ONLINE EFFICIENCY ESTIMATION ON THREE PHASE INDUCTION MOTORS USING THE AIR GAP TORQUE METHOD

Marcéu Oliveira Adissi

marceu.adissi@ifpb.edu.br

Instituto Federal da Paraíba IFPB

Rua Santa Rita de Cássia, 1900, 58103-772, Cabedelo, Paraíba

Hugo de Souza Pimentel

pimentelshugo@gmail.com

Universidade Federal da Paraíba UFPB

Cidade Universitária, 58051-900, Paraiba, Brazil

José Anselmo de Lucena Júnior

anselmojr_mec_ufpb@hotmail.com

Universidade Federal da Paraíba UFPB

Cidade Universitária, 58051-900, Paraiba, Brazil

Júlio César da Silva

cesarsilva1789@hotmail.com

Universidade Federal da Paraíba UFPB

Cidade Universitária, 58051-900, Paraiba, Brazil

Abel Cavalcante Lima Filho

abelima@gmail.com

Universidade Federal da Paraíba UFPB

Cidade Universitária, 58051-900, Paraiba, Brazil

Abstract. *Electric motors are responsible for 80% of the electric energy consumed in factories. In order to measure magnitude of mechanical variables accurately, most of the time it is necessary an invasive method placed in the motor, which makes it impractical for equipments with high price and difficult installation. The objective of this work is to apply the air gap torque (AGT) method in order to estimate efficiency in real time in three-phase*

Proceedings of the XXXVIII Iberian Latin-American Congress on Computational Methods in Engineering
P.O. Faria, R.H. Lopez, L.F.F. Miguel, W.J.S. Gomes, M. Noronha (Editores), ABMEC, Florianópolis, SC, Brazil, November 5-8, 2017.

induction motors, turning the process faster and more reliable. This method was considered the most adequate due to its accuracy and small invasiveness. It was built a test bench of controllable torque to execute the experimental study and to verify accuracy and repeatability of estimation methods in constant load conditions. The essential elements to acquire, process and monitor signals were voltage and current transformers, Hall Effect sensor, A/D converter, laptop and a torque meter. Estimated values presented good precision and repeatability when compared to the ones obtained using the torque meter, showing its potential to optimize industrial processes avoiding various types of losses and to increase energy efficiency.

Keywords: *efficiency; three phase induction motors; air gap torque.*

1 INTRODUCTION

Most of the industrial production processes utilize mechanical systems that work with electric motors, which are responsible for consuming more than two-thirds of all electricity used up in factories. Approximately 90% of motors used in factories are three-phase induction ones (Hanitsch, 2002), due to, mainly, its mechanical strength and cost-benefit relationship.

The main magnitude generated and offered by functioning motors is torque. In many sectors of factories, torque measurements can identify possible faults in the equipment, which makes its monitoring essential to avoid faults in industrial processes. (Lima-Filho et al., 2008).

Researchers have been studying methods to determine torque on rotating shafts for decades. Direct measurement modes are more accurate; however, they are highly invasive. Besides that, some of these methods face serious operational challenges. Torque estimated from electric signals of the motor turns the system less invasive, although, it ends up being less accurate. In lots of cases the high accuracy is not critical and the low invasiveness is necessary.

There are different methods to measure efficiency of induction motors, but applying theses methods while motors are working is impracticable because it needs to turn the machine off in order to install the instruments.

It is necessary to obtain the angular velocity on the motor shaft in the different methods to estimate efficiency. Due to difficulties found to implement traditional methods of velocity estimation and their system invasiveness, it was proposed a new method, simple and well adapted to the system conditions thought in this work. This method executes the velocity estimation directly from the air gap torque.

Measuring rotor velocity directly can be impracticable in some processes. Schauder (1992) and also Zhen and Xu (1998) presented a estimation method from comparison between mathematical models of the motor. Hurst and Habetler (1996) came up with a method from spectral analysis of current. But these methods present considerable limitations.

There are methods to estimate efficiency online, such as the nominal value method, slip method and method of the current. Hsu e Scoggins (1995) used air gap torque to estimate energy efficiency, like Lu et al. (2008) who proposed less invasive procedures including in their method the number of slots estimation and stator resistance.

Most of the time electric motors operate below 60% of their nominal load, due to oversized installations, resulting in energy waste. Because of the high costs to implement, operate and maintain the instruments, there are few monitored motors. (Lu et al., 2008).

Development of efficient methods and low cost instruments to estimated magnitudes on small, medium and large motors answers a necessity in industrial sectors, making its usage more efficient. The proposed system looks for fulfilling an existing gap monitoring and supervising industrial electromechanical systems with induction motors; presenting a torque and velocity monitoring solution on the search for better energy efficiency in electric motors, through non-invasive and accurate estimation methods.

Therefore, for being a non-invasive method with higher accuracy (Hsu et al., 1998), it was developed in this work a algorithm in programming language C to estimate efficiency from air gap torque, aiming to apply it in real time on a test bench in the GPICEEMA laboratory (Energy and Environment Study Instrumentation and Control Group) of the Federal University of Paraiba located in the campus I João Pessoa.

The purpose of this work is to develop, validate, implement and analyze a online system to obtain real time information of torque, shaft angular velocity and induction motor efficiency in a laboratory environment.

2 STATE-OF-THE-ART SURVEY OF TORQUE, VELOCITY AND EFFICIENCY ESTIMATION METHODS

2.1 Torque on shaft measuring

Currently, there are excellent instruments, depending on the application, to obtain static torque, but difficulties still exist when it wants to measure dynamic torque (Lima-Filho, 2009).

