Embedded System for Speed Estimation by Means of Sound Analysis in Three-Phase Induction Motors

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Abstract. Electric motors consume a large portion of the electric power generated. Three-phase induction motors are the most used in industries, for their robustness, reliability and easy operation. They are inserted in the most diverse processes as the main electromotive force. Measuring speed directly on the motor shaft is no trivial task, because it requires time and additional cost due to adaptations of speed transducers to the axis, which causes costly stops to the process in which this motor is inserted. For this reason, manufacturers and research centers around the world have been developing speed estimation methods based on sensorless techniques. The speed measurement in motors can be used for various applications from vector control of the machine to failure analysis. In this work, a new method was developed and installed in an embedded system to estimate the speed in threephase induction motors through the FFT motor sound analysis. This technique proved to be reliable, showing good accuracy in comparison to the measured speed on the shaft, demonstrating the effectiveness of the method and applicability in other areas of technical and scientific relevance such as analysis and prevention of bearing failures or any mechanism involving shaft rotation.

Keywords: Three-phase inductors motors · Sound analysis · Speed estimation
Embedded system · Sensorless measurements

1 Introduction

Three-phase induction motors (IM) are applied in the most diverse industrial sectors, from the petrochemical, sugaralcohol, mining, automotive, textile, among many others, being the most used driving force due to its low cost, robustness and efficiency.

Electric motors have a considerable share of the world's energy demand, with those operating in the industry responsible for the consumption of 60–70% of the world's electricity generated [1]. These operate below 60% of their rated load due to oversized installations, which ultimately increases the waste of electrical energy [2].

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The commercialization of the IMs intensified exponentially with the advent of the Variable-Frequency Driver (VFD), since it was used in applications that were previously made only by motors of direct current, due to the advantage of being relatively simple its speed control. The monitoring of IMs in the industry is still almost always done in large machines, however it is estimated that 98% of the motors in service have a power of less than 200 HP [3].

The search for speed estimation methods in electric motors has been studied by several researchers, in virtue of their great importance in monitoring, fault prevention, efficiency estimation and process control, in which speed estimation with good precision and accuracy is necessary.

For direct speed measurement in IMs, there is a good range of speed transducers on the market such as; tachometers, encoders, tachogenerators, resolvers, among other types, all with good precision and accuracy. However, thanks to the difficulty of access, it is not always possible to couple such instruments to the motor shaft, especially in motors allocated in industrial operations. Another relevant aspect is the cost of these instruments, which makes their applications unviable if the number of machines is high.

The sensorless measurement method has been shown to be an attractive and efficient alternative when compared to other speed estimation methods. Such a technique consists in estimating speed without the need to couple measuring instruments to the motor shaft. This extends its application to difficult to reach motors, where the conventional direct measurement method would be impractical.

The method of slot harmonics is a sensorless technique that uses the signature of the IM phase current spectrum and the search for harmonics generated by the motor protrusions - which arise from the rotor slots and their eccentricity - to estimate the speed of the motor [4]. This is one of the most widely used methods to estimate the speed in induction motors non-invasively [5–7]. The Fast Fourier Transform (FFT) can be used to obtain the frequency spectrum, however other transforms can also be used (e.g., Wavelet transform, Hilbert transform). The choice of which transform to use will depend on the type of application and the signal to be acquired.

The main disadvantage of the slot harmonics method is the need for a high number of samples to obtain a satisfactory spectral resolution, which requires high processing costs. Furthermore, the susceptibility to noise, whether caused by mechanical or electrical means, makes the method not suitable for estimating the speed in real time.

Another innovative technique for speed estimation in IMs is to use the torque in the air gap (Air-Gap Torque - AGT). The method was initially proposed by [4] and consists of obtaining a direct relation between the desired angular velocity and the already known AGT. A linearization relationship is found by tracing a line between the point which comprises the synchronous speed and zero torque and the point with the nominal speed and torque. It is possible to estimate the speed with a good accuracy from this relation and the equation of the straight line; however it is necessary to measure the input power in order to estimate the torque in the motor air gap. This may lead to delays in the estimations, although much lower than method of the slot harmonics.

