A Genetic Algorithm-Based Novel Speed Controller for Induction Motor Drives

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Abstract:

This paper describes a new method for the design of a speed controller using a genetic algorithm to improve the dynamic performance of induction motor drives. The control signal is based on the instantaneous speed deviation and acceleration of the motor and on a set of simple fuzzy control rules. A novel approach is proposed to generate the control rules, and thus increase the effectiveness of the controller. A genetic algorithm is used to search for optimal setting of the controller parameters. The proposed control algorithm was successfully implemented using a 1.5 hp three-phase induction motor fed from a pulse width modulation inverter and a digital signal processor (DSP-TMS320C31). Simulation and experimental results show a good performance of the system under study with the proposed speed controller over a range of operating conditions.

1. Introduction

Pulse width modulation (PWM)-fed induction motor drives are increasingly used for the operation of many kinds of industrial production and automation processes. For applications that require a high dynamic performance, vector control of induction motors is widely employed [1-2]. In general, the requirements for a high performance motor drive system include the following: 1) fast step tracking response without overshoot, 2) the steady state errors in both the command tracking and load regulation cases must be zero, 3) the maximum speed dip and the restore time due to step load change must be kept so small as possible. Conventional proportional plus integral (PI) controller is often used to achieve these requirements. However, this conventional PI controller cannot lead to good dynamic responses in both the command tracking and load regulation characteristics. It is well known, from experience, that if the regulation characteristics with small speed dip in a short time for a step load change is required, relatively large overshoot and long settling time in the speed tracking transient response may result [3-4].

The well known fuzzy logic controller (FLC) can be used to overcome this difficulty. Fuzzy logic control is important to consider in view of its potentially lower computational burden and good robustness. The application of fuzzy control techniques appears to be particularly useful whenever the system to be controlled is complex and has uncertainty and imprecision. These properties certainly apply to induction motor drives. However, the design of fuzzy controllers is usually done on an ad hoc, trial and error basis.

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On the other hand, genetic algorithms (GAs) have been introduced as an efficient optimization technique [5]. The successful application of GAs to various control system problems [6-7] has proven the efficiency of GAs as a method for control system design. Incorporation of a GAs into fuzzy logic controller design adds an intelligent dimension to these controller and reduces the time consumed in the design process.

This paper presents a new approach to the design of a fuzzy logic-based controller using GA and demonstrates its effectiveness for performance improvement of induction motor drives. Briefly, the motor status is expressed in terms of speed deviation and acceleration in the phase plane, which is divided into four quadrants having simple control rules. Two fuzzy membership functions are defined to reflect the actions of the control rules. A new tuning parameter is introduced in designing the fuzzy logic-based controller to determine not only the quadrants' control rules, but also the best location for each quadrant on the phase plane. GA is utilized to search for optimal settings of the controller parameters. Both simulation and experimental results clearly show that the proposed controller improves the dynamic performance of the induction motor studied over a wide range of operating conditions.

2. System Description

The system under study is a squirrel cage induction motor (IM) fed by a voltage source inverter (VSI). Pulse width modulation patterns that operate the VSI are generated by a space vector current controller. The idea utilized in this system is to control the inverter switches in a way to force the currents in the motor to follow references generated from a rotor speed encoder. This type of control is easy to realize with transistorized inverter where high switching frequencies are possible. In addition, it offers a possibility of direct torque control not only in the steady state but also in the transient operation. The main elements of the control system can be summarized as follows:

- -current controller which generates six signals needed for the proper operation of the inverter.
- -vector control algorithm which produces the references signals fed to current controller.
- -The proposed speed controller which leads to a zero error between rotor speed and its reference.
- -The power circuit which consists of the induction motor and the inverter.