The direct measuring of torque can be classified as: for absorption, with electrical current strain gage and from the angle of twist (Holman, 1971). Direct method for absorption consists in absorbing the mechanical energy on the rotating shaft through braking. (Holman, 1971). A system is connected to the rotor in such a way it compresses the shaft and, even allowing it to rotate, provokes friction that imposes direct torque. Torque magnitude is adjustable according to the level of pressure imposed.

As for the resistance strain gage method, it varies its electrical resistance when the shaft is deformed. Strain gage captures the deformation of the motor shaft caused by torque and a transmitter sends the signal to a signal conditioner that allows knowing the torque. Generally, a Wheatstone bridge is used to condition the variation signal from the strain gage. As this circuit rotates with the shaft, the challenge of this method is how to transmit power supply and how to receive the measured signal to enable external environment reading.

Torque measuring method through angle of twist is a mechanism composed by two parallel gears and two detector separated by a shaft. Detectors can be optical (Meng and Liu, 2006), magnetic (Lemarquand, 1999) or capacitive (Wolffenbuttel and Foerster, 1990) and the difference of phase between signals is proportional to the angle of twist. Torque reading method based on angle of twist provides good long-term accuracy (Meier and Edeson, 2006), but the need for advanced transduction mechanisms that are sensitive to small angles of twist is still a challenge (Cheong e Kim, 1999).

Considering the shaft of electrical motors, indirect measurements of torque are related to other magnitudes that are easier to be measured, for example, slip and electric current.

The method based on the indirect measuring of air gap torque (AGT) is one of the most accepted in the scientific community (Lima-Filho, 2009; Lu et al., 2006). This method was developed by Ojo et al. (1990) and verified by many experiments to confirm its efficiency (Hsu e Scoggins, 1995; Lu et al., 2008).

For this method, losses after electromechanical conversion have to be considered, as: additional losses and mechanical losses. This one was chose to be utilized in this work due to its advantages and to be able to monitor in real time, with limited memory and frequency, in systems with dynamic torque and variable electric conditions. (Adissi, 2012)

2.2 Angular Velocity Measuring

Generally, models based on the values of voltage and current are used, besides other parameters like stator impedance and temperature (Cirrincione et al., 2004; Schauder, 1992; Zhen e Xu, 1998). Usually, these models need a high processing power which makes them unreliable for low velocities (Hurst and Habetler, 1996).

2.3 Loss and Energy Efficiency Measuring

Methods are commonly classified based on their invasiveness level and estimation accuracy. Invasiveness level can be determined by the type of data necessary for the method, equipment shape and installation and data storage cost, motor operation planning, and equipment cost. Accuracy is evaluated through comparison with a second measure of efficiency.

How to estimate losses and/or output power differences the methods. A estimation can consist of a only base or it can compare basic procedures according with their theory bases and source of error, they are: direct measuring on the shaft method, nominal value method, slip method, electrical current method, equivalent circuit method, segregated loss method, air gap torque method.

The chart on "Fig.1" compares, in a simplified way, the seven methods. Axis x represents the error on the estimation, as axis y represents how invasive the method is, knowing that the size of circle is dispersion of the method. The ideal would be to have no error and not to be invasive; the one which approximates the most from it is air gap torque.

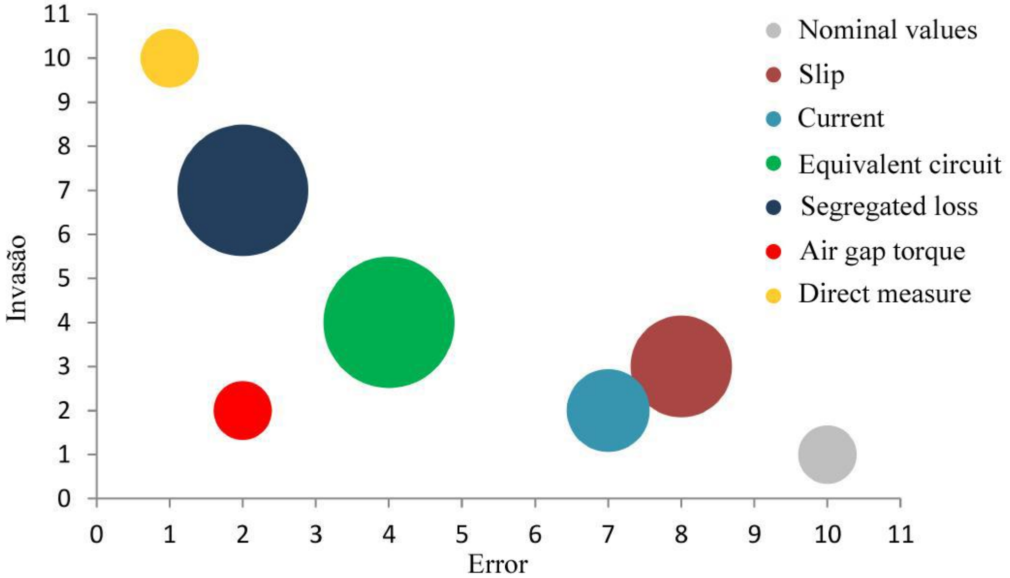


Figure 1. Invasion and error on efficiency measuring (Kueck *et al.*, 2007; Lu *et al.*, 2006)

3 UTILIZED METHODS

3.1 Air gap torque method

Air gap is the region inside the machine between the rotor and the stator which performs the interface between the electromagnetic and mechanical parts of the motor, as seen in "Fig. 2".

Electrical input power defined by motor voltages and currents is transmitted to the air gap region as magnetic power, which is transmitted to the rotor by imposing torque and generating magnetic power. Aig gap torque (AGT) is represented by the air gap power divided by its angular velocity.

