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Performance & Analysis of Fuzzy Logic Controller Based Induction Motor Drive System Using Simulink

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Abstract - Variable speed drives are growing and varying. Drives expanse depend on progress in different part of science like power system, microelectronic, control methods and so on. In this paper, the motor drive system comprises a voltage source inverter-fed induction motor (VSIM): namely a three-phase voltage source inverter and the induction motor. The squirrel-cage induction motor voltage equations are based on an orthogonal d-q reference-rotating frame where the co-ordinates rotate with the controlled source frequency. The paper presents a novel fuzzy logic controller for high performance induction motor drive system. The inputs to the fuzzy logic controller are the linguistic variables of speed error and change of speed error, while the output is change in switching control frequency of the voltage source inverter. In this paper a comparison between fuzzy logic controller and traditional PI controllers are presented. The results validate the robustness and effectiveness of the proposed fuzzy logic controller for high performance of induction motor drive. Simulink software that comes along with MATLAB was used to simulate the proposed model.

Keywords - Induction motor, Simulink software, Fuzzy logic controller.

I. INTRODUCTION

Simulink induction machine models are available in the literature [1-2], but they appear to be black boxes with no internal details. Some of them in [1-2] recommend using S- functions, which are software source codes for Simulink blocks. This technique does not fully utilize the power and ease of Simulink because S-function programming knowledge is required to access the model variables. Another approach is using the Simulink Power System Block set [3] that can be purchased with Simulink. This block set also makes use of S-functions and is not as easy to work with as rest of the Simulink blocks. Reference [4] refers to an implementation approach similar to the one in this paper but fails to give any details. In this paper, a modular, easy to understand Simulink induction motor model is described. With the modular system, each block solves one of the model equations. Though induction motors have few advantageous characteristics, they also possess nonlinear and time-varying dynamic interactions [5], using conventional PI controller, it is very difficult and complex to design a high performance induction motor drive system. The fuzzy logic control (FLC) is attractive approach, which can accommodate motor parametric

variations and difficulty in obtaining an accurate mathematical model of induction motor due to rotor parametric and load time constant variations.

The FLC is a knowledge-based control that uses fuzzy set theory and fuzzy logic for knowledge representation. This paper presents a novel fuzzy logic controller suitable for speed control of induction motor drives.

II. SIMULINK IMPLEMENTATION

One of the most popular induction motor models derived from this equivalent circuit is Krause's model. An induction machine model can be represented with five differential equations. To solve these equations, they have to be rearranged in the state-space form: $\dot{X} = Ax + b$ where $X = [F_{qs} \ F_{ds} \ F_{dr} \ F_{qr} \ \omega_r]^T$ is the state vector. The inputs of a squirrel cage induction machine are the three-phase voltages, their fundamental frequency and the load torque. The outputs, on the other hand, are the three phase currents, the electrical torque and the rotor speed. The d-q model requires that all the three-phase variables have to be transformed to the two-phase synchronously rotating frame. Consequently, the induction machine model will have blocks transforming

the three-phase voltages to the d-q frame and the d-q currents back to three-phase. The induction machine model implemented in this paper is shown in Fig. 1. It consists of five major blocks: the o-n conversion, abc-syn conversion, syn-abc conversion, unit vector calculation and the induction machine d-q model blocks. The following subsections will explain each block.

A. O-N Conversion Block

This block is required for an isolated neutral system, otherwise it can be bypassed. The transformation done by this block can be represented as follows:

$$\begin{bmatrix} v_{an} \\ v_{bn} \\ v_{cn} \end{bmatrix} = \begin{bmatrix} +\frac{2}{3} & -\frac{1}{3} & -\frac{1}{3} \\ -\frac{1}{3} & +\frac{2}{3} & -\frac{1}{3} \\ \frac{1}{3} & \frac{1}{3} & +\frac{2}{3} \end{bmatrix} \begin{bmatrix} v_{as} \\ v_{bs} \\ v_{cs} \end{bmatrix} \quad (1)$$