3. Genetic Algorithm

Genetic algorithm (GA) is a global search technique based on an analogy with biology in which a group of solutions evolves through natural selection and survival of the fittest [5]. GA represents each solution by a binary bit string. Such a string is made up of sub-strings, each sub-string representing a different parameter. In the terminology of GAs the bits are referred as '*genes*' and the total string as a '*chromosome*'. Several chromosomes representing different solutions comprise a '*population*'. GA is not gradient based, and uses an implicitly parallel sampling of the solution space. The population approach and multiple sampling means that it is less subject to becoming trapped in local minima than traditional optimization techniques, and can explore a large solution space. GA has been shown to be powerful at reaching a very near optimal solution in a computationally efficient manner. The structure of GA is quite simple. The GA starts with random generation of initial population strings, and evaluation of each string's fitness. The algorithm then proceeds by selecting, according to whatever strategy is used, two '*parent*' solutions, interchanging portions of their strings and thus generating two '*offspring*' solutions. This process is called a 'crossover'. The process is repeated until the new population size is completed. To ensure further variety the 'mutation' operator with a small probability is applied during the crossover for random switching of one or more bits. Finally, the new population replaces the old (initial) one. This procedure continues until a specified termination condition is reached.

4. Proposed Control Technique

The control objective is to generate a torque command signal in order to improve the dynamic performance of an induction motor drive system. The control signal is based on the instantaneous speed deviation and acceleration of the motor and on a set of simple fuzzy control rules. A novel approach is proposed, as explained later on, to generate the control rules, and thus increase the effectiveness of the fuzzy logic-based speed controller. The motor condition is defined at every sampling time, kT_s, in terms of its speed deviation from the reference speed and scaled acceleration, $[\omega(k), F_* \dot{\omega}(k)]$, where

$$\dot{\omega}(k) = (\omega(k) - \omega(k-1)) / T_s \qquad (1)$$

T_s is the sampling interval and F is a predefined scaling factor. This condition represents a certain point, Z, in the $[\omega, F_* \dot{\omega}]$ phase plane as shown in Fig. 1. The polar displacement D(k) of this point from the origin, and the corresponding angle θ (k) are computed as:

$$D(k) = [(\omega(k))^2 + (F * \dot{\omega}(k))^2]^{0.5} \qquad (2)$$

$$\theta(k) = \tan^{-1}(F * \dot{\omega}(k) / \omega(k)) \qquad (3)$$

The phase plane is divided into four quadrants. Each quadrant has simple control rules according to the degree of deceleration and/or acceleration control required to restore the machine condition, after the disturbance, to the origin of the phase plane as soon as possible with an acceptable performance. Generally, deceleration control and hence a positive control signal, is only required when the motor status locates in a certain quadrant (say the first quadrant). Acceleration control and hence a negative control signal is required only when the motor status lies in the opposite quadrant (i.e. the third quadrant). Decreasing (or increasing) deceleration and increasing (or decreasing) acceleration as well are required when the motor status lies in the other two (i.e. the second and the fourth) quadrants. Two fuzzy membership functions, N(θ), shown in Fig. 2, associated with the desired deceleration and P(θ) associated with the desired acceleration, are defined in terms of the polar angle θ defined by equation (3) to reflect the actions of the control rules. The defining relations for N(θ) and P(θ) are:

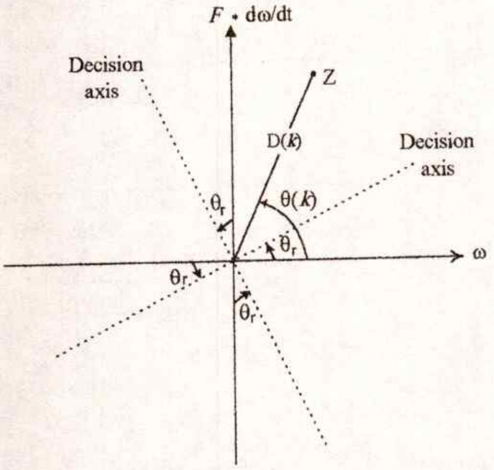

Fig. 1 Definition of IM condition in the phase plane

$$
N(\theta) = \begin{cases} 1 & \text{for } : \theta \le \theta_i \\ (\theta_1 - \theta)/(\theta_1 - \theta_i) & \text{for } : \theta_i < \theta \le \theta_1 \\ 0 & \text{for } : \theta_1 < \theta \le \theta_2 \\ (\theta - \theta_2)/(\theta_f - \theta_2) & \text{for } : \theta_2 < \theta \le \theta_f \end{cases} \qquad (4)
$$

