High-Performance SVPWM-VCIM Drive with Adaptive Neuro-Fuzzy Speed Controller

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Abstract— This paper presents a novel space vector pulse-width modulated vector controlled induction motor drive with adaptive neuro-fuzzy based speed controller. SVPWM is superior to other PWM schemes from the view point of dc-link voltage utilization and current harmonics. The proposed neuro-fuzzy controller incorporates fuzzy logic algorithm with a five-layer artificial neural network (ANN) structure. The conventional PI controller is replaced by Adaptive Neuro-Fuzzy Inference System (ANFIS), which tunes the fuzzy inference system with hybrid learning algorithm. This makes fuzzy system to learn. The performance of the proposed neuro-fuzzy based SVPWM-VCIM drive is investigated at different operating conditions. The results of the proposed controller are also compared to those obtained by a conventional PI controller. The simulation study indicates robustness and suitability of drive for high performance drive applications.

Keywords—Adaptive Neuro-Fuzzy Inference System (ANFIS), Artificial Neural Network (ANN), Space Vector Pulse-Width Modulation (SVPWM), hybrid learning algorithm, Vector Controlled Induction Motor (VCIM).

I. INTRODUCTION

Space Vector Pulse Width Modulation (SVPWM) [1] has become one of the most popular PWM methods for three phase inverters because it is more easily realized digitally, outputs higher voltage (as modulation index $m = 2/\sqrt{3}$) than regular sinusoidal PWM under the same dc link voltage and less harmonics in the output voltage. Similarly, vector controlled induction motor (IM) drive is a very accepted method for high performance system response. This method employs the conventional Proportional – Integral (PI), Proportional – Integral – Derivative (PID) controller or their adaptive versions, for variable speed drive applications. However, the design of these controllers depends on exact mathematical model with accurate parameters. The difficulties of obtaining the exact parameters of the induction motor leads to cumbersome design approach. Also the conventional fixed gain PI and PID controllers are very sensitive to disturbances, parameter variations and system

non-linearity. On the other hands, the design of intelligent controllers based on Artificial Intelligence (AI) does not need the exact mathematical model of the system. Therefore Artificial Neural Network (ANN) and Fuzzy Logic Control (FLC) demands special attention for speed control of high performance IM drives.

Fuzzy Logic Controller yields superior and faster control [2]-[3], without the need of accurate mathematical model of the system and works well for complex, non-linear, multi-dimensional system with parameter variations or with less precise signals. The main design problem lies in the determination of consistent and complete rule set and shape of the membership functions. A lot of trial and error has to be carried out to obtain the desired response which is time consuming. On the other hand, ANN alone is insufficient if the training data are not enough to take care of all the operating modes.

Adaptive Neuro-Fuzzy Inference System (ANFIS) is used as an intelligent tool to design FLC [4]-[10]. It helps to generate and optimize membership functions as well as the rule base from the simple data provided. ANFIS combine the learning power of neural network with knowledge representation of fuzzy logic. This paper presents a novel speed control scheme for SVPWM-VCIM drive based on Neuro-fuzzy controller (NFC). The proposed NFC is adapted by a hybrid learning algorithm in order to minimize the square of the error between desired and actual output. A 5-layer ANN structure is utilized to train the parameters of the FLC, which eliminates unwanted trial and error as was in the case for a conventional fuzzy logic control. A complete simulation model for SVPWM-VCIM drive incorporating the proposed NFC is developed. The performance of the proposed NFC based SVPWM-VCIM drive is investigated at different operating conditions. A comparison is made with the conventional PI speed controller response. Section II presents Space Vector PWM inverter for induction motor drive. Section III presents the mathematical modeling of IM and vector control scheme. Section IV presents the design aspects of proposed NFC [11]-[12]. Section V and VI presents the performance evaluation and conclusion respectively.

II. SPACE VECTOR PWM INVERTER

PWM control of the inverter switches requires to synthesize the desired reference stator voltage space vector in an optimum manner with the following objectives [1]:

- 1) A constant switching frequency f_s .

