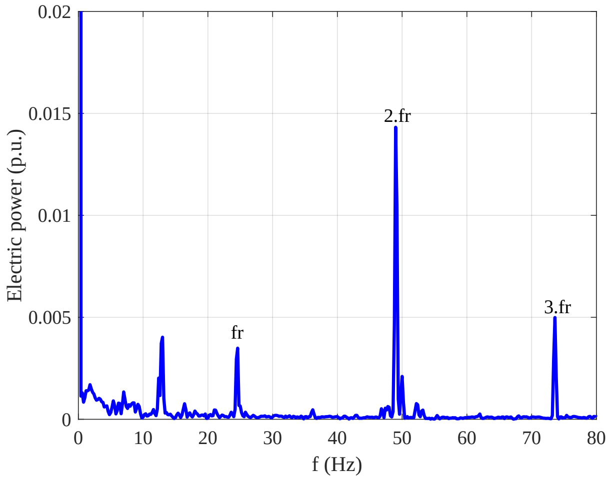


Fig. 5: Electric power frequency spectrum - Jaw coupling - 50 % of load - 2 mm radial misalignment.

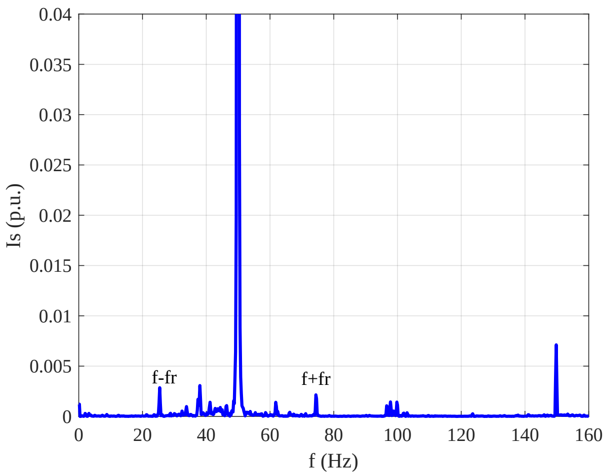


Fig. 6: Stator current frequency spectrum - Jaw coupling - 75 % of load - aligned shafts.

Fig. 7, the frequency spectrums of the stator currents are presented for the cases of alignment and 2 mm radial misalignment, respectively. In Fig. 7, components at $f - f_r$, $f + f_r$ and $f + 2f_r$ are clearly observed. These components are practically not seen in Fig. 6. It is important to highlight that these harmonic components do not provide mechanical power transmitted to the load; however, their flow through the windings generates electrical losses.

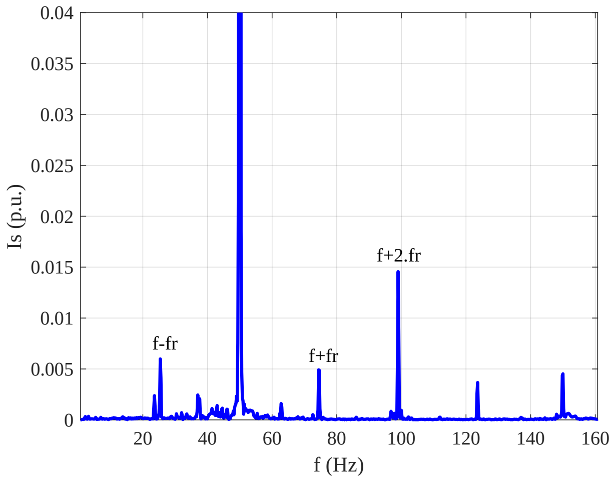
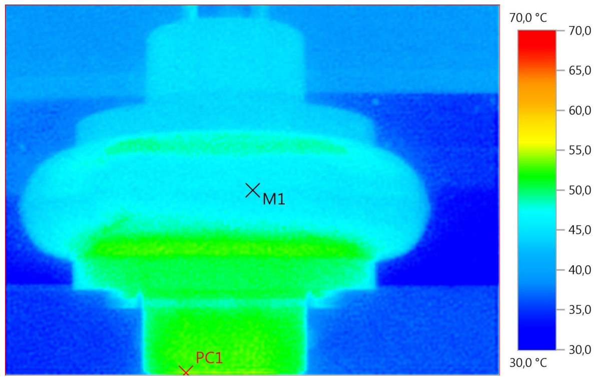
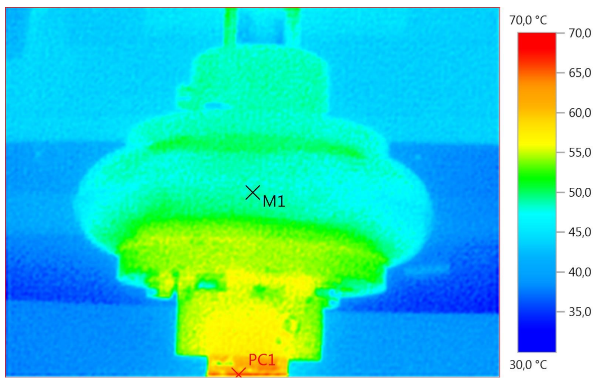