$$
P(\theta) = 1 - N(\theta) \qquad \text{for all } \theta \qquad (5)
$$

The fuzzy membership functions described by equations (4) and (5) can be portrayed in terms of a pair of what can be termed "decision axes", shown in Fig. 1, on the phase plane. A trial and error approach was initially utilized to determine the best settings of these angles. It was found by the authors that, for best results, the angles θ_i to θ_f should again progress in 90 degree steps, but that an offset angle θ_r between the phase plane axis set (i.e. the ω and $F{*}\dot{\omega}$ axes) and the decision axis set (i.e. quadrant boundaries) should be introduced as shown in Fig. 1. This offset angle θ_r, which can be regarded as another tuning parameter, specifies the best location for each quadrant with its particular control rules on the phase plane. In effect, the offset angle θ_r rotates the decision axis set clockwise or anti-clockwise until the minimum of a predefined performance index is obtained. This has the effect in turn of changing the final shapes of fuzzy membership functions over the whole universe of discourse, *i.e.* another set of control rules is generated according to the degree of rotation θ_r. The resulting two membership functions then lead to the desired control signal, T_{com} (k), given by:

$$
T_{com}(k) = G(k)\,[\,N(\theta(k)) - P(\theta(k))\,]\,T_{max} \qquad (6)
$$

where G(k) is the gain whose value is defined as :

$$
G(k) = D(k)/D_r\,, \quad \text{for } D(k) < D_r \qquad (7)
$$

$$
G(k) = 1\,, \quad \text{for } D(k) \ge D_r \qquad (8)
$$

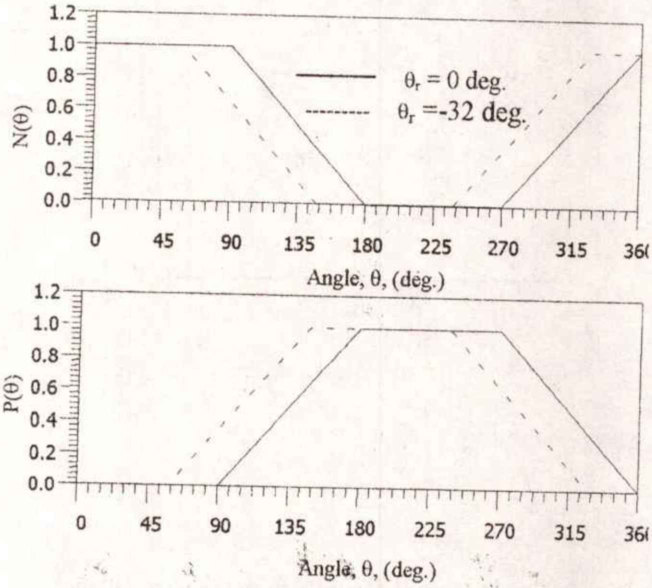

Fig.2 Proposed fuzzy membership functions

The parameter D_r is a set value of polar displacement at which the gain is required to saturate at unity. It is observed that only one output signal (speed deviation) is needed for the calculation of the control signal, and the design framework of the speed controller is based upon a set of simple control rules. However, the implementation of the above fuzzy control scheme requires the following steps in each sampling time:

Step1: Motor speed deviation, $\omega(k)$, is sampled and the scaled acceleration, $F \cdot \dot{\omega}(k)$, is computed.

Step2: $D(k)$ and $\theta(k)$ are determined using equations (2,3).

Step3: Values of both fuzzy membership functions, $N(\theta)$ and $P(\theta)$, are calculated.

Step4: The control signal $T_{com}(k)$ is determined using equation (6).