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- 2) Smallest instantaneous deviation from its reference value.
- 3) Maximum utilization of the available dc-bus voltages.
- 4) Lowest ripple in the motor current and
- 5) Minimum switching loss in the inverter.

The above conditions are generally met if the average voltage vector is synthesized by means of the two instantaneous basic non-zero voltage vector that form the sector (in which the average voltage vectors to be synthesized lies) and both the zero voltage vectors, such that each transition causes change of only one switch status to minimize the inverter switching loss.

Figure.1 Three phase voltage source inverter

Figure.2 Space vector diagram of the available switching vectors.

In terms of the instantaneous stator phase voltages, the stator space voltage vector is

TABLE I
SUMMARY OF INVERTER SWITCHING STATES

Voltage vector	sw _A	sw _B	sw _C	v _{an}	v _{bn}	v _{cn}
$\overline{V_0}$	0	0	0	0	0	0
$\overline{V_1}$	0	0	1	$-V_{dc}/3$	$-V_{dc}/3$	$2V_{dc}/3$
$\overline{V_2}$	0	1	0	$-V_{dc}/3$	$2V_{dc}/3$	$-V_{dc}/3$
$\overline{V_3}$	0	1	1	$-2V_{dc}/3$	$V_{dc}/3$	$V_{dc}/3$
$\overline{V_4}$	1	0	0	$2V_{dc}/3$	$-V_{dc}/3$	$-V_{dc}/3$
$\overline{V_5}$	1	0	1	$V_{dc}/3$	$-2V_{dc}/3$	$V_{dc}/3$
$\overline{V_6}$	1	1	0	$V_{dc}/3$	$V_{dc}/3$	$-2V_{dc}/3$
$\overline{V_7}$	1	1	1	0	0	0

“0”=off, “1”=on

$$\overline{v_s}(t) = v_a(t)e^{j0} + v_b(t)e^{j2\pi/3} + v_c(t)e^{j4\pi/3} \quad (1)$$

Assuming the stator neutral as a reference ground

$$v_a = v_{an} + v_n; v_b = v_{bn} + v_n; v_c = v_{cn} + v_n; \quad (2)$$

Also

$$e^{j0} + e^{j2\pi/3} + e^{j4\pi/3} = 0 \quad (3)$$

The instantaneous stator voltage space vector can be written in terms of the inverter output voltage as in (4).

$$\overline{v_s}(t) = v_{an}e^{j0} + v_{bn}e^{j2\pi/3} + v_{cn}e^{j4\pi/3} \quad (4)$$

Fig.1. shows three phase voltage source inverter with induction motor drive.

The inverter has six states when a voltage is applied to the motor and two states (S_0 and S_7) when the motor is shorted through the upper or lower switch resulting in zero volts being applied to the motor. The six vectors including the zero voltage vectors can be expressed geometrically as shown in Fig. 2. Table I depicts summary of inverter switching states. SVPWM seeks to average out the adjacent vectors for each sector. Using the appropriate PWM signals a vector is produced that transitions smoothly between sectors and thus provide sinusoidal line to line voltages to the motor. In order to generate the PWM signals that produce the rotating vector, formulae must be derived to determine the PWM time intervals for each sector. Fig. 3. shows the pulse patterns generated by space vector modulation in sector 1.

Figure.3 Pulse patterns generated by space vector modulation in sector 1

The above space vector pulse-width modulation can be carried out by comparing control voltages with a triangular waveform signal at the switching frequency to generate switching functions.

