A Genetic Algorithm Approach for Sensorless Speed Estimation by using Rotor Slot Harmonics

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Abstract— **In this paper a sensorless speed estimation method with genetic algorithm for squirrel cage induction motors is presented. Sensorless speed estimation methods generally are based on motor current. Frequency spectrum of the current has components representing rotor slot harmonics. These frequency components are used to estimate the speed of the motor given the number of rotor slots. In the literature, individual algorithms have been used to calculate the speed from the rotor slot harmonics. Unlike the literature, genetic algorithm is used to extract the motor speed from rotor slot harmonics components in the proposed method. The experimental study was carried out to prove this method under steady state conditions. The experimental results show that the proposed method is suitable for sensorless speed estimation and its average error is the 0.29 rpm at 50 Hz.**

Index Terms— **Genetic algorithm, induction motor, rotor slot harmonics, sensorless speed estimation**

I. INTRODUCTION

THE induction motors are widely used in industry because of inexpensive cost and their robustness. The motors drive various vital components and loads in industrial processes. Condition monitoring for both inductions motor and combined systems has become necessary to avoid unexpected failure. Fault detection algorithms dependent on the current spectrum analysis and the detection of some harmonic components which occur according to motor speed [1-3]. In such algorithms, accuracy of speed knowledge is critical for the effective condition monitoring and fault diagnosis. Moreover, motor speed and rotor position require a feedback for various applications, but most of these systems do not have any speed sensor in industrial setups. Speed sensors such as encoders, tacho-generator and Hall effects sensors are connected to the system to obtain the speed value. These sensors need cabling to connect to motor. It makes the cost of the motor system increased. In addition to this, faulting probability of the speed sensors is higher then induction motor. Robustness of whole system decreases. The sensorless speed estimation is a viable alternative to avoid the problems which associates with the system including speed sensor. Many approaches have been done to obtain the speed from electrical quantities of motor during recent years. Various motor speed estimation methods have been presented. They can be summarized in two main sections as follows [4]:

– Methods are based on motor mathematical models to deduce observers and adaptive schemes,

– Methods are based on spectral component estimation of the voltage or current.

The methods using motor mathematical models have advantage of short processing time. But, they have disadvantages depending on many time variations and requiring a lot of knowledge of motor parameters. Otherwise, current and voltage sensing are required for these methods [5]. The second mentioned methods need only voltage or only current measurement. There are also independent of electromagnetic motor parameters. But, these methods cause longer processing times according to first mentioned methods.

Current and voltage measurement equipments are generally present to protect from over voltage and over current in most industrial systems including motor. The voltage and current data could be obtained by adding some hardware. Using of voltage measurements has some problems such as distorted waveform (especially system with induction motor which is supplied by inverter). So, the algorithms, which is based on voltage spectral analysis, have not been encouraged this problem. Motor current have been preferred due to the filtering behavior of the motor stator winding. Because the speed observers of a squirrel cage induction motor are available in the stator currents, the speed could be obtained by analysis of frequency spectrum of the current [6]. Harmonic components in the spectrum are related to the number of rotor slots and named Rotor Slot Harmonics (RSH). Resolution of the frequency spectrum effects directly speed estimation accuracy. The high resolution improves accuracy of calculations, but it increases the number of computation. Different spectral analysis methods are compared in detail in [7] and [8] (such as Chirp-Z Transform (CZT), Fast Fourier Transform (FFT), Hilbert Transform, and Interpolated FFT). The CZT gives good spectral resolution, but it increases the number of operations. Adequate accuracy level is obtained by using FFT. Moreover, the number of operations is lesser than

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using CZT. So, FFT is generally used to obtain the frequency spectrum of the current.

In the literature, authors have mainly focused on the optimization of search algorithms of the rotor slot spectral components [8-11]. Various studies are available such as fast orthogonal search algorithm, which's result data have lower resolution current spectrum, could be used to identify RSH [12]. The algorithm allows estimation of the speed for real-time performance by an embedded digital signal processor.

A scheme, which combines Hilbert transform and interpolated FFT, is used to improve the estimation accuracy of the speed [13]. Hence, the algorithm realizes direct motor torque control and soft-starting process control without any tachometer.