Fig. 7: Stator current frequency spectrum - Jaw coupling - 75 % of load - 1.5 mm radial misalignment.



(a) Aligned.



(b) Radial misalignment (1 mm).

Fig. 8: Thermal images in a rubber tire-type coupling.

On the other hand, as it was advanced in the introduction, the additional efforts that occur in a flexible coupling due to the misalignment operating conditions increase its temperature. In [13], this effect is analysed for couplings of different characteristics and for different misalignment levels. With misaligned couplings, temperatures increase between 20 °C and 30 °C depending on the type of coupling. In Fig. 8, a comparison is presented on a rubber tire-type coupling. This is coupled to the 5.5 kW IM transmitting its nominal power. In Fig. 8(a) and Fig. 8(b), a thermal image is presented for the case of aligned shafts and 1 mm radial misalignment, respectively. The figures show the temperature increase registered in the coupling in presence of misalignment.

3.2. Misalignment Effects on the Efficiency

In order to weigh the loss of efficiency in cases of misalignment, the test bench described in Sec. 3.1. was used. Before each test, the motor was kept in nominal operating conditions for one hour in order to achieve thermal equilibrium. The ambient temperature was maintained at 25 °C. The efficiency measurement was made through the procedure called "direct method" [22] that is measuring the power consumed by the motor and the power transferred to the load. The efficiency was obtained according to Eq. (3):

$$\eta = \frac{P_m}{P_e} \cdot 100, \qquad (3)$$

where P_m is the mechanical output power and P_e is the consumed power by the IM.

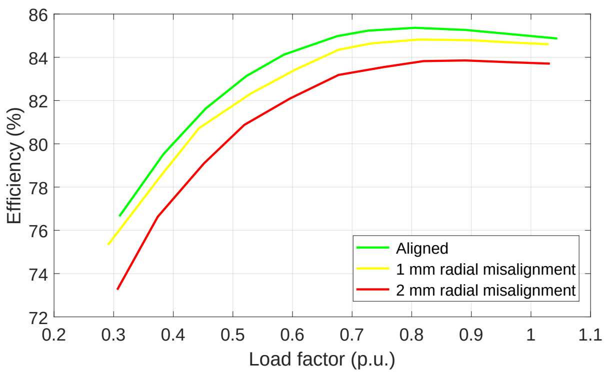


Fig. 9: Motor efficiency with jaw coupling - radial misalignment.

Figure 9 shows the efficiency curves as a function of the load factor for a jaw coupling. A first test was performed with the aligned shafts and then the procedure with radial misalignment of 1 and 2 mm was repeated. The comparison allows verifying that there is an efficiency reduction in cases of misalignment for all load states analysed. The efficiency reduction is more evident as the misalignment between the motor shafts and load increases. Figure 10 shows the efficiency values measured with the same coupling, as in Fig. 11, but in this case for angular misalignment. It can be noted that the efficiency loss for angular misalignment is less than for radial misalignment.