For an induction motor with an isolated neutral

$$v_a(t) + v_b(t) + v_c(t) = 0 \quad (5)$$

To synthesize an average space vector $\overline{v_s}$ with phase components v_a , v_b and v_c following relation can be stated as the ratio of v_{contr} (control voltages) to v_{sw} (the

amplitude of the constant switching frequency triangular signal)

$$\frac{v_{contr,a}}{v_{sw}} = \frac{v_a - v_k}{V_{dc}/2}$$

$$\frac{v_{contr,b}}{v_{sw}} = \frac{v_b - v_k}{V_{dc}/2}$$

$$\frac{v_{contr,c}}{v_{sw}} = \frac{v_c - v_k}{V_{dc}/2}$$

where,

$$v_k = \frac{\max(v_a, v_b, v_c) + \min(v_a, v_b, v_c)}{2}$$

III. VECTOR CONTROLLED INDUCTION MOTOR DRIVE

A. Induction Motor Modeling

The mathematical model of a three- phase squirrel cage induction motor in synchronous rotating reference frames is given by equation (10)-(13) as follows.

$$\begin{bmatrix} v_{qs}^e \\ v_{ds}^e \\ v_{qr}^e \\ v_{dr}^e \end{bmatrix} = \begin{bmatrix} R_s + L_s p & \omega_s L_s & L_m p & \omega_s L_m \\ -\omega_s L_s & R_s + L_s p & -\omega_s L_m & L_m p \\ L_m p & (\omega_s - \omega_r) L_m & R_r + L_r p & (\omega_s - \omega_r) L_r \\ -(\omega_s - \omega_r) L_m & L_m p & -(\omega_s - \omega_r) L_r & R_r + L_r p \end{bmatrix} \begin{bmatrix} i_{qs}^e \\ i_{ds}^e \\ i_{qr}^e \\ i_{dr}^e \end{bmatrix}$$

(10)

$$T_e = \frac{3}{2} \frac{P}{2} L_m (i_{qs}^e i_{dr}^e - i_{ds}^e i_{qr}^e) \quad (11)$$

$$\frac{d\theta_r}{dt} = \omega_r \quad (12)$$

$$T_e = J_m \frac{d\omega_r}{dt} + B_m \omega_r + T_L \quad (13)$$

Where v_{ds}^e, v_{qs}^e are d-q axis stator voltages respectively;

$i_{ds}^e, i_{qs}^e, i_{dr}^e, i_{qr}^e$ are d-q axis stator currents and d-q axis rotor currents respectively; R_s, R_r are the stator and rotor resistance per phase respectively; L_s, L_r, L_m are the self inductances of the stator and rotor and the mutual inductance respectively; P is the number of poles; p is the differentiation operator (d/dt); ω_e, ω_r are the speed of the rotating magnetic field and the rotor speed respectively; T_e, T_L are the electromagnetic developed torque and the load torque respectively; J_m is the rotor inertia; B_m is the rotor damping coefficient and θ_r is the rotor position.

The transformation from abc to dq0 variables is given by equation (14).

$$f_{dq0} = \begin{bmatrix} T_{abc}^e \end{bmatrix} f_{abc}^e \quad (14)$$

$$\begin{bmatrix} T_{abc}^e \end{bmatrix} = \frac{2}{3} \begin{bmatrix} \cos(\omega t) & \cos(\omega t - \frac{2\pi}{3}) & \cos(\omega t + \frac{2\pi}{3}) \\ \sin(\omega t) & \sin(\omega t - \frac{2\pi}{3}) & \sin(\omega t + \frac{2\pi}{3}) \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix} \quad (15)$$

where $\begin{bmatrix} T_{abc}^e \end{bmatrix}$ is transformation matrix given by equation (15) and f may represents current or voltage.