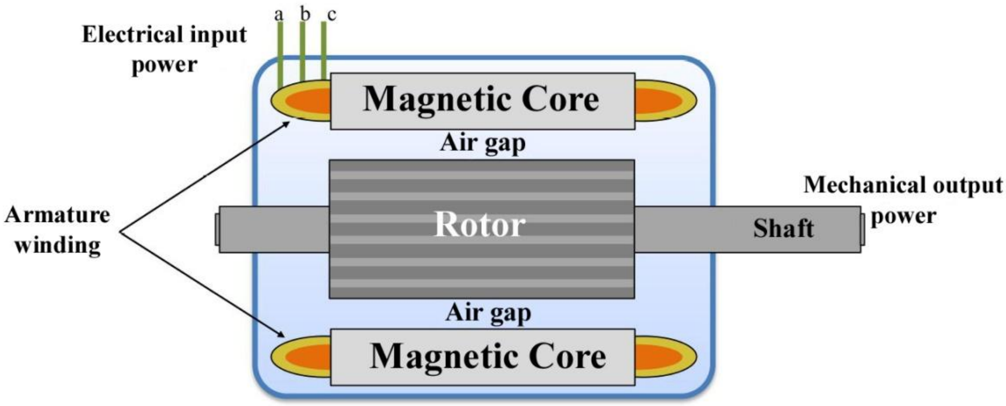


Figure 2. Inside of the motor, indicating where the air gap is located (Lima-Filho, 2009)

The air gap torque equation can be represented by "Eq. (1)", where *ia*, *ib* and *ic* are line currents in the motor input, *p* is number of poles and R is stator resistance per phase and v_a, v_b and v_c are voltages phase to ground.

$$T_{ag} = \frac{P\sqrt{3}}{6}\{(ia - ib) \int[v_{ca} + R(2i_{ab} + ib)]dt + (2ia - ib) \int(v_{ab} - R(ia - ib)\}\, dt \quad (1)$$

v_{ca} and v_{ab} are voltages phase to phase. Thus, it is possible to determine air gap torque only with the processing of the measurements from two voltage sensors and two current sensors (Lima-Filho, 2009). "Equation (1)" is related to the magnetic field generated and then it is valid for different type of sensors, as for induction motors Δ or Y connected.

The voltage and current measurements, v_{ab} and *ia* respectively, interfere considerably in the estimated value, a lot more than the others variables. On the other hand, stator resistance has a very small influence. The sequence of functions to estimate the air gap torque is illustrated in "Fig. 3".

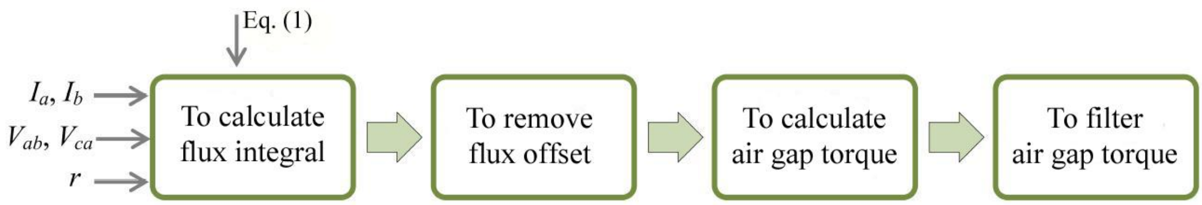


Figure 3. Sequence to determine the air gap torque

3.2 Velocity estimation

Velocity can be estimated from air gap torque. Due to problems found in the implementation of traditional methods of velocity estimation, it was developed a new method that consists of establishing a direct relation between the angular velocity searched and the air gap torque known. Plotting a line over the curve in "Fig. 4", a good approximation is obtained for the curve in the region between velocity and nominal torques, and synchronous velocity and zero torque.

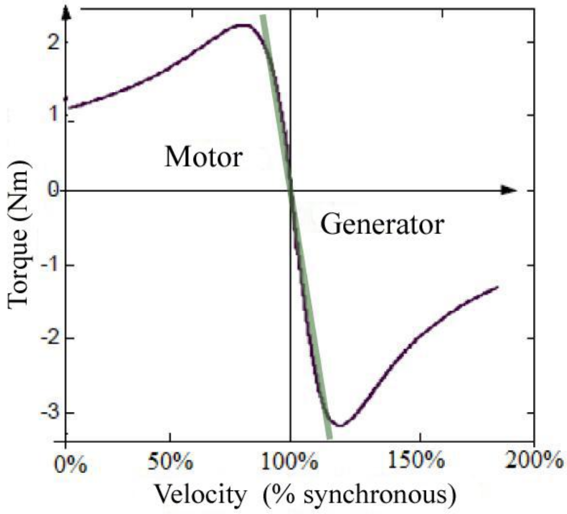


Figure 4. Linear relationship between torque and angular velocity

It was established a linear relationship between velocity and air gap torque. The parameters of this relationship must be determined by two points known in the curve. If it's possible to perform tests with no load and constant ones, the parameters a and b of the line can be determined precisely. If it is not possible, the two points of the line are given by torque zero and synchronous velocity (ω_g) point, and nominal torque and velocity (ω_n) point, resulting in a low invasiveness of the system.