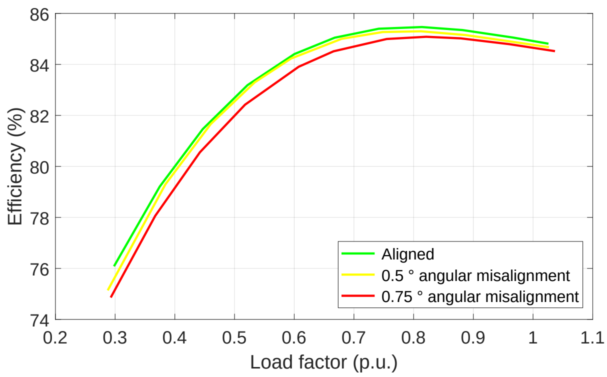


Fig. 10: Motor efficiency with jaw coupling - angular misalignment.

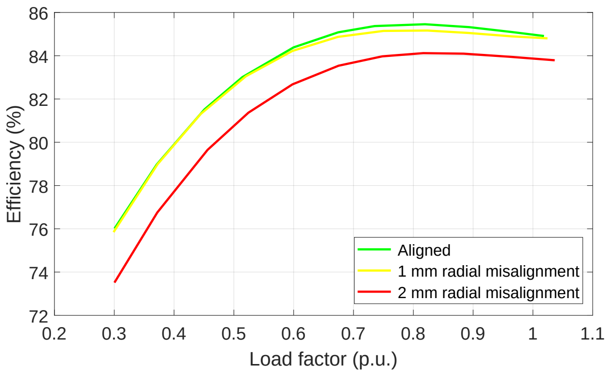


Fig. 11: Motor efficiency with rubber tire-type coupling - radial misalignment.

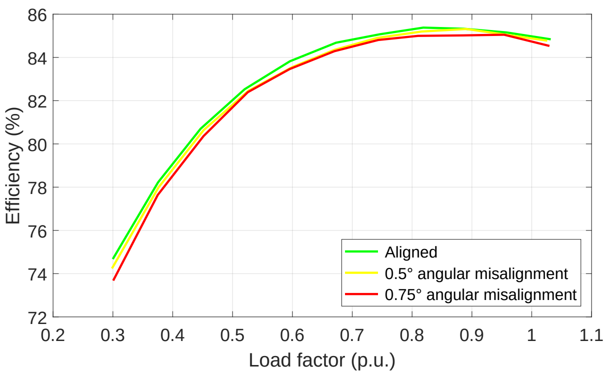


Fig. 12: Motor efficiency with rubber tire-type coupling - angular misalignment.

The results for a rubber tire-type coupling are presented in Fig. 11 and Fig. 12. In this case, as in the previous one, a more significant efficiency reduction for radial misalignment is observed. Moreover, it is observed that for 1 mm radial misalignment, the efficiency loss is almost imperceptible, while for a 2 mm radial misalignment, it is much more evident. In both cases, for the motor in nominal load condition, efficiency losses greater than 1 % were recorded.

Tab. 1: Permissible misalignment for different couplings (different manufacturers considered).

	Rubber tire-type coupling	**Jaw coupling**	**Metal ribbon coupling**	**Gear coupling**
Radial misalignment (mm)	0.5–1	0.3–0.5	0.5	0.8–1.2
Angular misalignment (°)	1–3	1–1.5	0.5	1.5

Table 1 indicates the permissible misalignment levels defined by the flexible coupling manufacturers with characteristics similar to those used in the tests. It should be noted that these couplings were selected using the usual procedure based on transmitted torque, rotation speed and shaft diameter. Limit values vary significantly from one manufacturer to another; therefore, in some cases, ranges of values are indicated. The results presented in this paper consider misalignments that reach values greater than the admissible ones. This is intended to include possible frequent cases in practice, in which the limits imposed by the manufacturer are exceeded due to poor maintenance procedures.

