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Induction Drive Speed Control Using a Neuro Fuzzy Controller

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Abstract: — Induction motors have been mostly used in all industrial applications over the last years. Since its design and construction is simple and due to its low cost. However control of induction motor is complex due to its nonlinear characteristics and its parameters always changes with its operating conditions. Speed control of induction motor drive with neuro fuzzy controller is presented in this paper. Speed control of induction motor with fuzzy controller uses asymmetric membership functions requires manual adjusting to get its optimized performance based on trial and error. Also this conventional fuzzy controller requires large number of membership functions, weights and rules particularly on self tuning. This leads to increase the computational burden to avoid the drawback in fuzzy controller; the proposed NFC uses unsupervised self tuning method to adjust membership functions and weights. The proposed NFC uses only speed error as its input to reduce the computational burden so that performance of drive is similar to the conventional fuzzy controllers the performance of induction motor drive with NFC is in simulation conditions.

Keywords—Back Propagation (BP), Digital Signal Processor (DSP), Indirect Field-Oriented Control (FOC), Induction Motor(IM), Neuro–Fuzzy Control, Real-Time Implementation, Self-Tuning.

INTRODUCTION

The Induction Motors (IMs) have been mostly used as workhorse in the industry from many years due to its low cost, and simple and vigorous construction. Though, the IM control is compound owing to its nature of nonlinear, and the parameters that alter with conditions of operating. Traditionally, the conventional fixed-gain proportional–integral (PI) and PI–derivative (PID) controllers and their adaptive versions have been widely used for motor drives. More than the most recent two decades, investigators have been functioning to apply intellectual algorithms for drives of motor due to a few of their advantages as elevated with the conservative PID, PI controllers and their adaptive descriptions. In this paper, a neuro–fuzzy controller (NFC) is considered since the limitations of both fuzzy logic control (FLC) and artificial neural network (ANN) controllers. A fuzzy controller used for speed control of motor drive has asymmetric membership functions that require much more physical adjusting by the trial and error if optimized performance is wanted. Similarly, which is also particularly strong to make a sequential of training data for ANN that can hold all the operating modes? The NFCs, which overcome the disadvantages of FLC and ANN controllers, have been utilized by authors and other researchers for applications of motor drives. Even though many benefits of intellectual controllers, the industry has still hesitant to apply these controllers for drives that are commercial due to high calculation burden forced by large number of functions of membership, rules, and weights, particularly on self-tuning condition.

High calculation burden guides to low sampling frequency, which is not adequate for concurrent execution. In [13], only weights were tuned online, but the membership functions were fixed to keep the computational burden at reasonable level. The membership functions were adjusted in simulation by trial-and-error procedure. Moreover, a high-torque ripple was observed due to the low sample rate for the conventional two-input NFC. A fast processor may be used to implement such high computational intelligent algorithms, but the high cost of the fast processor is another concern for the industry. Conventional NFCs usually utilize two inputs $\Delta\omega$ and $\dot{\omega}$ (speed error and acceleration, respectively), which lead to a large number of membership functions and rules. The adoption of $\dot{\omega}$ can improve the controller's robustness. However, the difficulty of measuring fast and precise acceleration, deteriorates this ability and even makes utilization of acceleration useless. Therefore, in order to reduce the computational burden, a simplified NFC with one input, three membership functions, and a four-layer structure is proposed in this paper. A controlled self-tuning scheme is developed based on the information on back-propagation (BP) algorithms and requirements of vector control. The major task of the regulation method is to regulate the membership functions parameters and weights so as to diminish the square of the speed error between actual and reference values. The performance of the proposed simplified NFC-based IM drive is tested in both experiment and simulation. It is found that the projected NFC does not reduce the performance of the system as compared to the conservative NFC. Besides, the proposed NFC is found superior to the conventional PI controller.