Fig. 1 O-N Conversion Block

B. Unit Vector Block Calculation

Unit vectors $\cos \theta_e$ and $\sin \theta_e$ are used in vector rotation blocks, "abc-syn conversion block" and "syn-abc conversion block". The angle θ_e is calculated directly by integrating the frequency of the input three-phase voltages, ω_e .

$$\theta_e = \int \omega_e dt. \quad (2)$$

The unit vectors are obtained simply by taking the sine and cosine of θ_e . This block is also where the initial rotor position can be inserted, if needed, by adding an initial condition to the Simulink "Integrator" block. Note that the result of the integration in (2) is reset to zero each time it reaches $2n$ radians so that the angle always varies between 0 and $2n$.

C. abc-syn conversion block

To convert three-phase voltages to voltages in the two phase synchronously rotating frame, they are first converted to two-phase stationary frame using (3) and then from the stationary frame to the synchronously rotating frame using (4) where the superscript "s" refers to stationary frame.

D. syn-abc conversion block

This block does the opposite of the abc-syn conversion block for the current variables.

E. Induction machine d-q model block

The resulting model shown in Fig. 2 is modular and easy to follow. Any variable can be easily traced using the Simulink 'Scope' blocks. The blocks in the first two columns calculate the flux linkages, which can be used in vector control systems in a flux loop.

The blocks in Column 3 calculate all the current variables, which can be used in the current loops of any current control system and to calculate the three-phase currents. The two

$$\begin{bmatrix} v_{qs}^s \\ v_{ds}^s \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & -\frac{1}{\sqrt{3}} & \frac{1}{\sqrt{3}} \end{bmatrix} \begin{bmatrix} v_{as} \\ v_{bs} \\ v_{cs} \end{bmatrix} \quad (3)$$

$$\begin{cases} v_{qs} = v_{qs}^s \cos \theta_e - v_{ds}^s \sin \theta_e \\ v_{ds} = v_{qs}^s \sin \theta_e + v_{ds}^s \cos \theta_e \end{cases} \quad (4)$$

blocks of Column 4, on the other hand, calculate the torque and the speed of the induction machine, which again can be used in torque control or speed control loops. These two variables can also be used to calculate the output power of the machine.

Fig. 2 : d-q Model of Induction Machine

III. OPEN LOOP CONSTANT V/Hz OPERATION

Fig. 2 shows the implementation of open-loop constant V/Hz control of an induction machine. This figure has two new blocks: command voltage generator and 3-phase PWM inverter blocks. The first one generates the three-phase voltage commands and it is nothing more than a "syn-abc" block explained earlier. The latter first compares the reference voltage, V_{ref} to the command voltages to generate PWM signals for each phase, then uses these signals to drive three Simulink "Switch" blocks switching between $+V_{d/2}$ and $-V_{d/2}$ (V_d : dc link voltage). The open-loop constant V/Hz operation is simulated for 1.2s ramping up and down the speed command and applying step load torques. The results are plotted in Fig. 3 where the response of the drive to changes in the speed command and load disturbance scan be observed.

IV. FUZZY LOGIC CONTROL ALGORITHM

A fuzzy algorithm consists of situation and action pairs. Conditional rules expressed in IF and THEN statements are generally used as shown in fig. 4. For example, the control rule might be: if the output is lower than the requirement and the output is dropping moderately then the input to the system shall be increased greatly. Such a rule has to be converted into a more generally statement for application to fuzzy algorithms. To achieve this the following terms are defined: error equals the set point minus the process output, error change equals the error from the process output minus the error from last output and control input applied to the process. In addition, it is necessary to quantize the qualitative statements and the following linguistic sets are assigned: 1. Large Positive (LP) 2. Medium Positive (MP) 3. Small Positive (SP) 4. Zero (ZZ) 5. Small Negative (SN) 6. Medium Negative (MN) 7. Large Negative (LN).

Fig. 3 Open Loop Constant V/Hz Response

Thus the statement of the example control will be: if the error is large positive and the error change is small positive then the input to the system is large positive.