Eventually, most of studies have been focused on methods which are used to transform time domain to frequency domain. Determination of RSH components and estimation of speed according to RSH are made by individual approaches in their studies. Some studies using Artificial Neural Network (ANN) [14-16] and genetic algorithm (GA) [17-19] are available in the literature. But these studies use methods which are based on motor mathematical model.

An ANN approach is presented for sensorless speed estimation using RSH in [21]. To calculate the motor speed, each related RSH component is extracted from the spectrum by using ANN. 1.5 rpm average calculation error is reached.

In this paper, the motor current spectrum is obtained by using FFT due to a smaller number of operations and adequate accuracy level. RSH in the spectrum are used to estimate motor speed by using GA.

II. MATERIAL AND METHOD

Various sensorless speed estimation techniques have been received with increasing attention for squirrel cage induction motor. These techniques can be divided two main parts. One of them is model based approaches. But, most of these approaches are sensitive to motor parameters and load type. Accuracy of these parameters directly affects performance of these methods. So, the accuracy of speed estimation is limited for the model-based approaches. In the second part is based on the spectrum analysis of stator current. The stator current harmonics are included RSH which are proportional to motor speed [5]. RSH could be used to estimate the motor speed depending on the number of rotor slots [1]. Moreover, an accurate model of the motor parameters and the load type information are not required in these methods. In this paper, the speed estimation is made by using RSH in frequency spectrum of motor current. Only this method is mentioned in this section because the proposed algorithm bases on RSH analysis of the current.

A. The speed estimation by using rotor slot harmonics

The stator current data of squirrel cage induction motor has speed observers. The motor speed can be estimated by mean of spectrum analysis of the current. The speed estimation method does not depend on any motor parameters. The method requires only the knowledge of the number of rotor slots and the number of motor pole pairs. The rotor slots produce changes on air-gap flux with a spatial distribution dependent on the number of rotor slots. These changes are rotor slot mmf harmonics and these effect the stator current in continuous variations. Frequency of RSH components is calculated by using Eq. (1) [1].

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

where: $n_d = 0, \pm1, \pm2, \ldots$ $k = 0, 1, 2, \ldots$ $v = 0, \pm1, \pm3, \ldots$

f_1 is fundamental frequency component of stator current. p is the number of pole pairs of motor. R is the number of rotor slots (bars). s is per unit motor slip. v is the order of stator time harmonics presenting in the stator current. n_d is known as eccentricity order and it's value is zero for healthy motor. When $n_d = 0$ and $k = 1$ values are replaced in Eq. (1), 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 v values are calculated by using s and Eq. (2). Then 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 calculated from nameplate information of motor. The fundamental frequency component f_1 is easily determined from the frequency spectrum. It is need that R value is informed from manufacturer of the motor. But R is always integer and motor speed is approximately known under no-load condition. So, this R values could be obtained by no-load motor test [6].

The main problem is to determine that the concerned RSH component in Ed. (2) occurs due to which v value. Furthermore, RSH component for whole values of v is not available in the spectrum. In addition to this, amplitude of certain RSH component may be very small. To estimate the motor speed from RSH is difficult because of above mentioned reasons. In the literature individual algorithms have been used for speed estimation [4,6,8,13]. In this paper, the proposed method uses GA to extract the v value and slip knowledge by using one of the RSH components in scanning region of current spectrum.

B. The proposed sensorless speed estimation method

The proposed method uses frequency spectrum of stator current. The frequency spectrum is obtained by using FFT. Many frequency components are available in the spectrum.

Squirrel cage induction motors under steady state operation run in the slip region that is between the slip corresponding to maximum torque and synchronous speed. The slip corresponding to maximum torque depends on the structure of the motor. It is generally below the 10%. Therefore, search region of the frequency spectrum is determined by using Eq.(2) for s values between 0 and 10% and . The determined search region is shown in Fig. 1. RSH components are searched in this region. But, there are many components which are amplitude are at small level. These components are eliminated by determining a threshold value. It reduces the number of operations at searching process of probable RSH. Any operation is not done for fundamental harmonic components in this region because of easy determination. RSH components, fundamental harmonic components and threshold value are shown in Fig. 2. Because motor speed is known from experimental study, v values are directly shown in the spectrum for every RSH components in Fig. 2. However, in the practice motor speed is unknown and wants to find out. So, it is not certain that RSH component corresponds to which v value. For overcoming of this problem GA is used in this paper. Frequency value of any RSH component in the region is used in GA process. End of the GA process, s and v values are found out. So, motor speed is calculated by using the obtained s value and Eq. (3). The block diagram of the proposed method is given in Fig. 3.