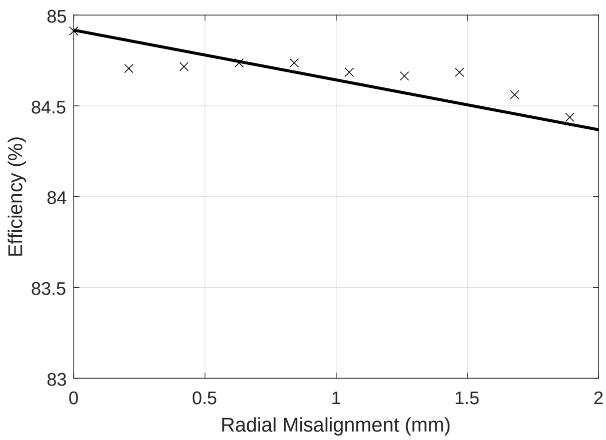


Fig. 13: Motor efficiency with rubber tire-type coupling vs. radial misalignment.

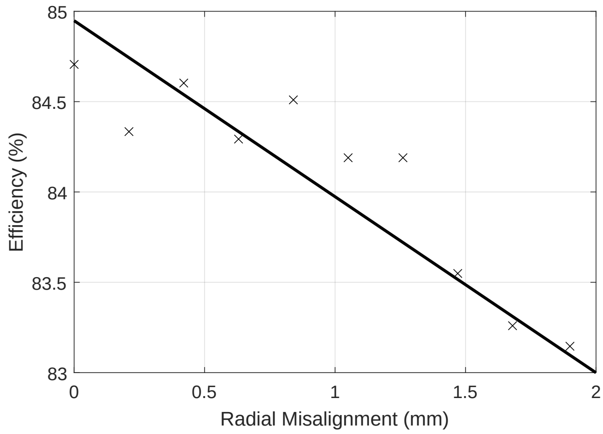


Fig. 14: Motor efficiency with jaw coupling vs. radial misalignment.

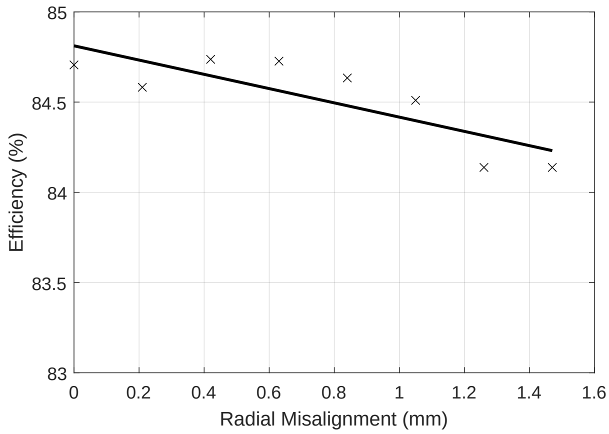


Fig. 15: Motor efficiency with metal ribbon coupling vs. radial misalignment.

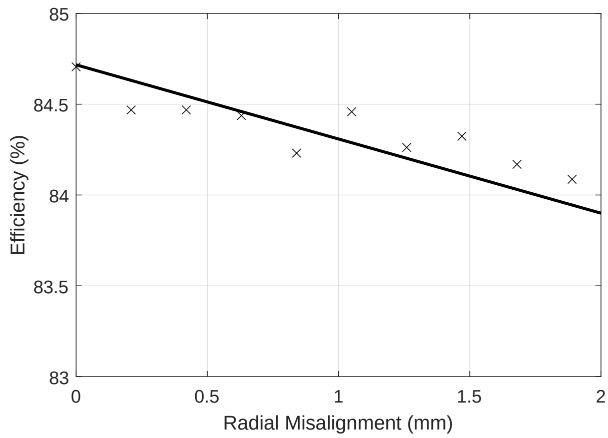


Fig. 16: Motor efficiency with gear coupling vs. radial misalignment.