In spite of the fact that the methods mentioned above are a considerable advance in speed estimation in induction motors, they still require the acquisition of the power of the motor and a methodology of data processing to reach an estimated value, which demands operational cost and specific sensors.

This paper proposes a new approach to speed estimation in three-phase induction motors, based on the principle of acoustic signal acquisition and analysis through an embedded system.

2 System Description

2.1 Test Bench

It was designed and built an experimental workbench consisting of two motors: a three-phase induction motor and a DC motor, the latter functioning as a load simulator. The configuration of this test bench allows to apply a known torque, constant or not, to the axis of the three-phase induction motor, which in turn can be actuated in two different ways: conventional (direct, through the electric grid) or via VFD.

The experimental workbench for conducting measurement tests and estimation of speed, torque and efficiency is shown in Fig. 1. It consists essentially of a three-phase induction motor (manufacturer WEG, model W22 Plus, nominal power 4.9 HP, nominal speed of 1725 rpm) (1) that has as function to provide an action torque through its axis to the sets attached to its front; one bearing support with two bearings (2); a torque transducer (3); a DC motor (manufacturer Varimot, model 132S, nominal power 7.4 HP, nominal speed of 1800 rpm) (4), which generates a braking torque on its axis, by means of the direct voltage obtained by rectifying the alternating voltage of 220 V of the electric grid.

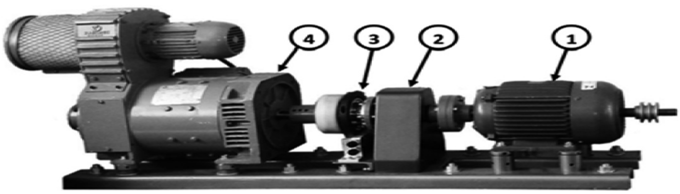


Fig. 1. Workbench for torque tests on three-phase induction motors [4].

2.2 Algorithm for FFT Calculation

The Fourier Transform (FT) is a tool for representing an aperiodic and time-continuous signal in terms of its frequency components, thus providing a spectral representation of the signal [8]. In a similar way, the Discrete Time Fourier Transform (DTFT) is used to represent a discrete-time aperiodic signal by means of its frequency components [9] which also leads to a spectral representation of the signal. According to [10] the main difference between FT and DTFT is that the FT represents signals with continuous sine-wave or exponential functions, while the DTFT uses sine-wave or exponential-time functions in discrete time.

The DTFT of a sequence x(n) is defined as [11]:

$$X(e^{j\omega}) = \sum_{n=-\infty}^{+\infty} x(n)e^{-j\omega n} \tag{1}$$

As $X(e^{j\omega})$ is constructed only of complex exponential functions of periodicity 2π, it also presents this periodicity, that is, $X\left(e^{j\omega}\right) = X(e^{j(\omega+2\pi)})$.

However, while DTFT is an important tool for the analysis of discrete signals, it has certain practical limitations when used as a computational tool. A disadvantage is that a direct computation of $X(e^{j\omega})$ using the definition requires an infinite number of floating-point operations, this being aggravated by a second disadvantage in the computational aspect, the fact that the transformation itself must be calculated in an infinite number of frequencies [12].

In order to make the calculation of the DTFT possible in a computer, it is necessary to choose a finite number of frequency points, which is equivalent to sampling the FT at a certain number of points. Assuming some considerations about the interval in which the spectrum is effectively considered and that the acquisition process of the samples digitizes the relevant portion of the continuous signal by T_0 seconds, the next step is to assume that a periodic signal x(n) is cascaded from the N data samples acquired with the duration T_0 repeatedly [13]. In this way, the coefficients of the FT are determined using N data samples of a period, relating them by means of a multiplication, as explicit in (2).