To link the rotation angle θ_r directly with the calculation of the control signal $T_{com}(k)$, another angle, ϕ, is defined as:

$$\phi = \theta - \theta_r \tag{9}$$

The angle θ_r is considered positive when the rotation is anti-clockwise, while it is considered negative if the rotation is in the clockwise direction. The membership functions, $N(\phi)$ and $P(\phi)$, can then take the form:

$$N(\phi)=\begin{cases} 1 & \text{for}: 0 \le \phi \le 90 \\ (180-\phi)/90 & \text{for}: 90 < \phi \le 180 \\ 0 & \text{for}: 180 < \phi \le 270 \\ (\phi - 270)/90 & \text{for}: 270 < \phi \le 360 \end{cases} \tag{10}$$

$$P(\phi) = 1 - N(\phi) \qquad \text{for all } \phi$$

and the control signal, $T_{com}(k)$, is then computed as:

$$T_{com}(k)=G(k)\,[N(\phi(k)) - P(\phi(k))]\,T_{max} \tag{11}$$

5. GA-Based Controller Parameters Selection

The tuning parameters of the proposed fuzzy control scheme are F, D_r and θ_r, while T_{max}, the maximum size of the control signal, is a prespecified, constant parameter. For optimal settings, the following discrete-type, quadratic performance index, J, is defined:

$$J = \sum_{k=1}^{N} [kT \cdot \omega(k)]^2 \tag{12}$$

As is seen, the speed deviation, $\omega(k)$, is weighted by the respective time kT. In addition, N denotes the total number of time steps. This index is chosen because a low value of it reflects small settling time, small steady state error, and small overshoots in motor speed. The tuning parameters are adjusted to minimize this performance index.

The tuning parameters are coded in a binary string. GA is then used to search for the optimal set of parameters which minimize the performance index. In this study, tournament selection [8] is employed. This enables the GA to work without the explicit definition of a fitness function. Tournament selection proceeds as follows: the population is repeatedly divided into random tournaments consisting of two strings per tournament; the fittest string in each tournament is retained in the mating pool while the looser is removed; the process is repeated until the mating pool has the same size as the population. The crossover probability is chosen to be 0.7 in order to give some of the population the chance to survive into the next generation without any changes. A small mutation probability (0.001) is used so that the process does not lose its characteristics of inheritance. otherwise the GA will be ineffective.

6. Simulation Results

The system performance with the proposed controller has been investigated for two types of disturbances: step change in the reference speed "ω_{ref}" and step change in the load. For studies of the first type of disturbance, the motor is postulated to run at no-load. Fig. 3a shows variation of the performance index J with the number of generations. The GA produced optimal tuning parameters (F, D_r, θ_r) of 0.001, 10.65, and -32° respectively as shown in Fig. 3b, for the particular system and disturbance studied. It is noticed that the sign of the rotation angle θ_r is "minus" sign, which means the decision axis set was rotated in the clockwise direction in order to minimize the given performance index.