Fig. 4 : Block Diagram of Fuzzy Logic Control Algorithm

V. FUZZY CONTROL ACTION

1. Specify and store the minimum and the maximum ranges of the error signal $E = e_r(k)$, the error change $dE = d(e_r(k))$ and the control input change dF .
2. If the minimum and maximum ranges of step one are different, then quantize into a common universe of discourse using scaling factors such that the maximum and minimum of the quantized error signal E , the quantized error change dE and the quantized control input changed f are all the same.
 - i) Define the symmetrical linguistic fuzzy subsets of E , dE and dF .
 - ii) Calculate the error e_r and the error change d_e for the current sampling period and find their quantized values E and dE respectively in the common universe of discourse.
 - iii) From the E and dE , the contribution of each rule given in table 1 in the fuzzy subsets of control input dF and scaling of its membership grades using the rule can be found.
 - iv) The result of application of all rules is membership function grades of control input dF through the universe of its discourse. To calculate the crisp or numerical value of dF , the COA Criteria is used as follows:

$$dF(k) = \frac{\sum_{j=1}^n \mu_{Gr}(df_j) * df_j}{\sum_{j=1}^n \mu_{Gr}(df_j)} \quad (5)$$

Where n is the number of quantization levels of the output.

- v) Add the control input change $dF(k)$ to the previous value $F(k-1)$ to calculate the new control action to be taken for the k_{th} sample: $F(k)=F(k-1)+dF(k)$.

Table. 1. Fuzzy Control Rule Decision Table

$\dot{e} \backslash e_r$	NL	NM	NS	ZZ	PS	PM	PL
NL	NL	NL	NL	NM	NM	NS	ZZ
NM	NL	NM	NM	NS	NS	ZZ	PS
NS	NM	NM	NS	NS	ZZ	PS	PS
ZZ	NM	NS	NS	ZZ	PS	PS	PM
PS	NS	NS	ZZ	PS	PS	PM	PM
PM	NS	ZZ	PS	PS	PM	PM	PL
PL	ZZ	PS	PM	PM	PL	PL	PL

VI. CLOSED LOOP CONSTANT V/Hz OPERATION

The closed loop circuit has the fuzzy logic controller as the new component as shown in fig. 5. The inputs to the fuzzy logic controller are the speed error and rate of change of speed error. The output is fed to the power converter-PWM inverter, which is used to adjust the inverter switching control frequency. The output of FLC controls the firing angle of the inverter, thereby varying the output voltages. The reference speed of the PWM inverter is modified each time when there is a different output of the fuzzy controller. These outputs are found from the truth table (rule table). The PWM inverter output is then fed to the induction machine where a constant V/Hz operation is carried out which is shown in fig. 6.

Fig. 5 : Block Diagram of Closed Loop using Fuzzy Controller

Fig. 6 : Closed Loop Constant V/ Hz with Fuzzy Controller

VII. LABORATORY PROTOTYPE IMPLEMENTATION

This paper is intentioned three phases induction motor drive based fuzzy logic controller (FLC). Constant flux technique (V/F) [6][7][8] is used for induction motor speed control. For test of proposed fuzzy logic controller performance, driver is implemented.

A. Block diagram of implemented circuit

Block diagram of implemented drive has shown in figure (1). Using fuzzy logic principles in induction motor speed control has described. Figure (7) shows block diagram of PI fuzzy logic controller [9][10]. Speed error ($\Delta\omega_1 = \omega_i - \omega_{f1}$) is calculated with comparison between reference speed command and speed signal feedback. Speed error and speed error changing are fuzzy controller inputs, so must speed error changing ($\Delta(\Delta\omega) = \Delta\omega_2 - \Delta\omega_1$) is to be calculated.

Input variables require be normalized which range of membership functions specify them, in figure (7) normalization factors have shown with K1 and K2. Suitable normalization has direct influence in algorithm optimality and faster response [9][11].

Figure (8) shows normalized membership functions for input and output variables. Fuzzy logic controller operation is based on control expression of table II.