$$X_k = \sum_{n=0}^{N-1} x(n)W_N^{kn} \tag{2}$$

The expression in (2) can be understood as the Discrete Fourier Transform (DFT) of a sequence $x(n)$, $0 \leq n \leq N-1$. The factor W_N, called twiddle factor is defined as:

$$W_N = e^{\frac{-j2\pi}{N}} = \cos\left(\frac{2\pi}{N}\right) - j\text{sen}\left(\frac{2\pi}{N}\right) \tag{3}$$

The DFT calculation, as expressed in (2), contains redundant complex products, and such replicates of these products can be eliminated to produce a faster execution [14]. In 1965, mathematicians Cooley and Tukey presented a rapid technique for calculating DFT [15] which became known as Fast Fourier Transform (FFT).

The computational effort of a DFT can be calculated by:

$$CE = N^2 \tag{4}$$

Where N is the number of elements of the signal under analysis. Thus, an 8-position vector would require the computation of 64 complex multiplications. If the vector of

N positions is divided into two parts, one referring to the even indexes and another to the odd indexes, the DFT of a signal can be written as [16]:

$$X_k = \sum_{n=0}^{N/2-1} x(2n)W_N^{kn} + \sum_{n=0}^{N/2-1} x(2n+1)W_N^{kn} \tag{5}$$

The calculation for the computational effort referring to the operation described in (5) will now not refer to the original length of the vector (N), but to twice that length. Therefore, we have:

$$EC = 2\left(\frac{N}{2}\right)^2 = 2\frac{N^2}{4} = \frac{N^2}{2} \tag{6}$$

It can be observed that dividing the sample in terms of even and odd indexes results in a 50% reduction of the computational effort to calculate a DFT. The main idea is that the process continues until there are only two values for the DFT computation. This operation is called decimation in time [16] and is illustrated for a better understanding in Fig. 2.

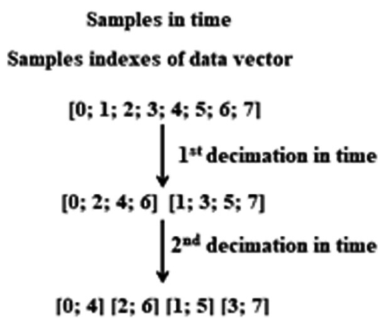
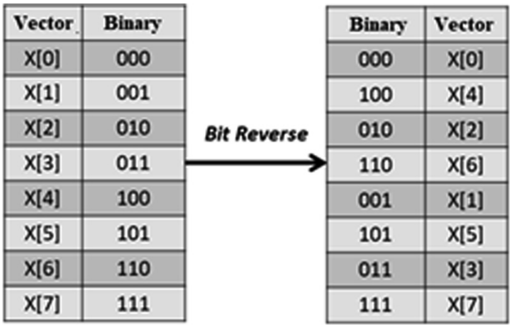


Fig. 2. Illustration of the decimation in time process.

The decimation in time performs the ordering of the samples at the input of the data in the time domain and it was implemented by the routine called bit reverse, which is illustrated in Fig. 3. Basically, the bit reverse operation consists of representing the indexes relative to the positions of the samples in a binary number vector and then doing the inversion in the order of the elements.

After the reordering step of the samples, the next step is to proceed with the operation known as Butterfly. The Butterfly uses the symmetry property of the samples present in the FFT logic [16], so that it allows a high computational gain. Figure 4 shows the butterfly process basic scheme.

For the evaluation of the algorithms developed for the analysis of the signals a comparison was made between the performance presented by them and the result of MATLAB® software, a widely used and accepted tool in the scientific environment. A sine wave with fundamental frequency of 1280 Hz was generated iteratively within



Vector	Binary
X[0]	000
X[1]	001
X[2]	010
X[3]	011
X[4]	100
X[5]	101
X[6]	110
X[7]	111

Bit Reverse

Binary	Vector
000	X[0]
100	X[4]
010	X[2]
110	X[6]
001	X[1]
101	X[5]
011	X[3]
111	X[7]

Fig. 3. Reorganization of a vector by bit reverse.

