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An artificial neural network approach for sensorless speed estimation via rotor slot harmonics

Hayri ARABACI*
Department of Electrical and Electronics Engineering, Engineering Faculty, Selçuk University, Konya, Turkey

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Abstract: In this paper, a sensorless speed estimation method with an artificial neural network for squirrel cage induction motors is presented. Motor current is generally used for sensorless speed estimation. Rotor slot harmonics are available in the frequency spectrum of the current. The frequency components of these determined harmonics are used to estimate the speed of the motor in which the number of rotor slots is given. In the literature, individual algorithms have been used to calculate the speed from the slot harmonics. Unlike the literature, in the proposed method, an artificial neural network is used to extract the speed from the rotor slot harmonic components in the spectrum. This experimental study is carried out to prove the method under steady-state conditions. The experimental results show that the proposed method is suitable for speed estimation and its average error is below 1.5 rpm.

Key words: Sensorless speed estimation, induction motor, rotor slot harmonics, artificial neural network

1. Introduction

Induction motors are widely used in industry because of their robustness and low cost. Various vital components and loads are driven by the motor in industrial processes. Condition monitoring has become necessary to avoid unexpected failure of both the induction motor and combined systems. Fault detection algorithms depend on the analysis of the motor current spectrum and the detection of some speed-dependent harmonic components [1–3]. For effective condition monitoring and fault diagnosis in such algorithms, accuracy of speed knowledge is critical, but most motors and combined systems have no speed sensor in industrial setups.

Motor speed and rotor position are needed as feedback for various applications. Speed sensors, like encoders, tachogenerators, and Hall effect sensors, are connected to the system to obtain the speed value. Additionally, these sensors need a cable to connect to the motor. Thus, it contributes towards increasing the cost of the motor system. The cost of installation of the speed sensor could be comparatively close to the cost of the system with a small motor. Moreover, the fault probabilities of the speed sensors are higher than those of an induction motor. When the whole system is considered, this situation reduces the robustness of the whole system. Sensorless speed estimation is fast emerging as a viable alternative to avoid the problems that occur after the installation of a speed sensor in the system.

In recent years, many approaches have been implemented to replace conventional speed transducers with methods that obtain the speed from motor electrical quantities. To estimate the motor speed, various methods have been presented. They can be summarized in 2 main sections, as follows [4]:

– Methods using motor mathematical models to deduce observers and adaptive schemes,

*Correspondence: hayriarabaci@selcuk.edu.tr

– Methods using spectral estimation of the voltage or current spectral components.

The methods based on the motor's mathematical models have the advantage of a short processing time and are already used for control applications, but they depend on many time variations and require a lot of knowledge of motor parameters. In addition, they require both current and voltage sensing [5].

Methods using spectral estimation are independent of electromagnetic motor parameters and require only voltage or only current measurement, but these methods cause longer processing times. Current and voltage measurement equipment is generally present to protect against overvoltage and overcurrent in most industrial systems with induction motors. By adding minimal hardware to the system, the motor voltage and current signals can be sampled. The problems of voltage measurement, such as distorted waveform (especially in the inverter supplied induction motor), which are based on supply voltage spectral analysis, have not been encouraged. Motor current methods due to the filtering behavior of the motor stator winding encourage measurement problems. Because the speed information of a squirrel cage induction motor is available in the stator currents, the speed can be obtained by analysis of the frequency spectrum of the current [6]. Harmonic components in the spectrum are related with the rotor slot harmonics (RSHs). The spectral resolution directly affects the accuracy of the estimation. Thus, the resolution of the spectrum should be increased to improve the accuracy of calculations. However, it increases the number of computations. Detailed comparisons of different spectral analysis methods were made in [7] and [8] (such as chirp-z transform (CZT), fast Fourier transform (FFT), Hilbert transform, interpolated FFT). The conclusion is that the CZT gives good spectral resolution, but it increases the number of operations. Results obtained using FFT show an adequate accuracy level. FFT is generally used to obtain the frequency spectrum of the current.