Velocity is estimated directly from the air gap torque using "Eq. (2)", where $\widehat{\omega}$ is angular velocity, a and b are the parameters of the line equation.

$$\widehat{\omega} = a\hat{T}_{ag} + b \quad (2)$$

3.3 Energy efficiency estimations

The efficiency calculated can be expressed by "Eq. 3", where $\hat{T}$ is the torque on the motor shaft and $\widehat{\omega}$ is the angular velocity.

$$\hat{\eta} = \frac{\hat{T}\widehat{\omega}}{-v_{ca}(ia + ib) - v_{ab}ib} x100\% \quad (3)$$

The sequence of functions to estimate the energy efficiency from line voltages v_{ab} e v_{ca} , line currents i_a e i_b, torque on the shaft and angular velocity is represent in "Fig. 5".

Proceedings of the XXXVIII Iberian Latin-American Congress on Computational Methods in Engineering
P.O. Faria, R.H. Lopez, L.F.F. Miguel, W.J.S. Gomes, M. Noronha (Editores), ABMEC, Florianópolis, SC, Brazil, November 5-8, 2017.

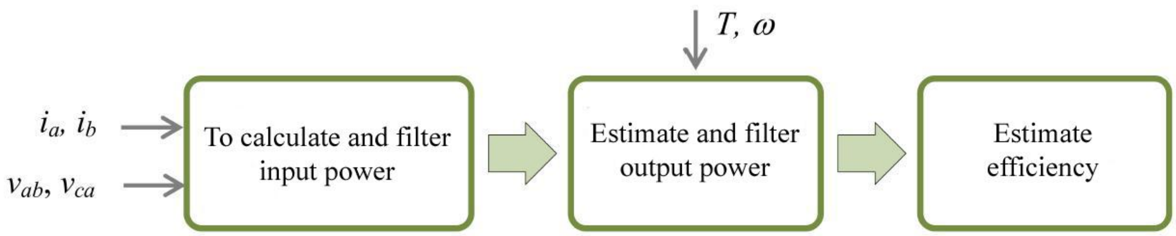


Figure 5. Sequence of functions to estimate energy efficiency

4 MATERIALS

4.1 Test bench of controllable torque

The test bench is capable of applying a constant load to the shaft of the three-phase induction motor (TIM), varying easily from zero to values over the nominal torque. TIM is started by frequency inverters, thus it is possible to vary the frequency transmitted to the motor, varying them from low to high rotation velocity.

On the rotation shaft of the test bench there are the following components coupled: a three-phase induction motor tested (1), a housing to support two bearings (2), a torque transducer (3), a DC generator to apply loads (4), a velocity transducer (5).

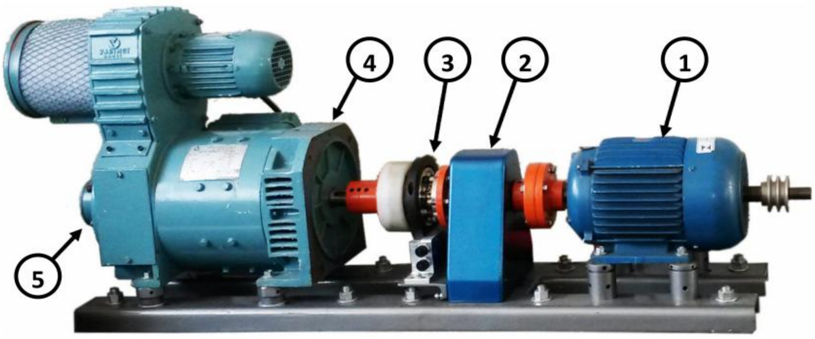


Figura 6. Test bench to torsion experiments on three-phase motors.

In order to apply the load to the TIM using a DC motor (4), the procedure is to vary the incoming field of the motor that works as a load generator (DC motor) using the variable voltage (varivolt). As the load increases, it is not recommended that the torque goes over than its nominal value.

Using torque and velocity quantities measured on the shaft, it is possible to know the motor efficiency. These values work as references and to compare the three-phase induction motor velocity estimation, torque and efficiency in the test bench.

4.2 Induction motor and its triggering system

A TIM similar to the "Fig. 6" was utilized, with incoming voltage of 380V, nominal current of 7,8 A, nominal velocity of 1730 rpm, nominal power of 5 cv / 3,7 KW and nominal torque of 20.4 Nm.

Figure 7. Three-phase induction motor *Voges* VTOP 5 CV

The nominal frequency of the motor is 60 Hz, the same of the Brazilian electrical network, but using the inverter it is possible to vary controllably the frequency, varying directly the synchronous velocity of the motor. The frequency inverter used was CFW 700 designed by WEG.

A DC machine (132S Varimot Motor) was used to apply torque to the motor. It was used a single phase variable autotransformer connected to the electrical network, providing variable voltage levels in its output that is connected to a rectifier circuit composed by a resistance, a capacitor and a rectifier bridge.