Fig. 7 : Block Diagram of PI Fuzzy Logic Controller

Fig. 8 : Input and output Membership functions

TABLE II : FUZZY CONTROLLER OPERATION

	Δe	NS	NM	NS	ZE	PS	PM	PB
e	Output							
NB	NB	NB	NM	NM	NS	NS	ZE	
NM	NB	NM	NM	NS	NS	ZE	PS	
NS	NM	NM	NS	NS	ZE	PS	PS	
ZE	NM	NS	NS	ZE	PS	PS	PM	
PS	NS	NS	ZE	PS	PS	PM	PM	
PM	NS	ZE	PS	PS	PM	PM	PB	
PB	ZE	PS	PS	PM	PM	PB	PB	

B. Laboratory results

For evaluation of implemented drive, different responses of drive are presented. Sampling time and interrupt time are 2ms and 20us respectively. Step response of for 600 rpm reference speed with no load and full load condition has represented respectively in figure (9-a) and (9-b). Responses have drawn for 2 sec that motor speed is according to RPM. These responses is compared a driver responses with classical controller. In figures, driver responses with fuzzy controller are specified "FUZZY" and classical controller is represented "PI". In full load, driver response has almost

similar trajectory with classical and fuzzy controller. Rise time nearly is 0.1 sec also in responses has be seen no overshoot. In no load, driver with fuzzy controller has response faster than classical controller response. Driver with fuzzy controller has almost received to reference speed at 0.1 sec, as this time in classical controllers nearly 0.15 sec. driver responses have not any overshoot. Steady state error is 5% for each response. Few speed subsidence in steady state shows that motor flux has been fixed, comparison with no load condition. Because with load changing motor speed has not changed much and speed regulation is nearly suitable.

Fig. 9 : Step response

In another test, sudden changing has exerted in motor command speed. Speed command changing has been in two cases: no load and full load with increasing and decreasing speed command. Driver responses are depicted in figure (10) for no load case. Figures (10-a) and (10-b) show driver responses. In sudden increasing speed, first motor command speed is 400 rpm. Reference speed is changed to 700 rpm at $t=1$ sec but in decreasing speed, primary motor speed is 700 rpm which is decreased to 400 rpm at $t=1$ sec. rise time in each case is nearly 0.1 sec. also there are no overshoot in responses and steady state error is dispensable. In these tests, speed regulation is almost suitable. In figure (11) has depicted driver response to sudden speed changing in full load case. Driver responses have shown in figures (11-a) and (11-b) for increasing and decreasing reference speed respectively. In these tests, also, reference speed changing is exerted at $t=1$ sec. steady state error is almost 5%. In each condition, driver rise time is less than 0.1 sec. driver response has not any overshoot.

Fig. 11 : Sudden speed command Changing-full load

VII. SIMULINK RESULTS

The output of the fuzzy logic controller (FLC) is used to adjust the inverter switching control frequency and the dc voltage at the inverter using a constant (VF) ratio. The induction motor drive system using FLC is shown in Fig 5. Results were obtained using a three-phase squirrel cage induction motor with 208 volt phase to phase voltage, 60Hz rated frequency, 750 rpm rated speed and 1/4 Hp rated power. The parameters of the motor at rated conditions in per unit are given by (all per unit values are based on Base=1/4 Hp, $V_{base}=208$ volt and $I_{base}=1.2$ amp) $R_s=198$ p.u., $R_r=1353$ P.u., $X_{ls}=117$ p.u., & $X_{lr}=117$ p.u., $X_M=2.2$ p.u.

Fig. 10 : Sudden speed command changing- no load

IX. CONCLUSION

Artificial intelligent technique can be used as electrical motor controller without requiring a system mathematical model. By this way, efficiency, performance and reliability of drives increase and volume, weight and cost of them decrease. The FLC does not need exact knowledge of induction motor and tolerate range load excursions and parametric variations. The control assignment rules are obtained using heuristic trial and error and human expertise. The simulation test results validate the FLC robustness for different speed trajectories. For test of performance of an electrical motor drive, with fuzzy logic controller was

implemented. It does not require an accurate motor and drive model. Induction motor drive was implemented with suitable speed regulation. Steady state error in speed control is acceptable and there is not any overshoot. Laboratory tests of speed driver show that design and implementation are suitable.

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