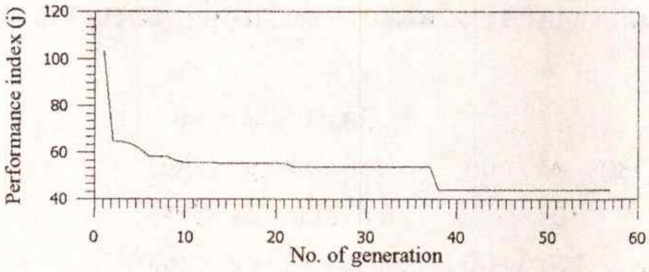

Fig. 3a Convergence of performance index

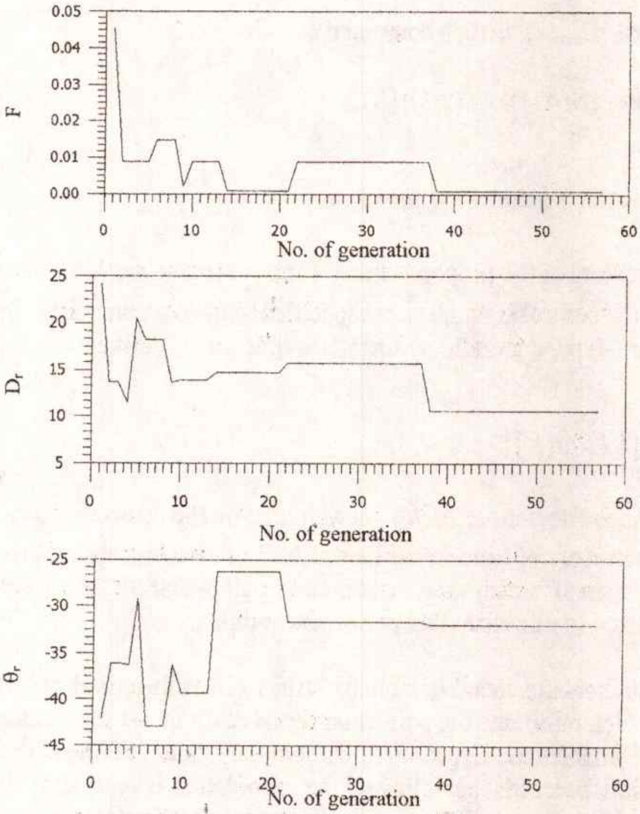

Fig. 3b Convergence of controller parameters

The performance of the IM with proposed controller following a step change in the reference speed at no-load is shown in Fig. 4, which shows the response to a step up in the reference speed from 100 rad/s to 150 rad/s at time 0.5 second and then a step down to 100 rad/s at time 1.0 second.

The second disturbance considered in the simulation study is a step change in the motor load. The motor response at reference speed of 150 rad/s for a step change in the load from 2 N.m to 5 N.m and vice versa is shown in Fig. 5. It is seen that the current increases to satisfy the load conditions and the speed follows the reference speed whatever the load disturbance is.

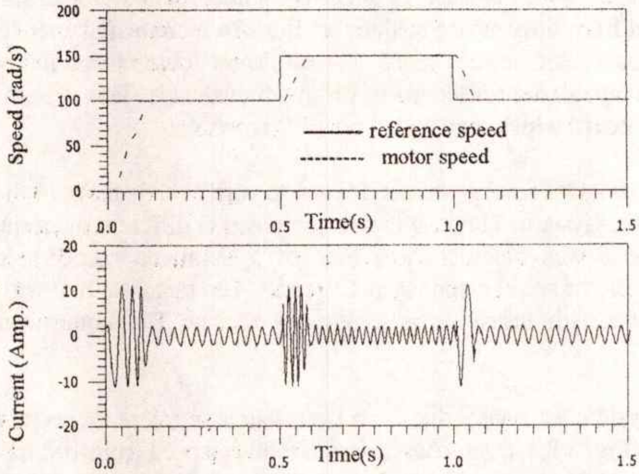

Fig. 4 Drive response for step change in reference speed

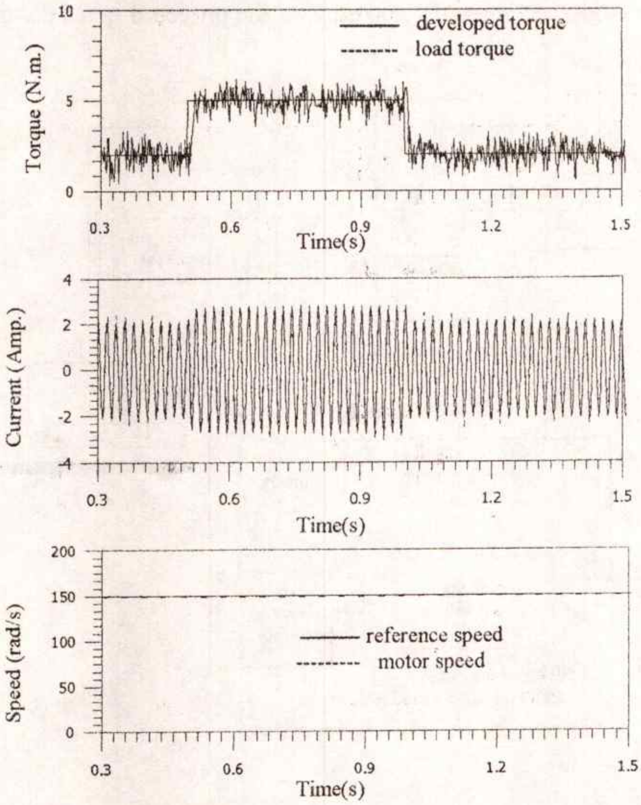

Fig. 5 Drive response for step change in load torque

It is noticed that the proposed fuzzy logic-based controller requires a lower computation burden and even makes use of lower control rules compared with the traditional fuzzy logic controller which utilizes the processes of fuzzification, inference, and defuzzification along with the knowledge base.