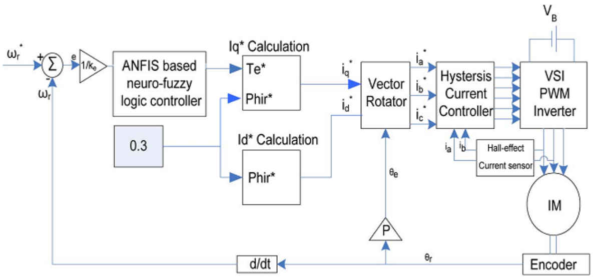

Fig.1. Block diagram of the proposed simplified NFC-based IM drive.

1. MOTOR DYNAMICS AND CONTROL STRUCTURE

A. IM Dynamics

The mathematical model of a 3-phase Y-connected squirrel-cage IM in a de−qe synchronously rotating reference frame is described in (1)–(4), shown at the bottom of the page, where v^eds and v^eqs are the d, q-axis stator voltages, i^eds and i^eqs are the d, q-axis stator currents, I^edr and I^eqr are the d, q-axis rotor currents, Rs and Rr are the stator and rotor resistances per phase, and Ls and Lr are the self-inductances of the stator and rotor respectively; Lm is the mutual or magnetizing inductance; ω_e is the speed of the rotating magnetic field; ω_r is the rotor speed; P is the number of poles; p is the differential operator (d/dt); Te is the developed electromagnetic torque; T_L is the load torque; J_m is the rotor inertia; B_m is the rotor damping coefficient; and θr is the rotor position. The motor parameters are given in the Appendix.

$$\begin{bmatrix} V^e qs \\ V^e ds \\ 0 \\ 0 \end{bmatrix} = \begin{bmatrix} Rs + PLs & \omega eLs & PLm & \omega eLm \\ -\omega eLs & Rs + PLs & -\omega eLm & PLm \\ PLm & (\omega e - \omega r)Lm & Rr + PLr & (\omega e - \omega r)Lr \\ -(\omega e - \omega r)Lm & PLm & (\omega e - \omega r)Lr & Rr + PLr \end{bmatrix} \begin{bmatrix} i^e qs \\ i^e ds \\ i^e qr \\ i^e dr \end{bmatrix} \quad (1)$$

$$T_e = J_m \frac{d\omega r}{dt} + Bm\omega r + T_L \qquad (2) \qquad (2)$$

$$T_e = \frac{3}{2}\frac{P}{2} Lm(i^e qsi^e dr - i^e dsi^e qr) \qquad (3)$$

$$\frac{d\theta_r}{dt} = \omega r \qquad (4)$$

B. Control Structure

The main feature of the field-oriented control (FOC) is to maintain the magnetizing current at a constant rated value by setting $I^eqr = 0$. Thus, the torque-producing current component I^eqs can be adjusted according to the torque demand. With this assumption, the mathematical formulations can be rewritten as:

$$\omega sl = \frac{Rr}{Lr}\frac{i^e qs}{i^e ds} \tag{5}$$

$$i^e ds = \frac{\lambda^e dr}{Lr} \tag{6}$$

$$T_e = \frac{3}{2}\frac{P}{2}\frac{Lm}{Lr}\lambda^e dr i^e qs \tag{7}$$

where ωsl is the slip speed and $\lambda^e dr$ is the d-axis rotor flux linkage. Equations (1)–(7) are used to simulate the whole drive system. The schematic diagram of the proposed NFC-based indirect FOC of IM is shown in Fig. 1. The basic configuration of the drive system consists of an IM fed by a current-controlled voltage source inverter (VSI). The normalized speed error Δω% is processed by the NFC to generate the reference torque T^*e (n). The command current I^*q (n) is calculated from equation(7) as follows:

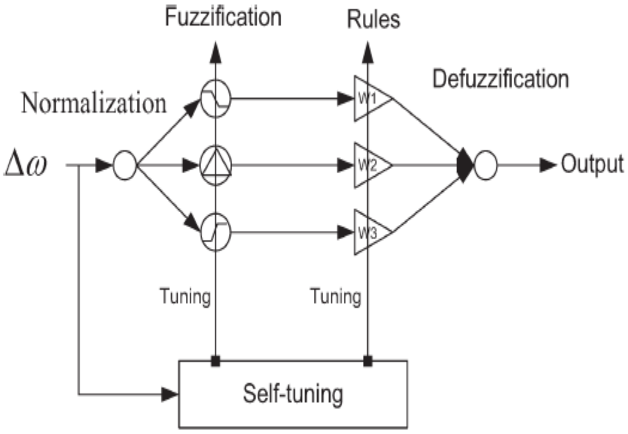

Fig. 2. Structure of the proposed NFC.