B. Vector Control

For high performance drive system response, the vector controlled induction motor is a very accepted method. It is based on the decoupling of flux and torque producing components of the stator current. Under this condition, the q-axis component of rotor flux is set to zero while the d-axis reaches the nominal value of the magnetizing flux. The torque equation can also be written as

$$T_e = \frac{3}{2} \frac{P}{2} \frac{L_m}{L_r} (i_{qs}^e \lambda_{dr}^e - i_{ds}^e \lambda_{qr}^e) \quad (16)$$

Since λ_{qr}^e is zero

$$T_e = \frac{3}{2} \frac{P}{2} \frac{L_m}{L_r} (i_{qs}^e \lambda_{dr}^e) = K_{te} i_{qs}^e \lambda_{dr}^e \quad (17)$$

where $K_{te} = \frac{3}{2} \frac{P}{2} \frac{L_m}{L_r}$ = torque constant

If the rotor flux linkage in equation (17) is maintained constant, then the torque is simply proportional to the torque producing component of the stator current, as in the case of the separately excited dc machine with armature current control. The other field oriented controller equations are

$$T_r \frac{d\lambda_{dr}^e}{dt} + \lambda_{dr}^e = L_m i_{ds}^e \quad (18)$$

$$\omega_e = \frac{L_m}{T_r} \frac{i_{qs}^e}{\lambda_{dr}^e} + \omega_r \quad (19)$$

T_r denotes the rotor time constant. The equation (18) resembles the field equation in a separately excited dc machine, whose time constant is usually in the order of seconds. Likewise, the induction motor rotor time constant is in the order of seconds.

The equations which transform the synchronous reference frame to stationary reference frame are:

$$i_{qs}^s = \cos \theta_e i_{qs}^e + \sin \theta_e i_{ds}^e \quad (20)$$

$$i_{ds}^s = -\sin \theta_e i_{qs}^e + \cos \theta_e i_{ds}^e \quad (21)$$

where i_{qs}^s, i_{ds}^s are stationary frame q and d axis stator current respectively.

IV. ADAPTIVE NEURO-FUZZY CONTROLLER

The proposed neuro-fuzzy controller incorporates fuzzy

Figure.4 ANFIS architecture of 2-input Sugeno fuzzy model with 2 rules logic algorithm with a five layer artificial neural network (ANN) structure as shown in fig. 4.

A tuning block is utilized to adjust fourth layer's parameters in order to correct any deviation of control effort. The normalized speed error and the rate of change of actual speed error are the inputs of the neuro-fuzzy controller, which are given by

$$Input1 = \varepsilon_{\omega} = \frac{\omega^* - \omega}{\omega^*} \times 100\% \quad (22)$$

$$Input2 = \Delta \varepsilon_{\omega} = \frac{\varepsilon_{\omega}(n) - \varepsilon_{\omega}(n-1)}{T} \times 100\% \quad (23)$$

where ω^* is the command speed and T is the sampling time.

Sugeno fuzzy model with five-layer ANN structure is used in proposed controller. In this five-layer ANN structure the first layer represents for inputs, the second layer represents for fuzzification, the third and fourth layers represents for fuzzy rule evaluation and the fifth layer represents for defuzzification.

A two input first order Sugeno fuzzy model with two rules is depicted in fig. 4.

In layer 1, every node i is an adaptive node with a node function

$$O_{1,i} = \mu_{A_i}(x) \text{ for } i=1,2 \text{ or } O_{1,i} = \mu_{B_{i-2}}(y) \text{ for } i=3,4 \quad (24)$$

(here we denote the output of the i th node in layer ℓ as $O_{\ell,i}$)

where x (or y) is the input to node i and A_i (or B_{i-2}) is a linguistic label such as 'small' or 'large' associated with this node. The membership function for A can be any appropriate parameterized membership function. In proposed scheme generalized bell function is used as a membership function given by equation (25).

$$\mu_A(x) = \frac{1}{1 + \left| \frac{x - c_i}{a_i} \right|^{2b_i}} \quad (25)$$

where $\{a_i, b_i, c_i\}$ is the parameter set. As the values of these parameters changes, various forms of bell shaped membership functions can be get for fuzzy set A . Parameters in this layer are referred to as premise parameters.

In layer 2, every node is a fixed node labeled Π , whose output is the product of all the incoming signals.

$$O_{2,i} = w_i = \mu_{A_i}(x) \mu_{B_i}(y), i=1,2 \quad (26)$$

Each node output represents the firing strength of a rule.