7. Experimental Results

Several dynamic tests were performed to investigate the validity of the proposed control method. The experimental set-up used for the practical investigation is shown in Fig. 6. The induction motor under test is coupled to a self- exited DC generator. The motor is energized from an inverter bridge, which consists of six IGBT's in conjunction with snubber circuits. The DC-link is provided from three-phase bridge rectifier. An incremental encoder is coupled to the motor shaft to measure the motor speed. Actual stator currents are measured using current sensors. The stator voltages are sensed using voltage transducers. This system is fully controlled by a DSP controller board which is installed on a PC computer.

A series of experimental results was carried out to verify the validity of the proposed control scheme for the drive system. The results were obtained at different operating points. First, the drive system response was obtained at a load of 5 N.m and a speed below the base speed. Figure 7 shows the motor speed response at 120 rad/s. The motor started with no overshoot and follows its command with nearly zero steady state error. The motor phase currents are also shown in Fig. 7.

Secondly, the system response due to a step change in reference speed was studied and the results are shown in Fig. 8 for a step change in a reference speed from 100 rad/s to 150 rad/s. It is shown that the rotor is accelerated smoothly to follow its reference value with nearly zero steady state error. Figure 8 shows the motor phase currents waveforms. It is noticed that the currents increased during step change of speed. Figure 9 shows the response of the control system for step down in reference speed from 150 rad/s to 100 rad/s. It is clear that the motor speed followed its reference. All these responses show the goodness of the proposed speed control technique.