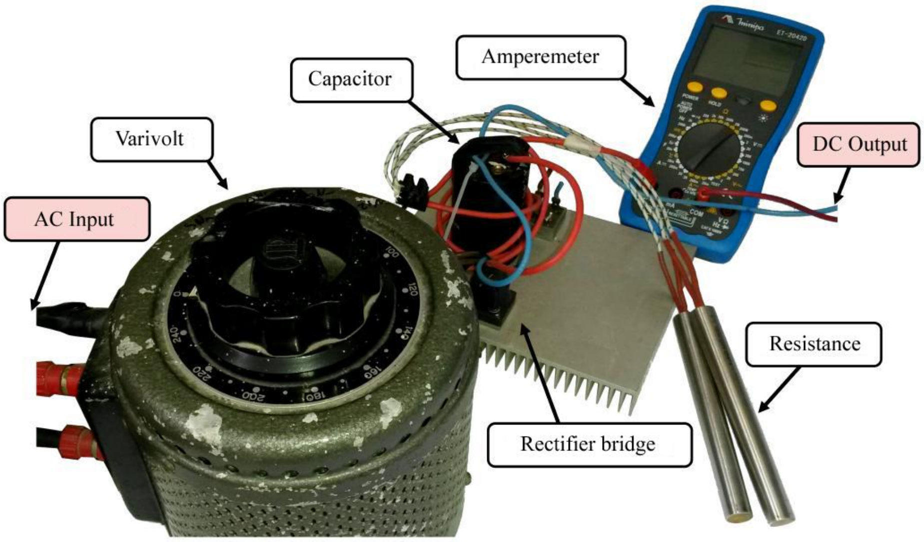


Figure 8. Field incoming circuit with variable voltage

4.3 Acquisition system

Voltage acquisition is performed by two transformers, as seen in “Fig. 9a”, (brand Tecnotrafo) that reduce electrical voltage between phases of the motor, in this case 380 V_{rms}, to compatible values with the A/D converter circuits (range from 0 to 3,3 V) . It was installed grain oriented transformer core. They have a narrower hysteresis loop, eliminating the delay between voltage and current almost entirely, during conversion from primary windings to secondary windings in the transformer.

Electric current consumed by motors is variable according to its power. Therefore, it must be installed in the motor wire a current transformer (brand Toroid R), “Fig. 9b”, with current in the primary dimensioned for the motor, and a maximum one of 5A in the secondary. Therefore, it was placed in the bench system a current sensor with maximum current of 5A to measure the output of the current transformer. It was chosen a Hall Effect sensor (integrated circuit, model ACS712, from the brand Allegro) because it presents a series of vantages, such as: external interference strength, high speed answer, easy installation, low cost and great precision. This sensor, showed in "Fig. 9c", is capable of measuring from direct to alternating with high frequency current and providing a proportional voltage signal to the current signal in its output.

(a) **(b)** **(c)**

Figure 9. (a) Voltage transformer. (b) Current transformer (c) Hall Effect sensor

4.4 Measuring instruments

One of the main advantages of this test bench is the measuring of the torque directly on the shaft using a torque meter with high accuracy. The gadget selected was the digital torque meter HBM T40B-200 ("Fig. 10"), with flange coupling, nominal torque capacity of 200 Nm, accuracy of 0,05%, capacity of measuring torques in rotations up to 20000 rpm. It has a precise measuring electromagnetic system of the rotation velocity, even in low rotations.

Figure 10. Digital torque meter HBM T40B-200

The data acquisition module is a electronic gadget that receives analog signal and its output is digital which can be read, stored or processed. It was utilized a A/D converter designed by National Instruments TM model USB-6215 ("Fig. 11"). The analog signals from the signal conditioning plate are: two of voltages, two of current, torque and velocity on the shaft.

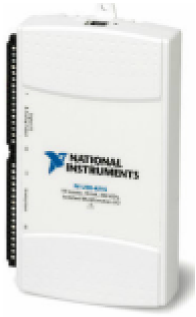


Figure 11. Conversion module A/D NI USB-6215

5 RESULTS

Experiments were held in steady state, i.e. with constant and steady variables during all the measuring. Utilizing the direct measuring system it is possible to know voltage, electric current and electrical input power. Air gap torque was calculated and expressed in “Table 1” among the others electrical quantities measured directly in order to assure motor knowledge.

Table 1. Measurements of electrical and magnetic quantities from the test bench

Input Frequency	Load ($\%_{nom}$)	RMS Current (A) i_a	RMS Current (A) i_b	RMS Voltage (V) v_{ab}	RMS Voltage (V) v_{ca}	Power (W)	Air gap torque (Nm)
60 Hz	5.15	2.95	2.95	406.83	405.74	371.84	1.70
	13.77	3.24	3.11	409.81	409.08	691.10	3.37
	54.46	5.38	4.73	400.80	399.77	2284.82	11.53
	91.18	7.54	7.96	397.15	392.56	3848.66	19.14
	103.09	8.59	8.81	395.30	391.57	4352.90	21.52
50Hz	4.75	3.35	3.31	389.90	386.52	292.94	1.52
	26.47	3.67	3.63	383.01	379.66	978.67	5.84
	50.15	4.72	4.68	378.33	374.97	1756.52	10.61
	91.42	7.41	7.35	373.98	370.70	3201.29	19.04
	98.28	7.90	7.85	375.06	371.38	3459.18	20.50
40 Hz	4.46	3.35	3.29	347.09	345.76	214.27	1.37
	18.09	3.61	3.56	350.33	348.82	565.11	4.13
	50.59	4.75	4.71	343.04	341.54	1417.06	10.66
	96.13	7.66	7.62	339.37	337.72	2717.18	19.96
	105.93	8.39	8.35	339.60	337.99	3017.61	22.00
30 Hz	4.17	3.38	3.31	307.06	302.63	147.17	1.20
	25.64	3.75	3.70	310.27	304.80	565.04	5.56
	51.67	4.75	4.72	305.76	301.17	1085.11	10.74
	96.08	7.70	7.68	298.19	294.40	2072.40	19.75

For each sampling, frequency was initially adjusted to 60 Hz, and then 50 Hz, 40 Hz and lastly to 30 Hz, resulting in synchronous speed of 1800 rom, 1200 rpm and 900 rpm, respectively. Different loads were utilized for each frequency, carrying out measurements for all the conditions adopted.

Torque on the shaft. Torque is applied on the induction motor through the direct current generator and its triggering system. It is applied a proportional load to the motor shaft varying the current over the generator field. For each synchronous speed, a wide range of torques was applied, from close to zero to over the nominal one. Torque was measured by the torque meter and estimated by the proposed system for every condition of frequency and relative load.