In the literature, authors have mainly focused their attention on the optimization of the search algorithm of the rotor slot spectral components [8–11]. The fast orthogonal search algorithm, which results in data that have a lower resolution current spectrum, can be used to identify speed-induced current harmonics [12]. Thus, the algorithm allows for real-time performance on an embedded digital signal processor to estimate the motor speed. A scheme based on combining Hilbert transform and interpolated FFT is used to improve the estimation accuracy of the speed from current signals [13]. Hence, the algorithm realizes direct motor torque control and soft-starting process control without the necessity of a tachometer. The fluctuation of a 3-phase supply current's zero crossings is used for sensorless speed estimation by FFT algorithms. This method is not suitable to convert it to the online speed measurement system, because of having cascaded digital band-pass filters [14]. Eventually, most of the studies focused on methods that are used to obtain the frequency spectrum. Determination of RSH components and estimation of speed according to RSHs are made by individual approaches. Some studies using artificial neural networks (ANNs) are available in the literature [15–20]. However, these studies have methods that are based on a mathematical motor model.

In this paper, the motor current spectrum is obtained using FFT due to a smaller number of operations and adequate accuracy level. RSHs in the spectrum are used to estimate the motor speed using an ANN. This paper is organized as follows. In Section 2, the related materials and methods, which are based on the estimation of the speed by RSHs, the use of the ANN to extract the motor speed, and the ANN structure, are given. In Section 3, the experimental study and results are presented. Finally, the results of this paper are discussed in Section 4.

2. Materials and methods

In recent years, various techniques have been reported that increase attention on sensorless speed estimation methods for squirrel cage induction motors. The speed estimation techniques can be investigated in 2 main sections. The first is a model-based approach, but most of these methods are sensitive to the motor parameters and load type. Thus, the performance of these methods is largely dependent on the accuracy of the parameters used for motor modeling. Consequently, the accuracy of speed estimation using these model-based approaches is limited.

In the second section, techniques are based on a spectrum analysis of the stator current. The stator current harmonics are included in the RSHs, which are proportional to the speed of the motor [5]. RSHs can be used to estimate the motor speed, given the number of rotor slots [1]. Furthermore, these methods do not require an accurate model of the motor parameters and the load type information. In this paper, the speed estimation is made using RSHs in the frequency spectrum of the motor current. Therefore, only speed estimation using RSHs is mentioned in this section.

2.1. estimation using RSHs

The speed information of a squirrel cage induction motor is available in each phase of the stator current. The speed estimation method using RSHs does not depend on any motor parameters. It only needs rotor slots and the number of motor pole pairs. The rotor slots produce changes in the air-gap flux with a spatial distribution dependent on the number of rotor slots. These changes, which are the rotor slot magnetomotive-force harmonics, interact with the stator current in continuous variations. In addition, the magnitudes of these harmonics are directly related to the rotor bar current value; their magnitudes decrease with reductions in the load. RSH frequencies are calculated using Eq. (1) [1]:

$$f_{sh} = f_1 \left[(k \cdot R \pm n_d) \frac{1 - s}{p} \pm v \right], \tag{1}$$

where f_1 is fundamental frequency of stator current, p is the number of pole pairs of the motor, $R$is the number of rotor slots (bars), and s is the per-unit motor slip. $n_d = 0, \pm 1, \pm 2, \ldots$

$k = 0, 1, 2, \ldots$ $v = 0, \pm 1, \pm 3, \ldots$

Here, v is the order of stator time harmonics, which are in the stator current. n_d is known as the eccentricity order and its value is 0 in a healthy motor. When the $n_d = 0$ and $k = 1$ values are replaced in Eq. (1), the principal slot harmonic is obtained, as in Eq. (2).

$$f_{psh} = f_1 \left[R \frac{1 - s}{p} \pm v \right] \tag{2}$$

The principal slot harmonic components corresponding to the v values are calculated using s and Eq. (2). Next, the motor speed is obtained in rpm by Eq. (3).

$$n = \frac{60 \cdot f_1}{p} (1 - s) \tag{3}$$

The values of p can be obtained from the information on the nameplate of the motor. The fundamental frequency component f_1 can be easily determined from the frequency spectrum. It needs the R value information, which can be obtained from the manufacturer of the motor. However, R is always an integer and the motor speed is approximately known under no-load conditions. Thus, this R value can be obtained by a no-load test of the motor [6].