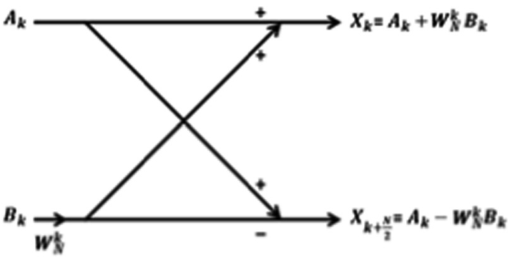


Fig. 4. Butterfly scheme illustration.

the FFT calculation code and then processing was performed normally. The sampling rate adopted was 40.960 Hz and the number of samples of the signal was 4096. In Fig. 5 the results of the algorithm running in MATLAB® and Arduino DUE, respectively, can be observed.

The error was calculated as the difference between the output value of MATLAB® and Arduino DUE. The mean value of the error was 1.0794×10^{-7}. The value of the standard deviation for the error signal was 36.568×10^{-7}. These measures were considered satisfactory for the research applications, since they reflect a good performance of the developed system. It is worth noting that the error occurred only with respect to the amplitude (dimensionless units), not identifying differences between the signals in relation to the information in the frequency.

2.3 Acquisition and Processing System

The embedded system used for acquiring and processing the sound signals used in the research is shown in Fig. 6. The system consists essentially of the development platform, Arduino DUE and the electret condenser microphone CMA4544PF-W.

Arduino DUE has high computational capabilities, as it has a 32 bits arm microcontroller, the Atmel SAM3X8E ARM Cortex-M3, which makes it a fast processing board. By prior configuration of its registers and internal timers, the acquisition frequency can be set to the value of 44.1 kHz.

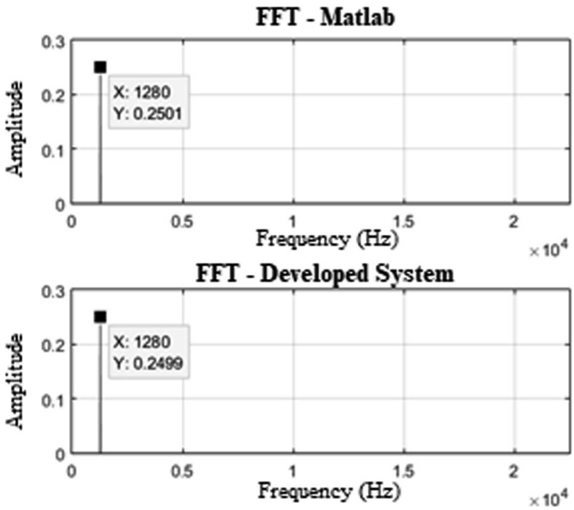


Fig. 5. FFT results – Matlab vs. proposed system.

Fig. 6. Embedded system for speed estimation by means of sound analysis.

The CMA-4544PF-W is an omnidirectional electret condenser microphone with sensitivity of −44 dB and with frequency of operation of 20 Hz to 20 kHz. Its frequency response curve (Fig. 7) shows to be quite stable, characterizing it as a good mechanism of transduction.

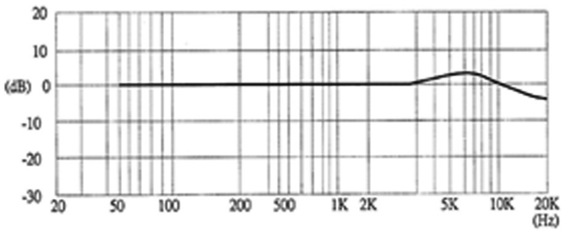


Fig. 7. Frequency response curve of the CMA-4555PF-W microphone.

Audio files are stored following the standard WAVE format, which ensures the storage of audio without any type of compression. Files are saved to a memory card so they can be viewed and analyzed. With the sound signal, the system proceeds with the speed identification, by detecting the peak of greater amplitude in the FFT (without considering its harmonics).