"Figure 12" expresses the values of measured (reference) and estimated (nominal and calibrated) torque in for charts, one for each synchronous velocity of the motor (1800, 1500, 1200 e 900 rpm). Silver dashed lines represent curves for nominal estimation and calibrated instrument errors.

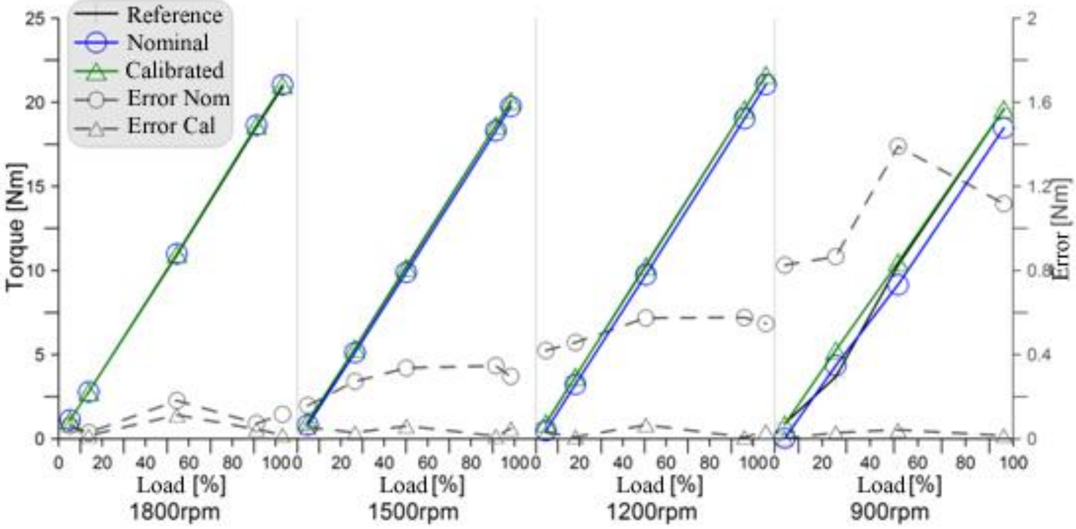


Figure 12. Constant torque on the shaft estimation

The curves are very close, meaning that a relatively low error occurred on the torque estimation. It is verified that the error increases as the frequency decreases, i.e. a greater error in low rotations.

Energy Efficiency. Energy efficiency is calculated using the direct measurement of the electrical input power and mechanical output power, estimated by the torque and velocity.

The values from estimated (nominal and calibrated) and measured (reference) efficiencies are represented in "Fig. 13" in four charts, one for each synchronous velocity of the motor (1800, 1500, 1200 e 900 rpm). Silver dashed lines represent curves for nominal estimation and calibrated instrument errors.

Proceedings of the XXXVIII Iberian Latin-American Congress on Computational Methods in Engineering
P.O. Faria, R.H. Lopez, L.F.F. Miguel, W.J.S. Gomes, M. Noronha (Editores), ABMEC, Florianópolis, SC, Brazil, November 5-8, 2017.

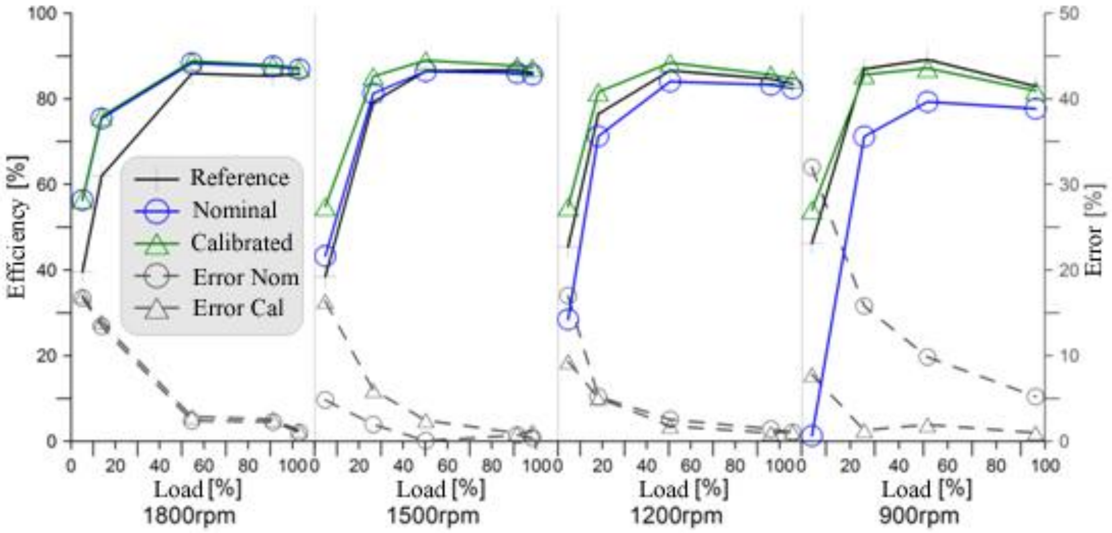
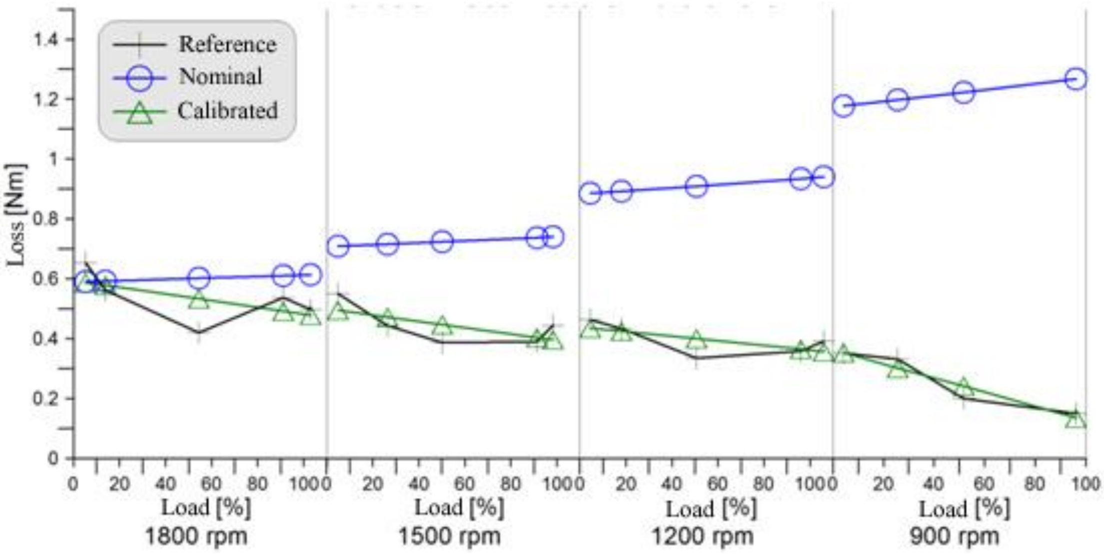