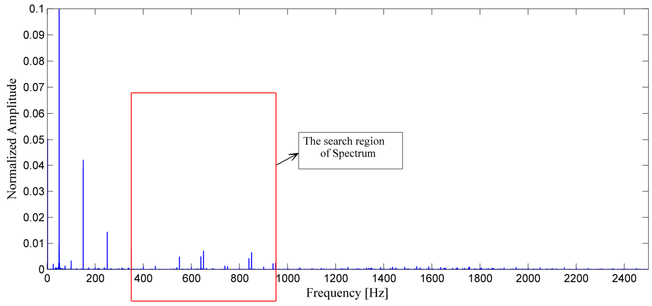

Fig. 1. The determined region to scan the RSH.

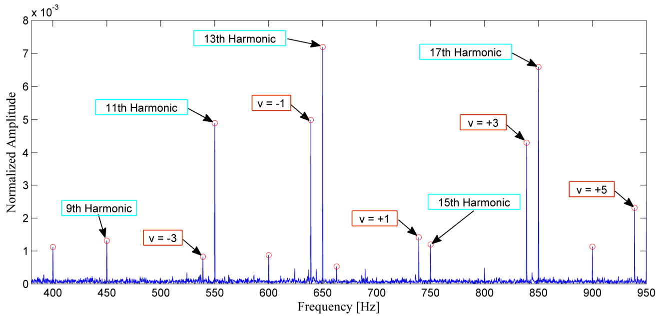

Fig. 2. The frequency components of scanned region for 1476.4 rpm at 50 Hz..

C. GA approach in sensorless speed estimation

The methods, which are based on RSH for sensorless speed estimation, generally use similar process stages. Initially, motor current is sampled from one stator coil. Then frequency spectrum of the current is obtained by using time-frequency transformation. RSH components are determined from the frequency spectrum. Motor speed is calculated via the RSH, v value, Eq. (2) and Eq. (3). But it needs to certainly know that the selected RSH frequency is for which the v value. This is main problem of the method. To date, individual algorithms have been used to calculate the motor speed from RSH components by Eq. (2). In this paper, GA is used to determine v and s values corresponding to related RSH component.

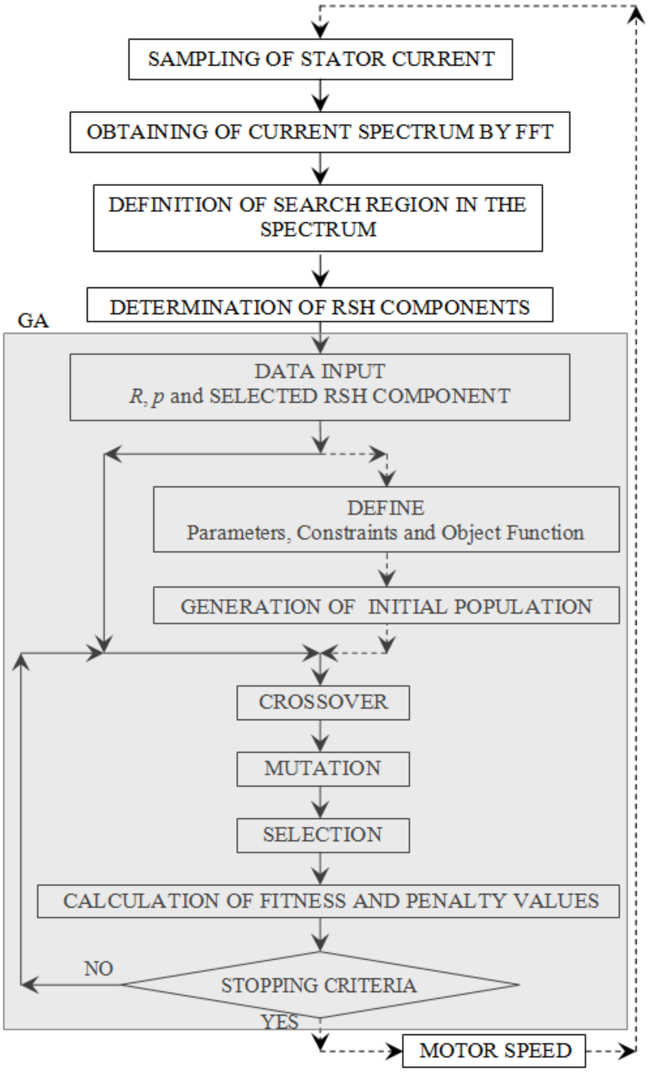

Fig. 3. The block diagram of the proposed method.