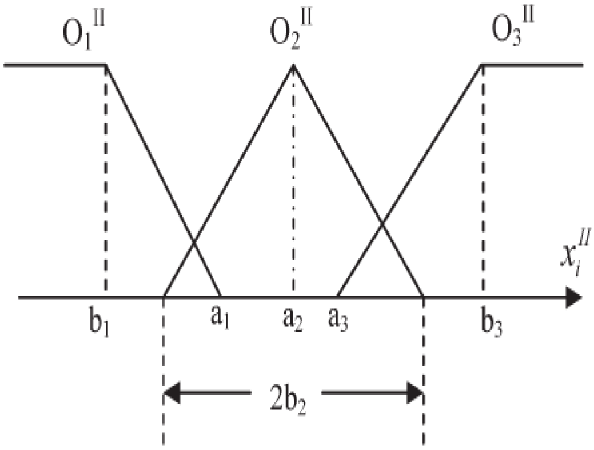

Fig. 3. Membership functions for input.

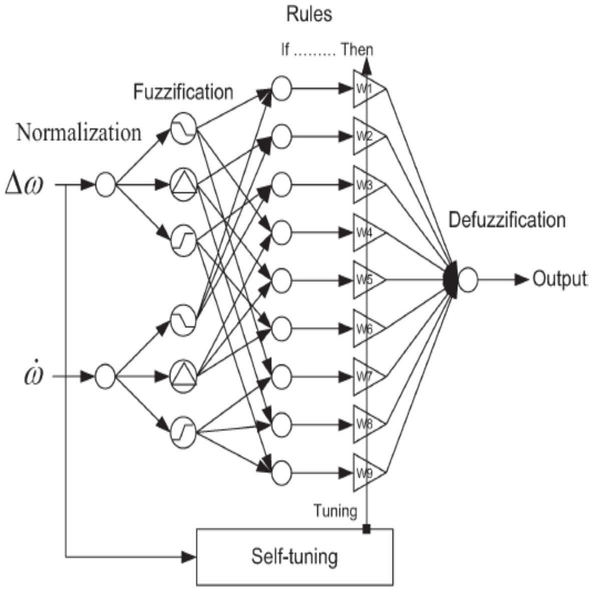

Fig. 4. Structure of a conventional NFC.

Currents I^*q and I^*d are transformed into i^*a, i^*b and i^*c by inverse Park's transformation. The phase command currents i^*a, i^*b and i^*c are then compared with the corresponding actual currents i_a, i_b, and i_c to generate pulse width-modulation (PWM) logic signals, which are used to trigger the power semiconductor switches of the 3-phase inverter. The inverter produces the actual voltages to run the motor.

2. DESIGN OF SPECIFIC NFCS

A. Proposed NFC

The proposed NFC incorporates fuzzy logic and a learning algorithm with a four-layer ANN structure, as depicted in Fig.2. The learning algorithm modifies the NFC to closely match the desired system performance. The detailed discussions on different layers of the NFC are given in the following.

Input Layer: The input of the proposed NFC is the normalized speed error, which is given by

$$o^I = \frac{\omega^* - \omega}{\omega^*} * 100\% \qquad (9)$$

where ω is the measured speed, ω is the command speed, and I denotes the first layer.