Figure 13. Constant energy efficiency estimation

Estimated losses by the system are the ones that occur between the air gap and the shaft of the motor. They are mechanical losses due to friction and ventilation and diverse additional losses. The literature considers that these losses are inversely proportional to velocity, i.e. losses are higher as velocity is lower. Thus, losses were estimated by the nominal method of pre-established values. For the calibrated method, the calculation of the loss was calibrated from the direct measure, reducing the error a lot. The air gap torque calculated has to be subtracted from the torque measured on the shaft in order to measure the losses of reference with the instruments.

It is noted that losses decrease as velocity gets lower, i.e. they are directly proportional. The tendency was the inverse of the one seen with nominal losses, which presents an ascendant line. In order to obtain the torque on the shaft, the losses have to be subtracted from the air gap torque. The estimation error of the losses by the nominal method explains the error on the torque estimation for low velocities. For 60 Hz, the nominal standardized loss resulted in a very close value to the real one measured.



Proceedings of the XXXVIII Iberian Latin-American Congress on Computational Methods in Engineering
P.O. Faria, R.H. Lopez, L.F.F. Miguel, W.J.S. Gomes, M. Noronha (Editores), ABMEC, Florianópolis, SC, Brazil, November 5-8, 2017.

Figure 14. Estimation of mechanical and constant additional losses

5.1 Determining the uncertainty in measurements

Uncertainty in the torque estimation. In order to determine the torque measurement uncertainty on the motor shat, 120 measurements were conducted under the same conditions. The chosen condition was to this analysis was close to the motor in its nominal point, i. e. with frequency of 60 GHz, load of 18.62 Nm, velocity of 1734.16 rpm and energy efficiency of 87.89%.

The reference torque measured using the torque meter was 18.62 Nm. The average of the estimations carried out by the system was 18.55 Nm. Therefore, tendency is -0.07 Nm. Measurements were between 18.47 and 18.62 Nm. Frequency for each measure was computed considering two decimal places, as seen on “Fig. 15”.

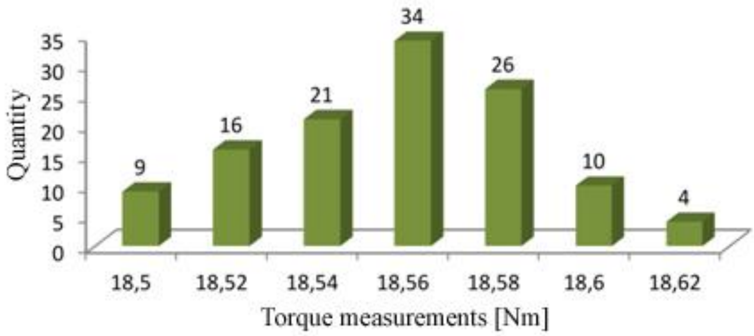


Figure 15. Chart of the torque on the shaft estimations

The measuring uncertainty is the measure of intensity of the random component of measuring error. It corresponds to the estimation of the standard deviation of measuring error distribution. Standard uncertainty can be estimated by statistical procedures from a set of n repeated measures, according to “Eq. 4”.

$$u_M(T) = \sqrt{\frac{\sum_{k=1}^{n}(T_K - \bar{T})^2}{n-1}} \quad (4)$$

Then, the measuring uncertainty in the torque estimation is:

$u_m(T) = 0.08$ Nm

Thus, using the measuring uncertainty, torque measured in these conditions can be expressed as:

Torque = (18.55 ± 0.08) Nm

Uncertainty in the efficiency estimation. 120 measurements were performed under the same conditions. The reference efficiency measured directly by the torque meter and the tachometer was 87.89 %. The average estimation performed by the monitoring system was 87.67%, therefore, the tendency was -0.22%. Measures were between 87.20% and 87.32%. Frequency for each measure was computed considering two decimal places, as seen on “Fig. 16”.

Proceedings of the XXXVIII Iberian Latin-American Congress on Computational Methods in Engineering
P.O. Faria, R.H. Lopez, L.F.F. Miguel, W.J.S. Gomes, M. Noronha (Editores), ABMEC, Florianópolis, SC, Brazil, November 5-8, 2017.