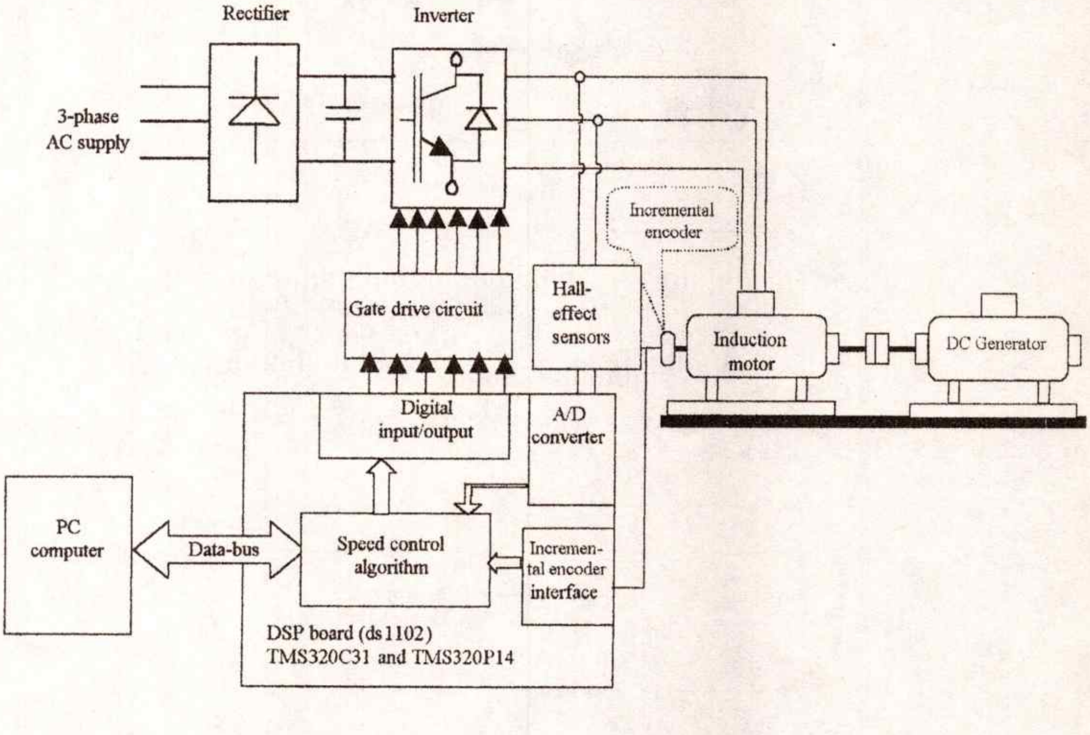

Fig. 6 Experimental set-up for DSP-based control of IM drive

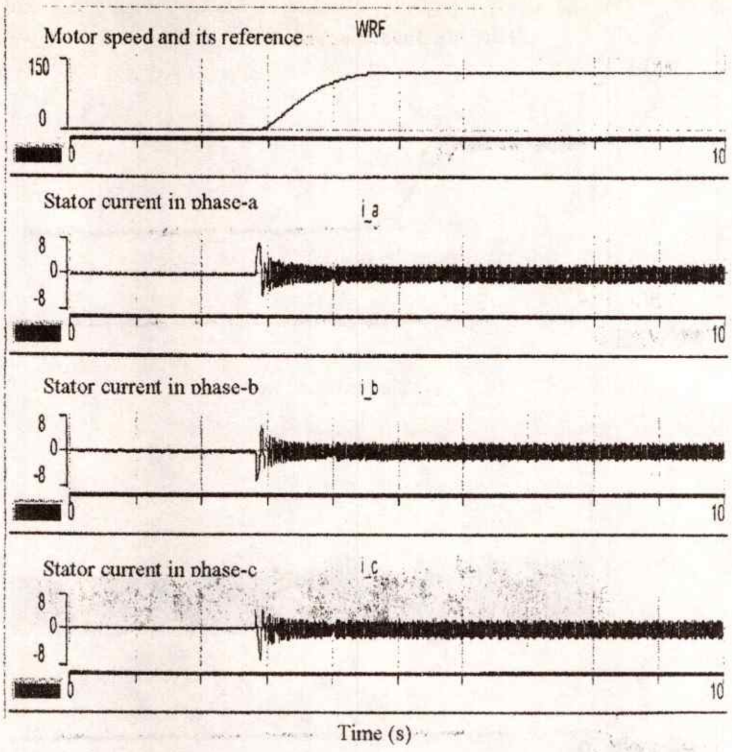

Fig. 7 Drive response at reference speed of 120 rad/s

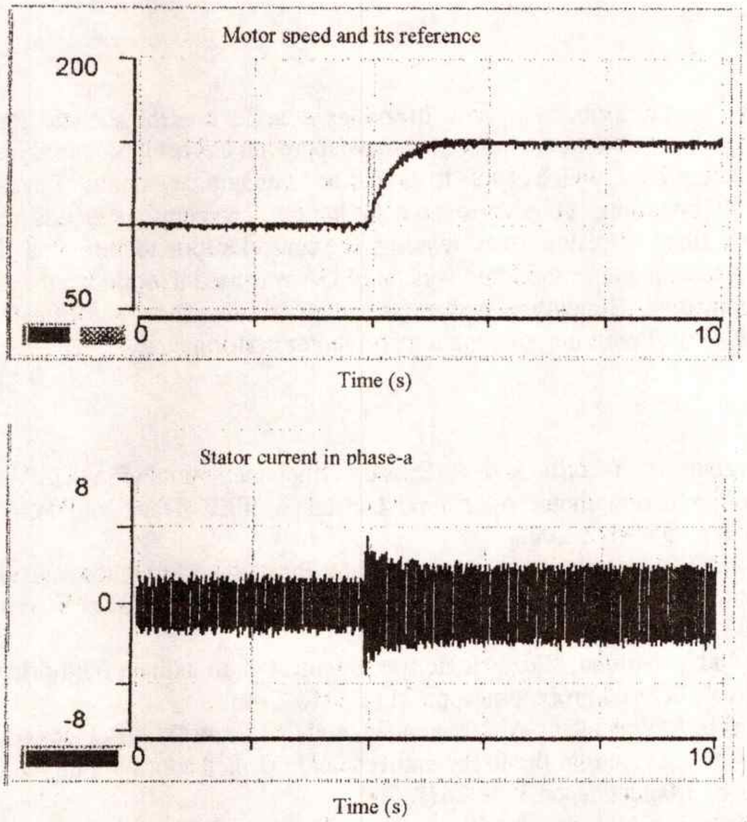

Fig. 8 Drive response for step-up change in reference speed

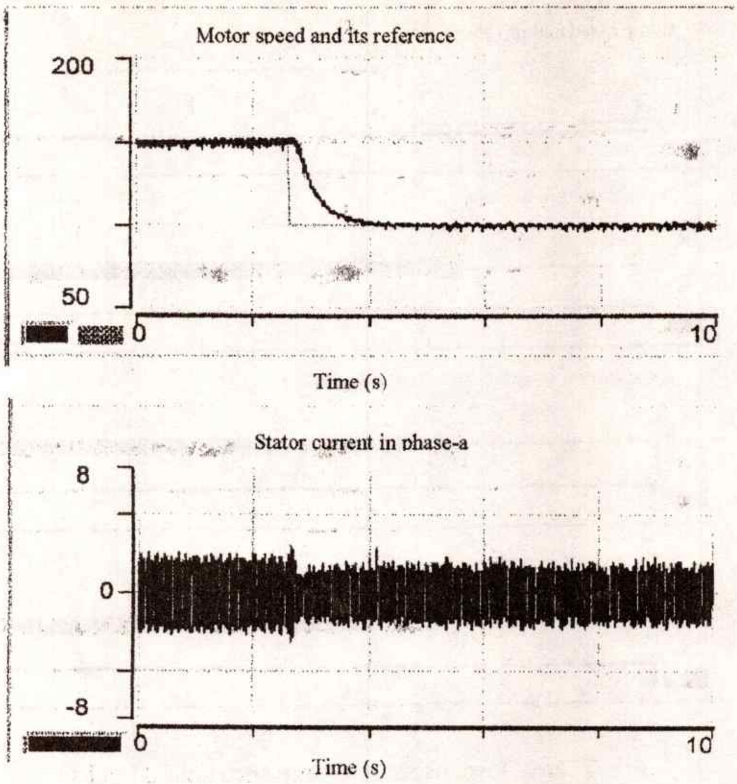

Fig. 9 Drive response for step-down change in reference speed

8. Conclusion

This study has described a new fuzzy logic-based control scheme for performance improvement of induction motor drives. A new approach has been proposed for the design of the fuzzy speed controller, which is able to yield a good dynamic response of the system studied over a range of operating conditions and disturbances. The control signal is generated on the basis of simple fuzzy decision rules relating the control efforts to the status of the induction motor in the phase plane. A modified version of GA was used to optimize the set of unknown controller parameters. Simulation and experimental results show the effectiveness of the proposed speed controller in improving induction motor performance.

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10. Appendix