Fuzzification Layer: In order to get fuzzy number from input three membership functions O^{II}_1 , O^{II}_2 , and O^{II}_3 are used, which are shown in Fig. 3. The three nodes in fuzzification layer of NFC shown in Fig. 2 represent these 3 membership functions. Here, O stands for output, superscript indicates the layer number, and subscripts indicate the node numbers. The linear triangular and trapezoidal functions are chosen as the membership functions so that the computational burden is low as compared to any exponential functions

$$o_1^{II} = \begin{cases} 1 & x^{II}{}_1 \le b_1 \\ \dfrac{x_i^{II} - a_i}{b_1 - a_1} & b_1 < x^{II}{}_i < a_1 \\ 0 & x_i^{II} \ge a_i \end{cases} \qquad \textbf{(10)}$$

$$O_2^{II} = \begin{cases} 0 & \left|x_i^{II}\right| \ge b_2 \\ 1 - \dfrac{x_i^{II} - a_2}{b_2} & \left|x_i^{II}\right| < b_2 \end{cases} \qquad \textbf{(11)}$$

$$O^{III}{}_3 = \begin{cases} 0 & x_i^{II} \le a_3 \\ \dfrac{xi^{II} - a_2}{b_3 - a_3} & a_3 < x_i^{II} < b_3 \\ 1 & x_i^{II} \ge b_3 \end{cases} \qquad \textbf{(12)}$$

where x^{II} is the input of the second layer, which is the output of the first layer. It is considered that $a_2 = 0$ so that the membership functions become symmetrical and it also further reduces the computational burden. Thus, the membership functions O^{II}_1, O^{II}_2, and O^{II}_3 represent negative, zero, and positive speed errors, respectively.

Rule Layer: No "AND" logic is needed in the rule layer since there is only one input in the input layer. The node equations in the rule layer are specified as

$$O_i^{III} = x_i^{III}\omega_j = O_i^{III}\omega_j \qquad (13)$$

where equation(13) is the input of the third layer, which is the same as the output of the second layer.

Defuzzification Layer: The center-of-gravity method is used to determine the output of NFC. The node equation is specified as:

$$Y_u = O_i^{VI} = \frac{\sum x_i^{VI}}{\sum O_j^{II}} = \frac{\sum O_i^{III}}{\sum O_j^{II}} \qquad (14)$$

Where $x^{III}{}_i$ is the input of the third layer, which is same as the output of the second layer.

B. Conventional NFC

In order to compare the performance of the proposed simplified NFC, a conventional two-input NFC is also designed, as shown in Fig. 4. The normalized speed error and its derivative are the two inputs to the conventional NFC. In order to make a fair comparison, the membership functions of conventional NFC are considered the same as those of the proposed NFC but with fixed parameters. Similar self-tuning methods are also used for both NFCs.

3. ONLINE SELF-TUNING ALGORITHM

Since it is impossible to determine or calculate the desired NFC output $I^e qs$ and find training data offline covering all operating conditions, a kind of unsupervised online self-tuning method is developed based on BP algorithm. The objective function to be minimized and is defined by instead of using the desired controller output $I^e qs$ as target, a reinforcement signal (r), which assesses the performance of the controller and evaluates the current state of the system, is employed to guide our control action into changing in the right direction as well as produce the desired response. The task of NFC is to modify its parameters so that the objective function of the reinforcement signal is decreased. The objective function to be minimized is defined by

$$E = \frac{1}{2}r^2 = \frac{1}{2}(\omega^2 - \omega)^2 \qquad (15)$$

Hence, the learning rules can be derived as follows:

$$a_i(n+1) = a_i(n) - \eta_{ai}\frac{\partial E}{\partial a_i} \qquad (16)$$

$$b_i(n+1) = b_i(n) - \eta_{bi}\frac{\partial E}{\partial bi} \qquad (17)$$

$$\omega_i(n+1) = \omega_i(n) - \eta_{\omega j}\frac{\partial E}{\partial \omega j} \qquad (18)$$

where η_{ai}, η_{bi}, and η_{wj} are the learning rates of the corresponding parameters. The derivatives can be found by chain rule as

$$\frac{\partial E}{\partial a_i} = \frac{\partial E}{\partial r}\frac{\partial r}{\partial \omega}\frac{\partial \omega}{\partial Y_U}\frac{\partial Y_U}{\partial O_i^{II}}\frac{\partial O_i^{II}}{\partial a_i} \qquad (19)$$

$$\frac{\partial E}{\partial b_i} = \frac{\partial E}{\partial r}\frac{\partial r}{\partial \omega}\frac{\partial \omega}{\partial Y_U}\frac{\partial Y_U}{\partial O_i^{II}}\frac{\partial O_i^{II}}{\partial b_i} \qquad (20)$$

$$\frac{\partial E}{\partial \omega_j} = \frac{\partial E}{\partial r}\frac{\partial r}{\partial \omega}\frac{\partial \omega}{\partial Y_U}\frac{\partial Y_U}{\partial \omega_j} \qquad (21)$$