In order to find the efficiency variation of the drive as a function of the misalignment degree, tests were carried out, maintaining the load factor at 0.95 and progressively increasing the misalignment. The tests were repeated for each of the four drives studied and for the two possible radial and angular misalignments. The cases of radial misalignment are presented in Fig. 13, Fig. 14, Fig. 15 and Fig. 16. In each figure, the values obtained in the tests and a linear approximation of them are shown. For rubber tire-type coupling, the efficiency loss is less than 0.5 % for the maximum misalignment allowed by that type of coupling and somewhat less than 1 % for twice the permissible misalignment. In the case of jaw coupling, the efficiency reduction for radial misalignment is 0.6 % for the maximum permissible misalignment. For metal ribbon coupling, the efficiency reduction is 0.5 % for the maximum misalignment allowed and, lastly, for gear coupling it is rather higher than 0.5 % of the manufacturer admitted misalignment.

Regarding angular misalignment, the rubber tire-type coupling causes an efficiency loss of 1.2 % with a 2 ° misalignment (the maximum allowed is 3 °). The jaw coupling presents an efficiency reduction of 1.16 % with 1.5 ° misalignment. In the metal ribbon coupling, practically no efficiency loss is observed with angular misalignment and, finally, an efficiency reduction of 1.8 % is produced for 1.5 ° misalignment (misalignment that is somewhat below the maximum allowable) with the gear coupling.

Table 2 and Tab. 3 present a more exhaustive comparison for the four types of couplings tested and the different misalignment levels caused. The values indicated by the tables are calculated based on linear approximation. In general terms, there is an efficiency reduction due to misalignment in all cases. In some cases, such as drives with angular misalignment with metal ribbon coupling, the efficiency reduction is irrelevant. However, in other cases, reductions between 1 % and 2 % could be verified. It is important to note that in the test, only angular misalignment and radial misalignment were caused independently. In practical cases, it is possible that both types of misalignment occur simultaneously, expecting a greater efficiency reduction percentage of the drive.

Tab. 2: Percentage efficiency variation for radial misalignment and load factor of 0.95 (obtained from linear approximation).

Radial misalignment (mm)	Rubber tire-type coupling	Jaw coupling	Metal ribbon coupling	Gear coupling
0.5	−0.17	−0.57	−0.24	−0.23
1	−0.33	−1.14	−0.48	−0.46
1.5	−0.49	−1.71	−0.7	−0.69
2	−0.64	−2.28	-	−0.92

Tab. 3: Percentage efficiency variation for radial misalignment and load factor of 0.95 (obtained from linear approximation).

Angular misalignment (°)	Rubber tire-type coupling	Jaw coupling	Metal ribbon coupling	Gear coupling
0.5	−0.28	−0.39	−0.1	−0.59
1	−0.56	−0.78	−0.2	−1.18
1.5	−0.84	−1.16	−0.3	−1.77
2	−1.12	-	−0.4	-

4. Discussion and Conclusions

In [11], the authors consider that the loss of efficiency in the presence of misalignment is negligible. In [23], for misalignment within the range allowed by the coupling manufacturer, efficiency losses of 1 % were obtained. In [16], with misalignments in excess of those allowed by the manufacturer, a loss of 2.3 % was observed, while in [24], it is claimed that the loss of efficiency could reach up to 10 %.

In this paper, it has been demonstrated that for certain models of flexible couplings and in the presence of misalignment levels that can be found in the industry, efficiency reductions of a drive cannot be underestimated. This reduction can even result in an order similar to the one that defines the transition from one efficiency class to another. That is, a drive could lower an efficiency class if certain alignment conditions are not achieved. For this reason, conclusions found in [10] regarding rejecting the efficiency reduction caused by misalignment are currently questionable. The importance of a good alignment not only lies in preventing vibrations or conserving the useful life of the coupling but also in ensuring adequate efficiency levels.