To measure the speed taken as reference for purposes of comparison with the proposed method, a tachometer from the manufacturer Minipa model MDT-2238B (Fig. 8) was used, which operates in two ways: by contact and by photo detection. Because it is practical, safe and has a smaller measurement failure, the speed was measured by the optical mode. In optical-read mode, the axis rotation speed can be measured in the range of 2.5 to 100,000 rpm with a detection distance between 50 to 500 mm and a resolution of 1 rpm (above 1,000 rpm in optical mode and an accuracy of ±0.05% reading +1 digit).

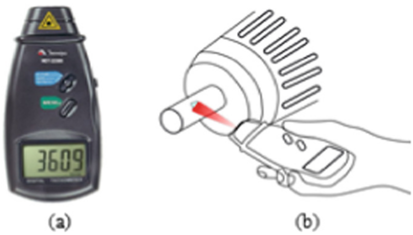


Fig. 8. Digital tachometer: (a) model MDT-2238B used at the research; (b) optical mode of operation.

3 Experimental Results

Using the controllable torque test bench, the necessary signals were acquired to verify the torque-to-speed ratio of the MIT and thus validate the speed estimation from the sound analysis through the embedded system. A torque scale ranging from 0 to 24 Nm was applied. During this interval, nine torque measurements and their respective speed were performed, as shown in Table 1.

Table 1. Torque, measured speed and estimated speed by the embedded system.

Torque (Nm)	Tachometer (rpm)	Embedded system (rpm)	Relative error %
0	1797	1795.716	0.071
3	1790	1789.59	0.022
6	1781	1781.634	0.035
9	1771	1773.06	0.116
12	1763	1762.038	0.054
15	1752	1751.634	0.020
18	1742	1740	0.114
21	1730	1728.978	0.059
24	1718	1716.732	0.073

The three-phase induction motor used has a power output of 4.9 HP and 4 poles, with a synchronous speed of 1800 rpm at 60 Hz with a slip of around 0.166%, considering the losses of mechanical or electrical origin negligible.

The torque vs. speed graph could be obtained (Fig. 9), allowing to verify that the torque and speed are inversely proportional and the relative error between the two curves presenting an average value of 0.0614 with a deviation of 0.038.

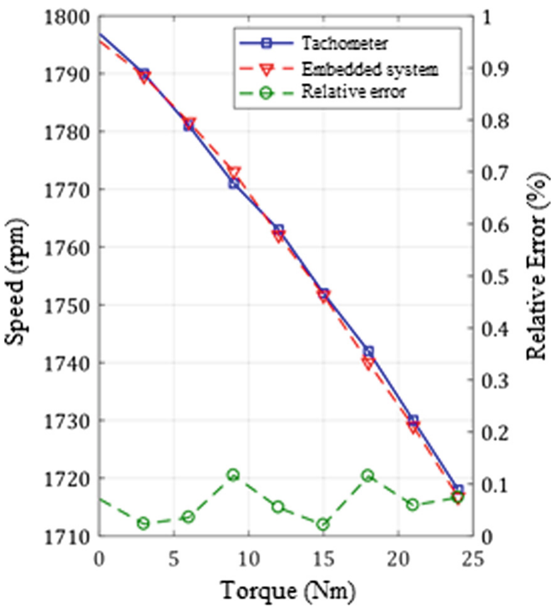


Fig. 9. Measured value vs. estimated value and relative error between the two measurements.

4 Conclusions

The embedded system presented minimal errors compared to the standard measurement system using the tachometer, which allows validating the embedded system for the application from which it was developed.

The method of speed estimation through the sound analysis was applicable, functional and without any type of motor invasion, which allows to be applied in the most varied circumstances.

The embedded system can be extended to other areas of interest and scientific relevance, including applications in analysis and prevention of failures in bearings and bearings supports in an industrial environment or in any mechanism that involves continuous rotary movement under normal working conditions.

Improvements to fix some of its limitations can be inserted, such as using an array of microphones and algorithms to identify different sources of sound emission, which would allow performing the measurement of speed simultaneously in several IM with only one device on industrial environments.

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