Where the common parts of equations(19)–(21) are

$$\frac{\partial E}{\partial r} = r = \omega^* - \qquad (22)$$

$$\frac{\partial r}{\partial \omega} = -1 \qquad (23)$$

$$\frac{\partial \omega}{\partial Y_U} = J(t) \qquad (24)$$

In equation (24), the Jacobean matrix J(t) cannot be found easily. In FOC, the IM system can be viewed as a single-input single output system; then, the J(t) can be estimated as a constant value KJ > 0. From equations (10)–(24), the update rules can be determined as follows:

$$a_1(n+1) = a_1(n) - \eta_{ai} k_j r(n) \frac{\omega_1(n).1 - O_1^{II}(n)}{\sum O_j^{II} b_1(n) - a_1(n)} \qquad (25)$$

$$b_1(n+1) = b_1(n) - \eta_{bi} k_j r(n) \frac{\omega_1(n).O_1^{II}(n)}{\sum O_j^{II} b_1(n) - a_1(n)} \qquad (26)$$

$$b_2(n+1) = b_2(n) + \eta_{b2} k_j r(n) \frac{\omega_2.1 - O_2^{II}(n)}{\sum O_j^{II} b_2(n)} \qquad (27)$$

$$a_3(n+1) = a_3(n) - \eta_{a3} k_j r(n) \frac{\omega_3(n).1 - O_3^{II}(n)}{\sum O_3^{II} b_3(n) - a_3(n)} \qquad (28)$$

$$b_3(n+1) = b_3(n) - \eta_{b3} k_j r(n) \frac{\omega_3(n) - O_3^{II}(n)}{\sum O_3^{II} b_3(n) - a_3(n)} \qquad (29)$$

$$\omega_j(n+1) = \omega_j(n) + k_\omega k_j r(n) \left(\frac{O_i^{II}(n)}{\sum O_i^{II}} \right) \qquad (30)$$

Based on the aforementioned update rules, the following steps are employed for tuning the parameters of a_1, a_3, b_1, b_2, b_3, and w_j .

Step 1: First, an initial set of fuzzy logic rules and initial values of a_1, a_3, b_1, b_2, b_3, and w_j are selected.

Step 2: The normalized speed error is calculated, which is input to the NFC.

Step 3: Fuzzy reasoning is performed for the input data. The membership values O^{II}_i are then calculated by using equations(10) – (12).

Step 4: Tuning of the weights wj of the consequent part is performed by using (25).

Step 5: Tuning of a_1, a_3, b_1, b_2, b_3, is done by substituting the tuned real number wj obtained in step(4),the measured reinforcement signal r, and the membership value OII i into (27)–(30).

Step 6: Repeat from step(3).

The tuning rate for weights is chosen to be $\eta_{wj} = 0.1$, and the tuning rate for the membership functions is chosen to be $\eta_{ai} = \eta_{bi} = 0.008$. The small values of tuning rates are chosen so that there will be a smooth transition from one state to another overshoot, and undershoot can be comparable to those of the NFCs. If the PI controller is made critically damped, it became too sluggish, and the response time is not even comparable to that of the NFCs.

4. RESULTS AND DISCUSSION

A. Simulation Results:

The performance of the proposed simplified NFC-based IM drive is investigated in simulation using Matlab/Simulink at different operating conditions. Fig. (5) to fig.(7) shows the simulated starting performances of the drive at full load with the, conventional two-input NFC, proposed NFC and PI controllers, respectively. It is clearly seen from these figures that the performance of the proposed simplified low computational NFC is similar to that of the conventional NFC and, at the same time, it is superior to that of the conventional PI controller in terms of peak over shoot and settling time. Fig.(7) shows the zoom-in view of the speed responses of the drive system with a step increase in the load from zero to rated level for the three controllers.