The induction motor used in the study here is a three-phase squirrel cage and has the following data:

Rated power : 1.1 kW
Rated line voltage : 380 V
No. of pole pairs : 2
Stator resistance : 7.4826 ohm
Rotor resistance : 3.684 ohm
Mutual inductance : 0.4114 henry
Stator leakage inductance : 0.0221 henry
Rotor leakage inductance : 0.0221 henry
Supply frequency : 50 Hz
Motor speed : 1400 rpm
Rated load torque : 7.5 N.m

حاكم سرعة جديد للمحركات الحثية مؤسس على خوارزم جينى

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ملخص البحث:

يقدم هذا البحث طريقة جديدة لتصميم حاكم سرعة باستخدام خوارزم جينى وذلك لتحسين الأداء الديناميكى للمحركات الحثية. فى هذه الطريقة يتم تحديد إشارة التحكم المناسبة بمعلومية كل من الانحراف فى السرعة اللحظية و التسارع فى سرعة المحرك ، وكذلك بناء على مجموعة قليلة من قواعد التحكم اللامنهجى البسيطة. و قد اقترح أسلوب جديد لإيجاد هذه القواعد ، و بالتالى زيادة فعالية حاكم السرعة. كما تم استخدام خوارزم جينى لتحديد أفضل القيم لثوابت هذا الحاكم.

تم اختبار كفاءة الحاكم المقترح نظريا و معمليا على محرك حثي قدرت ١,٥ حصان و مغذى بواسطة عاكس ذو نبضات متغيرة الاتساع و يتم التحكم فيه باستخدام معالج نبضات رقمى. أكدت نتائج الدراسات النظرية و المعملية فعالية حاكم السرعة المقترح فى تحسين أداء المحرك الحثي على مدى من ظروف التشغيل المختلفة.