The main problem is to determine from which v value the RSH component in Eq. (2) is derived. Furthermore, the RSH component for all of the v values is not available in the spectrum. In addition, the amplitude of certain RSH components may be very small. Due to the abovementioned reasons, the estimation of the motor speed from RSHs is difficult. In the literature, individual algorithms were used for this estimation [4,6,8,13]. In this paper, the proposed method uses an ANN.

2.2. The proposed method

Every stage of the proposed method is given step-by-step in the block schema and shown in Figure 1.

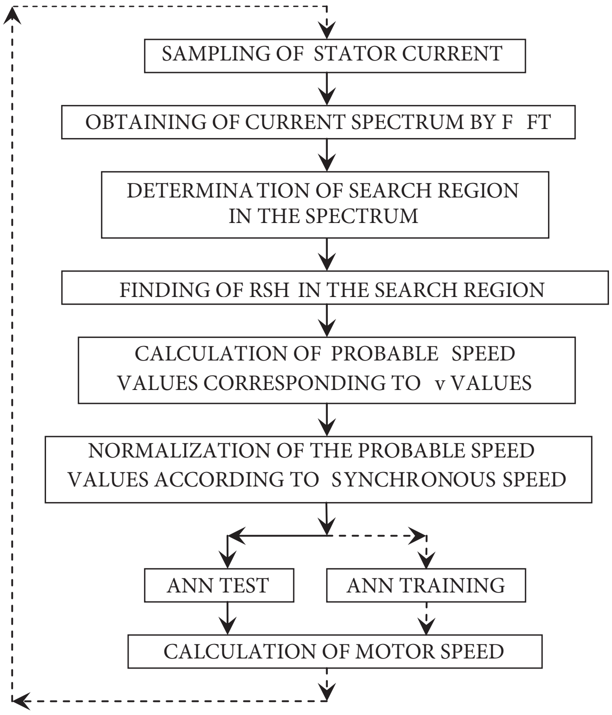

Figure 1. Block schema of the proposed method.

The proposed method is based on the extraction of RSHs from the frequency spectrum of the stator current. Therefore, the stator current is sampled using a data acquisition card. The frequency spectrum of this current is obtained using FFT. There are many frequency components in the spectrum. The number of components is reduced by determining a threshold value. The components, whose amplitudes are under this threshold value, are eliminated to reduce the number of harmonics, which will be investigated for the calculation of probable RSHs. Squirrel cage induction motors under steady-state conditions run between the slip values corresponding to the maximum torque and synchronous speed. The slip at the maximum torque depends on the structure of the motor. It is generally below 10%. However, the upper limit of the slip is taken as 0.16 to scan a wider region. Next, the search region is determined for s values between 0% and 16%. The determined search region of the spectrum is shown in Figure 2. Fundamental harmonic components are also available in this region. These RSH and fundamental harmonic components are shown in Figure 3. Because the speed value is known in Figure 3, the v values are directly shown in the spectrum for every RSH component. However, in practice, it is not certain which RSH components correspond to which v value. To overcome this problem, speed values are calculated via the harmonics in the selected region of the spectrum for the ± 1 and ± 3 values of v. The obtained speed values are given in Figure 4 for the mentioned v values. Because the increment between 2 calculated speeds for the sequent values of v is $2f_1$, the same speed values may be obtained for different RSH components and v values. These same speed values are used as one value. At the end of the investigation, different values of the obtained speed are determined as probable speed values. These probable speed values are normalized according to $\frac{60 \cdot f_1}{p}$ and are made suitable for ANN inputs. Because the normalized speed values cannot be larger than 1 for running the motor, values larger than 1 are eliminated. Finally the normalized probable speed values are obtained and they are for ANN inputs. In the end of the ANN test, the motor speed is calculated by the ANN output.