On the other hand, the studies carried out allow identifying the flexible couplings models that present greater tolerance to misalignment from the point of view of efficiency. In fact, for example, it is observed that the metal ribbon coupling presents very good performance for both types of misalignment. On the other hand, the rubber tire-type coupling mainly causes significant losses for angular misalignment, while the jaw coupling causes them for both angular and radial misalignment. Therefore, these conclusions could be useful for the proper selection of a coupling. Based on experimental tests with a 5.5 kW IM, the flexible couplings misalignment effect on the efficiency of a drive was analysed. This work allows affirming that although the loss of efficiency due to misalignment is below the values suggested by some previous researches [24], it is not in any way negligible. In some cases, and for misalignment levels often found in industrial applications, the loss of efficiency due to misalignment could compensate the benefits obtained by the use of high efficiency or premium efficiency IMs.

According to the results obtained, the need to achieve adequate levels of alignment becomes even more important. Thus, it is not only possible to maintain low levels of vibrations or to prolong the couplings and bearings lifetime, but also to optimize the installation efficiency and reduce energy consumption. Unlike previous studies, this work introduces the coupling type used as an analysis variable. In the same test bench, with a common assembly and measurement system, several of the most frequently used flexible couplings were tested. The work also offers new tools for a more suitable choice of coupling destined to a specific application.

References

[1] FERREIRA, F. J. T. E. and A. T. DE ALMEIDA. Overview on energy saving opportunities in electric motor driven systems - Part 1: System efficiency improvement. In: *IEEE/IAS 52nd Industrial and Commercial Power Systems Technical Conference (I&CPS)*. Detroit: IEEE, 2016, pp. 1–8. ISBN 978-1-4673-8672-2. DOI: 10.1109/ICPS.2016.7490219.

[2] DE ALMEIDA, A. T., F. J. T. E. FERREIRA and A. Q. DUARTE. Technical and Economical Considerations on Super High-Efficiency Three-Phase Motors. *IEEE Transactions on Industry Applications*. 2014, vol. 50, iss. 2, pp. 1274–1285. ISSN 1939-9367. DOI: 10.1109/TIA.2013.2272548.

[3] IEC Standard 60034-30 1st ed. *Rotating Electrical Machines-Part 30: Efficiency Classes of Single-speed, Three-phase, Cage-induction Motors*. Geneva: IEC, 2009.

[4] VERUCCHI, C. J., R. RUSCHETTI and G. KAZLAUSKAS. High Efficiency Electric Motors: Economic and Energy Advantages. *IEEE Latin America Transactions*. 2013, vol. 11, iss. 6, pp. 1325–1331. ISSN 1548-0992. DOI: 10.1109/TLA.2013.6710379.

[5] VAN WYK, A. L., M. A. KHAN and P. BARENDSE. Impact of over/under and voltage unbalanced supplies on Energy-Efficient motors. In: *IEEE International Electric Machines & Drives Conference (IEMDC)*. Niagara Falls: IEEE, 2011, pp. 1380–1385. ISBN 978-1-4577-0060-6. DOI: 10.1109/IEMDC.2011.5994808.

[6] SIRAKI, A. G., C. GAJJAR, M. A. KHAN, P. BARENDSE and P. PILLAY. An Algorithm for Nonintrusive In Situ Efficiency Estimation of Induction Machines Operating With Unbalanced Supply Conditions. *IEEE Transactions on Industry Applications*. 2012, vol. 48, iss. 6, pp. 1890–1900. ISSN 1939-9367. DOI: 10.1109/TIA.2012.2225813.

[7] DONOLO, P., G. BOSSIO and C. DE ANGELO. Analysis of voltage unbalance effects on induction motors with open and closed slots. *Energy Conversion and Management*. 2011, vol. 52, iss. 5, pp. 2024–2030. ISSN 0196-8904. DOI: 10.1016/j.enconman.2010.10.045.

[8] DONOLO, P., G. BOSSIO, C. DE ANGELO, G. GARCIA and M. DONOLO. Voltage unbalance and harmonic distortion effects on induction motor power, torque and vibrations. *Electric Power Systems Research*. 2016, vol. 140, iss. 1, pp. 866–873. ISSN 0378-7796. DOI: 10.1016/j.epsr.2016.04.018.