Processing steps of the used GA algorithm are given as follows:

1- Adapt the structure of chromosome according to constraints and limits of parameters

2- Form the objective function

3- Generate the initial population

4- Apply crossover, mutation, selection

5- Calculate the fitness and penalty values

6- Convergence and repeat of the test from step 4 until achieving the optimum solution.

In this study, aim is to find the value of v, and thus to

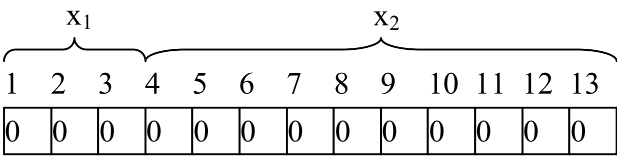

Fig. 4. . The structure of chromosome.

estimate the motor speed (or s). Therefore, each chromosome consists of v and s values. Chromosome is formed to be binary code. So, the binary-code GA is used in the proposed algorithm.

Values of v are odd number. Its minimum value and maximum value are -7 and 7 respectively. s is real number. Its minimum value and maximum value are 0 and 0.1 respectively. 0.0001 is enough for resolution of s. Hence, length of each chromosome is 13 bits (13 genes). First 3 bits (x1) represent v value. Other 10 bits (x2) represent s value. The structure of this chromosome is given in Fig. 4.

a- Initial population

The initial population is generated randomly without any limit, because of definition of limit is done at forming process of chromosome.

b- Constraints

Eq. (2) is used to form the object function. Values of R and p parameter are known. But, f_1 is calculated from frequency spectrum of current. So, the constraint function is obtained as shown in Eq. (4).

$$g(x) = f_{psh} - f_1\left[R\frac{1-x_2}{p} \pm x_1\right] \qquad (4)$$

where f_{psh} is value of RSH component which is selected from the scanning region of spectrum. x_1 is first 3 bits of jth x chromosome of every generation and is calculated as to Eq. (5).

$$x_1 = 2\cdot(x(1:3))_{10} - v_{\min} \qquad (5)$$

where vmin is minimum value of the v and determined to be -7 for study. x_2 represents motor slip and it's values is calculated by last 10 bits of jth x chromosome. Value of the x_2 is calculated by using Eq. (6).

$$x_2 = \frac{s_{\max}\cdot(x(4:13))_{10}}{2^{10}-1} - s_{\min} \qquad (6)$$

where s_{max} is acceptable maximum value of the motor slip under steady state condition and approved to be 0.1 for this study. s_{min} is also determined to be 0. Penalty values are calculated for each generation. The penalty values are used for selection.

c- Selection

The obtained penalty values by Eq. (4) are compared other individuals of related generation. The best chromosome is saved and carried next generation.

d- Crossover

Crossover is an operator used in order to produce better chromosomes and increase the diversity of the population. One-point is used for crossover is applied on the population. The individual populations are chosen and paired randomly. The selected pair of genes is exchanged from one point which is determined randomly.

e- Mutation

Mutation is applied on the population to avoid local optimum [20]. So the diversity is increased in the population. A number between 0 and 1 is produced randomly for mutation. This number is compared the mutation rate. If the number is under the mutation rate, mutation is applied one gene of the related chromosome. The gene is selected randomly. If the selected gene is 0, it is made 1, else 0.

f- Convergence test

New individuals are achieved every loop of the procedure. This process continues until reaching a predetermined generation number or meeting an object. The most important point is to determine the stopping criterion. In the study, the generation number is chosen as stopping criterion.