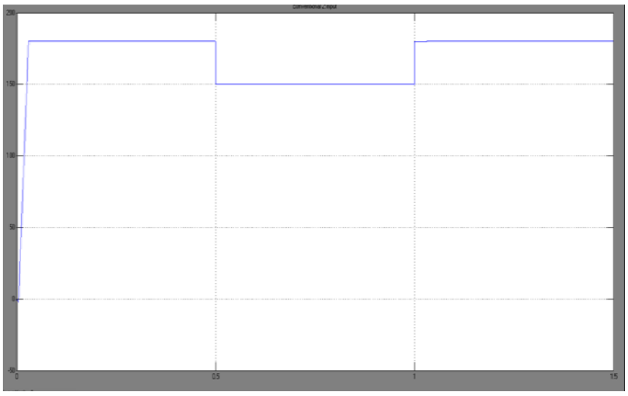

Fig.5 conventional NFC.

It is found that the proposed simplified NFC can handle the load disturbance with lesser dip in speed as compared to both conventional NFC and PI controller. The variation of rotor resistance is a crucial issue for IM drive performance. So, in order to test the performance of the drive with parameter variations, the performance of the drive is tested for all three controllers with doubled rotor resistance, and the corresponding speed responses are shown in Fig.(7). shows the speed responses of the drive system first with a step decrease in command speed from 180 to 150 rad/s, and then, a step increase in command speed from 150 to 180 rad/s using the proposed NFC, conventional NFC, and PI controller, respectively. In this, the proposed NFC exhibits a little larger undershoot than the PI controller but no overshoot and less settling time. It is found that the performance of the proposed simplified NFC is almost similar to that of the conventional NFC and, at the same time, it is superior to that of the conventional PI controller as the PI controller takes longer time to reach the steady state. Based upon tests, it is evident that the proposed NFC does not decrease system performance significantly as compared to the conventional two-input NFC. In addition, the simplified NFC provides superior performance as compared to the conventional PI controller.

Fig.6.Proposed NFC.

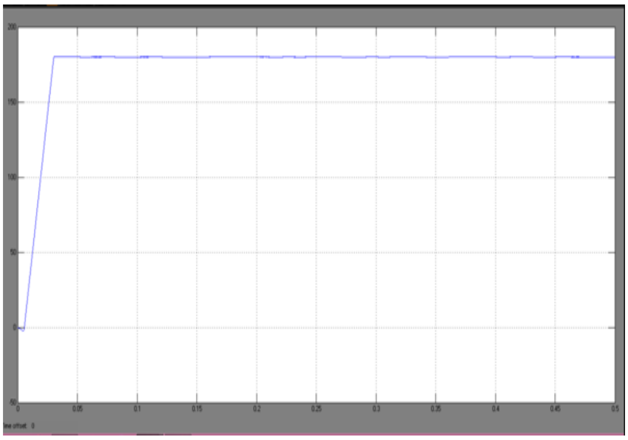

Fig .7.speed responses of the IM drive with double rotor resistance.

5. CONCLUSION

In this paper, speed control of induction motor drive based on neuro fuzzy controller has been developed. In the proposed NFC, both weights and membership functions are tuned online based on operating conditions. The proposed NFC uses only one input and the performance of proposed NFC is similar to the conventional two input NFC, at the same time it is superior to that of the conventional PI controller in terms of peak overshoot and settling time. The zoom in view of the speed responses of the drive system with a step increase in the load from zero to rated level for the three controllers. Compare to the proposed NFC, and conventional two in NFC .the proposed NFC can handle the load disturbance with lesser dip in speed as compare to both conventional and PI controller.

6. APPENDIX

Induction Motor Parameters(Referred To Stator Side): Power 250 W;
Stator resistance 6.5 Ω;
Rotor resistance 3.4 Ω;
Number of pole pairs 2;
Stator inductance 0.0103 H;
Rotor inductance 0.0154 H;
Mutual inductance 0.2655 H;
Inertia 0.0012 kg · m_2;
Rated speed 1725 r/min.

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