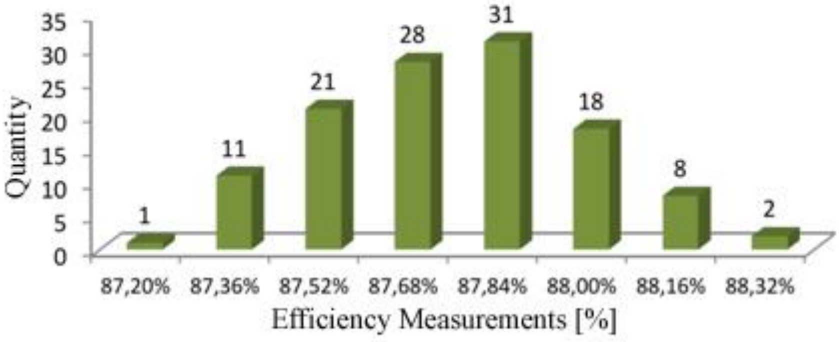


Figure 16. Chart of the energy efficiency estimations

Replacing the variables, the measuring uncertainty in the efficiency estimation is:

$u_M\,(E) = 0.32\%$

Thus, using the measuring uncertainty, the efficiency measure can be expressed as:

$\text{Efficiency} = (87.67 \pm 0.32)\%$

6 CONCLUSIONS

Monitoring energy efficiency in electrical motors is considered very important nowadays because it saves a lot of energy. Efficiency estimation is the last step of the algorithm and it is calculated based on torque, velocity and electric power calculated by the system.

Once the main information of the motor is known, it is easier to make decisions and control the whole process where the motor is placed. Hence, it is obtained a better operation and maintenance routine in factories, reducing costs and increasing efficiency.

Estimated values present good precision and repeatability when compared to the ones obtained using the torque meter HBM T40B-200. Expanded measuring uncertainty was 0.16 Nm when the torque on the shaft was 18.55 Nm. Efficiency uncertainty was 0.64% when efficiency was 87.67%.

The developed instrument can measure variables that are able to control and optimize industrial processes; avoiding faults resulted from overload and elevating energy efficiency, for example.

REFERENCES

Cheong, Y. D. e Kim, J. W., 1999. “Analysis and development of the angular twist type torque meter”. *Composite Structures*, volume 47(1–4): pp. 457 – 462.

Cirrincione, M., Pucci, M., Cirrincione, G. e Capolino, G.-A., 2004. “A new tls-based mras speed estimation with adaptive integration for high-performance induction machine drives”. *Industry Applications, IEEE Transactions on*, volume 40(4): pp. 1116–1137.

Hanitsch, R., 2002. “Energy efficient electric motors”. In “*RIO 02 - World Climate & Energy Event*”, pp. 45–50.

Holman, J., 1971. *Experimental methods for engineers*. McGraw-Hill.

Hurst, K. e Habetler, T., 1996. “Sensorless speed measurement using current harmonic spectral estimation in induction machine drives”. *Power Electronics, IEEE Transactions on*, volume 11(1):pp. 66–73.

Hsu, J. e Scoggins, B., 1995. “Field test of motor efficiency and load changes through air-gap torque”. *Energy Conversion, IEEE Transactions on*, volume 10(3): pp. 477–483.

Hsu, J., Kueck, J., Olszewski, M., Casada, D., Otaduy, P. e Tolbert, L., 1998. “Comparison of induction motor field efficiency evaluation methods”. *Industry Applications, IEEE Transactions on*, volume 34(1): pp. 117–125.

Lemarquand, V., 1999. “Synthesis study of magnetic torque sensors”. *Magnetics, IEEE Transactions on*, volume 35(6): pp. 4503–4510.

Lima-Filho, A. C., Belo, F. A. e Gomes, R. D., 2008. “Tests prove, self-powered, wireless, pump torque meter”. *Oil and Gas Journal*, volume 106(46): pp. 43–48.

Lima-Filho, A. C., 2009. *Study and Development of Solutions to Determine Torque in Oil Pump Units Used for Oil Extraction*. Doctoral dissertation, Federal University of Paraiba.

Lu, B., Habetler, T. e Harley, R., 2006. “A survey of efficiency-estimation methods for inserviceinduction motors”. *Industry Applications, IEEE Transactions on*, volume 42(4): pp. 924–933.

Lu, B., Habetler, T. e Harley, R., 2008. “A nonintrusive and in-service motor-efficiency estimation method using air-gap torque with considerations of condition monitoring”. *Industry Applications, IEEE Transactions on*, volume 44(6): pp. 1666–1674.

Meier, B. e Edeson, D., 2006. “Developments in continuous torque monitoring couplings”. In “Ethylene Producers’ Conference, Orlando, FL, Apr”, volume 26.

Meng, Z. e Liu, B., 2006. “Research on the laser doppler torque sensor”. *Journal of Physics: Conference Series*, volume 48: pp. 202–206.

Schauder, C., 1992. “Adaptive speed identification for vector control of induction motors without rotational transducers”. Industry Applications, IEEE Transactions on, volume 28(5): pp. 1054–1061.

Zhen, L. e Xu, L., 1998. “Sensorless field orientation control of induction machines based on a mutual mras scheme”. *Industrial Electronics, IEEE Transactions on*, volume 45(5): pp. 824–831.

Wolffenbuttel, R. e Foerster, J., 1990. “Noncontact capacitive torque sensor for use on a rotating axle”. *Instrumentation and Measurement, IEEE Transactions on*, volume 39(6): pp. 1008 – 1013.