III. EXPERIMENTAL STUDY AND RESULTS

Squirrel cage induction motor with 28 bars was used to carry out the experiments study. Its specifications were 2.2 kW, 3 phases, 2 pole pairs, 380V and 50 Hz. The experiments were made in the laboratory by using an experimental system. The motor was loaded by generator. Loading of the motor is leveled by using resistors which are conducted to the generator. The block diagram of the used experimental system is given in Fig. 5. The photograph of experimental system and its components are also given in Fig. 6. One phase current of the motor was sampled in steady state operation for various speed levels. Verification of estimated results with real speed values is made by using an encoder combining to motor-generator shaft in the experimental system.

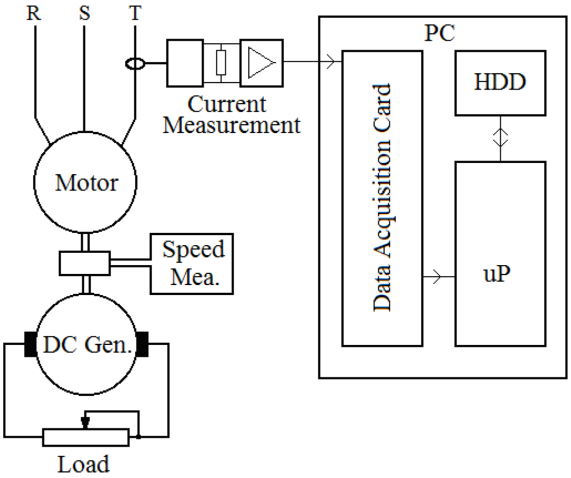

Fig. 5. The block diagram of experiment system.

Fig. 6. The photograph of experiment system and components.

The motor current was sampled from Hall-effect current sensor by using data acquisition card. The sampling rate was 5 kHz. FFT with Hanning window was used to obtain frequency spectrum of this current data. RSH components were determined from the scanning region. One of these determined RSH components was used in objection function of GA. Then GA iteration was started. End of the iteration, the calculated s value was used to estimate the motor speed via Eq. (3).

The estimated motor speeds and real speeds are compared and given in Table 1. Maximum error rate in rpm is 0.064% (0.96 rpm for 50 Hz). Finally the average error is calculated as 0.29 rpm.

TABLE I
COMPARISON OF EXPERIMENTAL RESULTS AND REAL SPEED VALUES FOR DIFFERENT LOAD LEVELS

Load Levels	Estimated Speed Values [rpm]	Real Speed Values [rpm]	Estimation Error [rpm]	Estimation Error [%]
Load 1	1468.4	1468.91	0.51	-0.034
Load 2	1468.6	1468.77	0.17	-0.011
Load 3	1468.9	1468.77	0.13	0.009
Load 4	1476.3	1475.95	0.35	0.023
Load 5	1476.4	1476.54	0.14	-0.009
Load 6	1476.6	1476.69	0.09	-0.006
Load 7	1485.8	1485.63	0.17	0.011
Load 8	1486	1485.63	0.37	0.025
Load 9	1486.1	1486.07	0.03	0.002
Load 10	1488.7	1489	0.3	-0.020
Load 11	1488.8	1489	0.2	-0.013
Load 12	1489	1489	0	0.000
Load 13	1492	1492.96	0.96	-0.064
Load 14	1492.2	1492.96	0.76	-0.051
Load 15	1492.4	1492.96	0.56	-0.037
Load 16	1497.3	1497.51	0.21	-0.014
Load 17	1497.4	1497.51	0.11	-0.007
Load 18	1497.6	1497.36	0.24	0.016

IV. CONCLUSION

This paper presents a GA approach for sensorless speed estimation using RSH. Frequency spectrum of motor current is obtained by FFT to reach the RSH. Each RSH components in this spectrum correspond to v values which are required to calculate the motor speed. One of the RSH components is used for GA in proposed method unlike the literature. The experimental results are obtained by means of a 2.2 kW induction motor running at 50 Hz under steady state conditions. The maximum calculation error is 0.96 rpm (0.06%). The average calculation error is 0.29 rpm (0.02%). Therefore, the experimental results show that the proposed method is feasible to estimate the speed in high accuracy. Furthermore, this proposed algorithm can enhance the performance and reliability of monitoring of squirrel cage induction motor without any speed sensor as in submersible induction motor applications.

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