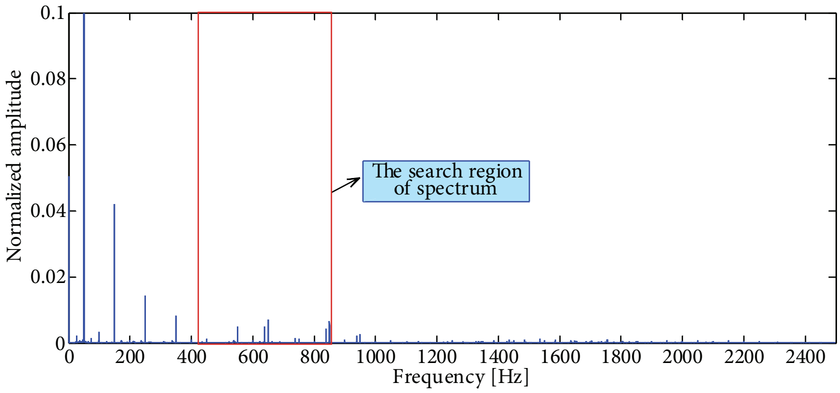

Figure 2. Determined region to scan the RSH components.

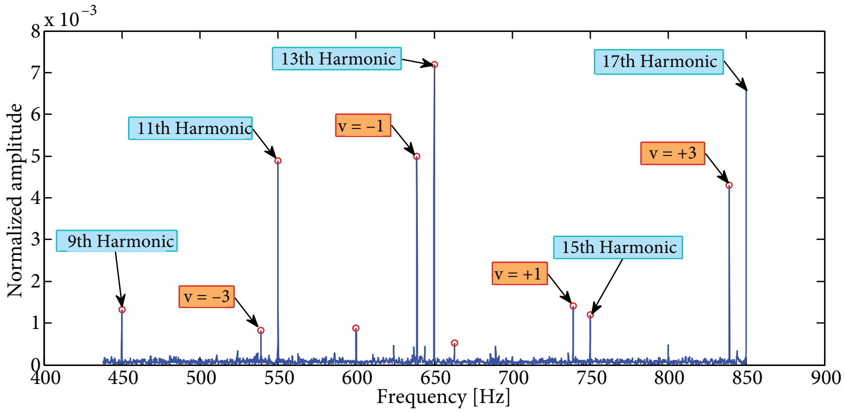

Figure 3. Frequency components of the scanned region for 1476.4 rpm.

2.3. ANN in sensorless speed estimation using RSHs

Methods for sensorless speed estimation using RSHs generally have a similar process. Initially, the motor current is sampled. Next, the frequency spectrum of this current signal is obtained using time-frequency transformation. RSH components in this spectrum are determined. The motor speed is calculated via the RSH and Eq. (2), but we certainly need to know the v value that corresponds to this RSH frequency. This is the main problem with this method. To date, individual approaches have been used to calculate the speed from RSH components by Eq. (2). In this proposed method, the motor speed is computed via the ANN, unlike in the literature.