[9] GARCIA, M., P. A. PANAGIOTOU, J. A. ANTONINO-DAVIU and K. N. GYFTAKIS. Efficiency Assessment of Induction Motors Operating Under Different Faulty Conditions. *IEEE Transactions on Industrial Electronics*. 2019, vol. 66, iss. 10, pp. 8072–8081. ISSN 1557-9948. DOI: 10.1109/TIE.2018.2885719.

[10] HINES, J., S. JESSE, J. KUROPATWINSKI, T. CARLEY, J. KUECK, D. NOWER and F. HALE. Motor Shaft Alignment Versus Efficiency Analysis. P/PM Technology. 1997, vol. 10, iss. 1, pp. 10–13. ISSN 0899-1804.

[11] YAO, Y., Y. LI and Q. YIN. A novel method based on self-sensing motor drive system for misalignment detection. *Mechanical Systems and Signal Processing*. 2019, vol. 116, iss. 1, pp. 217–229. ISSN 0888-3270. DOI: 10.1016/j.ymssp.2018.06.030.

[12] BOSSIO, J. M., G. R. BOSSIO and C. H. DE ANGELO. Angular misalignment in induction motors with flexible coupling. In: *35th Annual Conference of IEEE Industrial Electronics*. Porto: IEEE, 2009, pp. 1033–1038. ISBN 978-1-4244-4648-3. DOI: 10.1109/IECON.2009.5414696 .

[13] PIOTROWSKI, J. *Shaft Alignment Handbook*. 3rd ed. Ohio: CRC Press, 2006. ISBN 978-1-5744-4721-7.

[14] NOWER D. Misalignment: Challenging the Rules. *Reliability Magazine*. 1994, vol. 7, iss. 1, pp. 38–43. ISSN 1557-0193.

[15] OBAID, R. R. and T. G. HABETLER. Current-based algorithm for mechanical fault detection in induction motors with arbitrary load conditions. In: *38th IAS Annual Meeting on Conference Record of the Industry Applications Conference*. Salt Lake City: IEEE, 2003, pp. 1347–1351. ISBN 0-7803-7883-0. DOI: 10.1109/IAS.2003.1257726.

[16] GABERSON, H. A. Rotating machinery energy loss due to misalignment. In: *Proceedings of the 31st Intersociety Energy Conversion Engineering Conference IECEC 96*. Washington: IEEE, 1996, pp. 1809–1812. ISBN 0-7803-3547-3. DOI: 10.1109/iecec.1996.553377.

[17] VERUCCHI, C., J. BOSSIO, G. BOSSIO and G. ACOSTA. Misalignment detection in induction motors with flexible coupling by means of estimated torque analysis and MCSA. *Mechanical Systems and Signal Processing*. 2016, vol. 80, iss. 1, pp. 570–581. ISSN 0888-3270. DOI: 10.1016/j.ymssp.2016.04.035.

[18] ACOSTA, G. G., C. J. VERUCCHI and E. R. GELSO. A current monitoring system for diagnosing electrical failures in induction motors. *Mechanical Systems and Signal Processing*. 2006, vol. 20, iss. 4, pp. 953–965. ISSN 0888-3270. DOI: 10.1016/j.ymssp.2004.10.001.

[19] RUSCHETTI, C., C. VERUCCHI, G. BOSSIO, C. DE ANGELO and G. GARCIA. Rotor demagnetization effects on permanent magnet synchronous machines. *Energy Conversion and Management*. 2013, vol. 74, iss. 1, pp. 1–8. ISSN 0196-8904. DOI: 10.1016/j.enconman.2013.05.001.

[20] VERUCCHI, C., G. BOSSIO, J. BOSSIO and G. ACOSTA. Fault detection in gear box with induction motors: an experimental study. *IEEE Latin America Transactions*. 2016, vol. 14, iss. 6, pp. 2726–2731. ISSN 1548-0992. DOI: 10.1109/TLA.2016.7555245.

[21] STOPA, M. M. and B. DE J. C. FILHO. Load Torque Signature Analysis: An alternative to MCSA to detect faults in motor driven loads. In: *IEEE Energy Conversion Congress and Exposition (ECCE)*. Raleigh: IEEE, 2012, pp. 4029–4036. ISBN 978-1-4673-0803-8. DOI: 10.1109/ECCE.2012.6342276.

[22] VERUCCHI, C., C. RUSCHETTI and F. BENGER. Efficiency Measurements in Induction Motors: Comparison of Standards. *IEEE Latin America Transactions*. 2015, vol. 13, iss. 8, pp. 2602–2607. ISSN 1548-0992. DOI: 10.1109/TLA.2015.7332138.

[23] LUDECA Inc. *Evaluating Energy Consumption on Misaligned Machines*. Doral: Maintenance Study, 1994.

[24] DAINTITH E. and P. GLATT. Reduce Costs with Laser Shaft Alignment. *Hydrocarbon Processing*. 1996, vol. 75, iss. 8, pp. 55–60. ISSN 0018-8190.

About Authors

Carlos VERUCCHI was born in Olavarria, Argentina. He received the B.S. degree in electromechanical engineering from National University of the Center of the Province of Buenos Aires (UNCPBA), Argentina, in 1994 and the M.S. degree in engineering sciences from University of Concepcion, Chile, in 2000. He is currently a professor and researcher in the Engineering Faculty of the National University of the Center of the Province of Buenos Aires, in the research group INTELyMEC (applied research in electricity and mechatronics) and in the Commission of Scientific Research of the Province of Buenos Aires (CIC-PBA).

Esteban GIRALDO was born in Pereira, Colombia. He recived the B.S. degree in engineering mechatronics in 2013 from Universidad Tecnologica de Pereira. He is currently pursuing a Ph.D. in engineering in the National University of the Center of the Province of Buenos Aires (UNCPBA), Argentina. His interest in research includes the detection and diagnosis of faults in electric motors and transformers.

Matias MEIRA was born in Olavarria, Argentina. He received the B.S. degree in electromechanical engineering from National University of the Center of the Province of Buenos Aires (UNCPBA), Argentina, in 2016. He is currently pursuing a Ph.D. in engineering in the National University of La Plata (UNLP), Argentina and participates in the chairs of "Electrical Machines" in the Engineering School of UNCPBA.

Cristian Roberto RUSCHETTI was born in Olavarria, Argentina. He received the B.S. degree in electromechanical engineering from National University of the Center of the Province of Buenos Aires (UNCPBA), Argentina, in 2006 and the Ph.D. degree in engineering sciences from National University of Rio Cuarto (UNRC), Argentina, in 2012. He is a member of the INTELyMEC Group, of UNCPBA and of the Applied Electronics Group of the UNRC.

Jose Maria BOSSIO was born in Rio Cuarto, Aragentina. He received the Electrical Engineer degree from the Universidad Nacional de Rio Cuarto, Rio Cuarto, Argentina, in 2006. He is currently working toward the Ph.D. degree in engineering at the Universidad Nacional del Sur, Bahia Blanca, Argentina. Since 2001, he has been with the Grupo de Electronica Aplicada, Universidad Nacional de Rio Cuarto. He is also currently with the National Scientific and Technical Research Council - Argentina.

Guillermo Ruben BOSSIO was born in Rio Cuarto, Argentina. He received the Electrical Engineering degree from the Universidad Nacional de Rio Cuarto, Rio Cuarto, Argentina, in 1999, and the Doctor of Engineering degree from the Universidad Nacional de La Plata, Buenos Aires, Argentina, in 2004. Since 1994, he has been with the Grupo de Electronica Aplicada, Facultad de Ingenieria, Universidad Nacional de Rio Cuarto. He is also currently with the National Scientific and Technical Research Council - Argentina.

Appendix A

Induction Motor Parameters

- $P_N = 5.5$ kW,
- $U_{1N} = 380$ V,
- $I_{1N} = 11.6$ A,
- $n_N = 1450$ rev·min^{-1}.