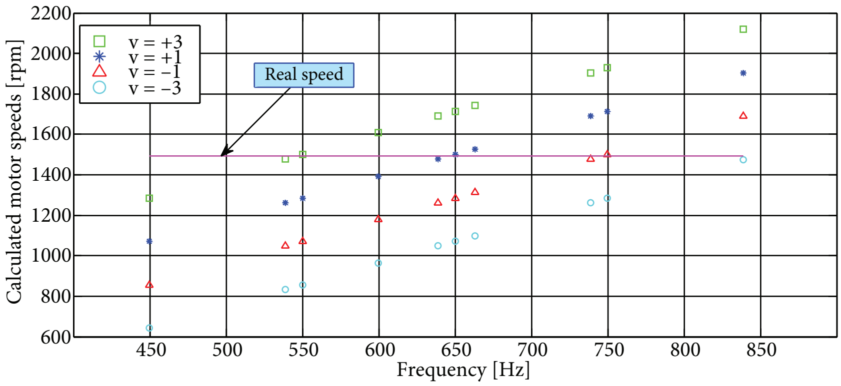

Figure 4. The calculated speeds for each v value.

ANN structure: A feedforward network with a backpropagation algorithm is used for the ANN, and 1 hidden layer is used between the input and output layers.

ANN inputs: The number of ANN inputs is 11. Thus, the calculated 11 probable normalized speed values are used as ANN inputs.

ANN outputs: The number of ANN outputs is 1. The output of the ANN gives a normalized motor speed value. This normalized value is multiplied by $\frac{60.f_1}{p}$ to obtain the motor speed in rpm.

Obtained from the experiments are 18 current datasets, of which 12 are used for ANN training and the other 6 are used for ANN testing. The training and testing are implemented in a different number of hidden units and iterations to find the optimal number of hidden units and iterations. The following 2 criteria are used for optimization:

Training error: The difference between real speeds and the training results in rpm is directly used as the training error.

Test error: The difference between real speeds and the speeds that are obtained from the test results is directly used as the test error.

The training results are given in Tables 1 and 2.

Table 1. Errors determined at a different number of hidden units for 1000 iterations.

Number of hidden units	20	200	300	400	500	550	600	650	700	800	900
Training error (rpm)	2.6	0.4	0.41	0.47	0.48	0.4	0.39	0.34	0.34	0.5	6.7
Test error (rpm)	15	5.9	24	5.97	4.3	7.8	3.63	1.5	5.6	14.5	13.5

Table 2. Errors determined at a different number of iterations for 650 hidden units.

Number of iterations	200	300	400	500	1500	2000	5000
Training error (rpm)	0.44	0.9	0.39	0.38	0.31	0.29	0.2
Test error (rpm)	2.84	2.08	1.66	1.6	1.48	1.51	1.7

Optimal values are reached at the end of the training. As shown in Tables 1 and 2, the most efficient number of hidden units in the hidden layer is 650 and the most efficient number of iterations is 1500. Finally, the average error of the training is calculated as 0.31 rpm and that of the test error is 1.48 rpm.

3. Experimental study and results

The experiments are carried out using a squirrel cage induction motor with 28 bars, whose specifications are 3 phases, 2 pole pairs, 380 V, 2.2 kW, and 50 Hz. The motor is tested in the laboratory using the experimental system. The tested motor is loaded by the generator. Motor load is leveled using resistors that are connected to the generator. The block diagram of the used experimental system is given in Figure 5. The photograph of experimental system and its components are also given in Figure 6. One phase current of the stator coils is sampled to calculate the motor speed under steady-state conditions for various speed values. The motor is tested under different load levels to obtain different speed values. Verification of the estimated results with real speed values is conducted using an encoder combined with a motor-generator shaft in the experimental system.

The motor current is sampled at 5 kHz from the Hall effect current sensor using a data acquisition card. The data are transformed to the frequency domain using FFT with a Hanning window. The probable speed values are prepared by the proposed process for the ANN input. The motor speeds are estimated by the proposed method by the ANN. A comparison of the estimated motor speeds and real speeds are given in Figure 7. The maximum error rate is 0.26% (3.9 rpm) around the maximum motor speed. When the motor load is increased, the related RSH component becomes clearer. Therefore, the error decreases at a lower speed, as shown in the experimental results in Figure 7.

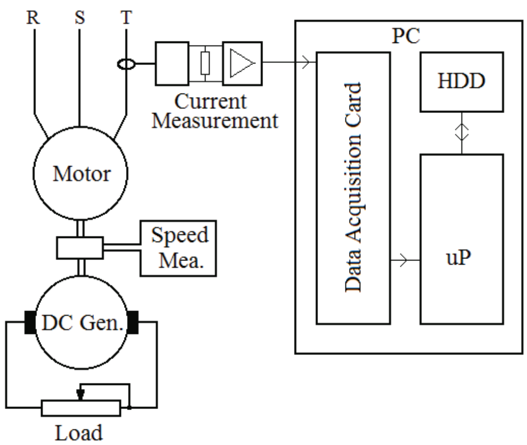

Figure 5. Block schema of the experimental system.

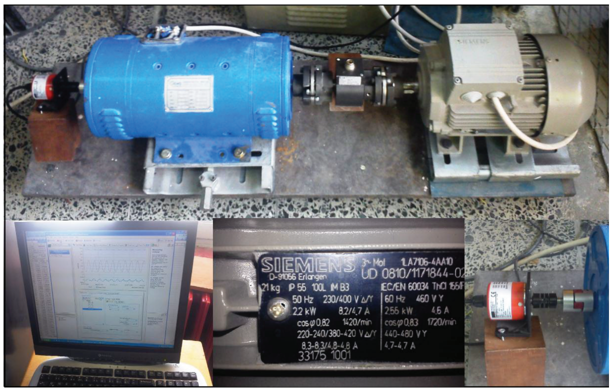

Figure 6. Photograph of experimental system and components.

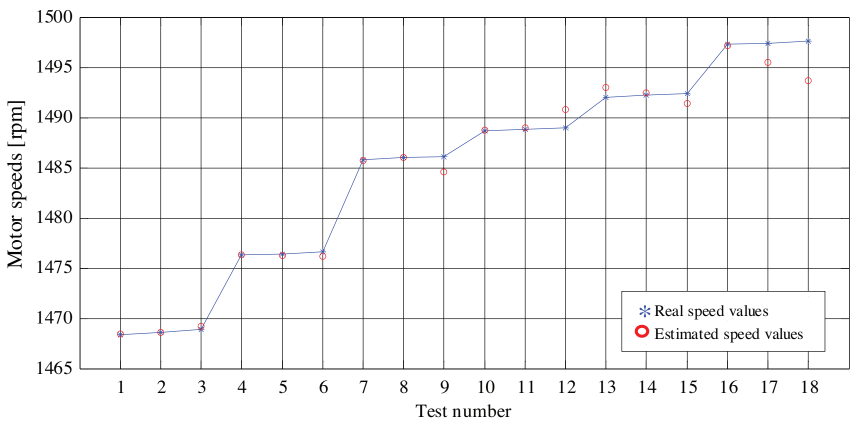

Figure 7. Comparison of the experimental results and real speed values for different load conditions.

4. Conclusion

This paper presents an ANN approach for sensorless speed estimation using RSHs. To obtain the RSHs the frequency spectrum of the motor current is obtained using FFT. Each RSH component in this spectrum corresponds to v values, which is required to calculate the motor speed. This process is performed using an ANN in the proposed method, unlike in the literature. The experimental results are obtained by means of a 2.2-kW induction motor running under steady-state conditions. The maximum error rate is 0.26% (3.9 rpm) around the maximum motor speed. In the literature, the error is calculated as between 3.6 and 5.9 rpm [4] and ± 5 rpm is an acceptable error rate [6,8,14]. Hence, the obtained maximum error with this proposed method is feasible for sensorless speed estimation. Meanwhile, the average calculation error is 1.5 rpm (0.1%). Thus, the experimental results show that the proposed method is suitable to estimate the speed with high accuracy. Furthermore, this proposed algorithm can enhance the performance and reliability of the monitoring of squirrel cage induction motors without the use of a speed sensor.

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