In layer 3, every node is a fixed node labeled N . The outputs of this layer are *normalized* firing strengths given by equation (27).

$$O_{3,i} = \bar{w}_i = \frac{w_i}{w_1 + w_2}, i=1,2 \quad (27)$$

In layer 4, every node i , is an adaptive node with a node function given by equation (28).

$$O_{4,i} = \bar{w}_i f_i = \bar{w}_i (p_i x + q_i y + r_i) \quad (28)$$

where $\bar{w}_i$ is a normalized firing strength from layer 3 and

$\{p_i, q_i, r_i\}$ is the parameter set of this node. Parameters in this layer are referred to as consequent parameters.

Layer 5 is the single node layer with a fixed node labeled Σ , which computes the overall output as the summation of all incoming signals.

$$O_{5,1} = \sum_i \bar{w}_i f_i = \frac{\sum_i w_i f_i}{\sum_i w_i} \quad (29)$$

Hybrid learning algorithm is used in proposed controller. In the forward pass of the hybrid learning algorithm, node output goes forward until layer four and the consequent parameters are identified by the least squares method. In the backward pass, the error signals propagate backward and premise parameters are updated by gradient descent. The consequent parameters thus identified are optimal under the condition that the premise parameters are fixed. Thus, the hybrid approach converges much faster since it reduces the search space dimension of the original pure back propagation.

The propose ANFIS had following features: Type- Sugeno; AndMethod- product; OrMethod- probor (probabilistic or); DefuzzMethod- wtaver (weighted average); ImpMethod (implication method)- product; AggMethod (aggregation method)- sum; No. of input- 2; No. of input membership function- 3; input membership function type- gbellmf (generalized bell curve membership function); No. of output- 1; No. of output membership function- 9; output membership function type - linear; No. of rules- 9. Fig. 5. presents proposed equivalent ANFIS architecture. Fig. 6. and Fig. 7. shows input membership functions and output surface of proposed ANFIS respectively.

Figure.5 Proposed equivalent ANFIS architecture.

Figure.7 Output surface of proposed ANFIS.

(a)

(b)

Figure.9 SVPWM waveforms (a) Phase components v_a , v_b , v_c and v_k (b) v_{sw}

Figure.6 Input membership function of proposed ANFIS.

(a)

Figure.10 SVPWM waveforms (a) duty cycle (b) switching function

V. PERFORMANCE ASSESSMENT OF NEURO-FUZZY CONTROLLER BASED SVPWM-VCIM DRIVE

A complete simulation model for SVPWM-VCIM drive incorporating the proposed NFC is developed as shown in Fig. 8. The performance of the proposed NFC based SVPWM-VCIM drive is investigated at different operating conditions. In order to prove the superiority of the proposed NFC, a comparison is made with the response of conventional PI speed controller based VCIM drive. The parameters of the induction motor and SVPWM considered in this study are summarized in Appendix. Fig. 9. shows waveforms of v_a , v_b , v_c , v_k and v_{sw} for SVPWM. Fig. 10.

shows waveforms of duty cycle ($v_{contr,a}$, $v_{contr,b}$, $v_{contr,c}$)

and switching function (S_a , S_b , S_c) for SVPWM. The performance of SVPWM-VCIM drive with NFC is presented during starting, load perturbation and speed reversal. Transient, steady state and dynamic behavior of the drive with PI speed controller is shown in Fig. 11. and with neuro-fuzzy speed controller is shown in Fig. 12. The reference speed is set at 185 rad/sec. The electromagnetic torque T_e raises to maximum during starting of the motor from standstill and then settles down over remaining period (steady state condition). Same is for currents. At steady state load torque T_L has been increased to 12 Nm from 3 Nm at time $t=0.3$ sec. and suddenly decreased to 3 Nm at $t=0.5$ sec. Finally the motor that is operating at 185 rad/sec, suddenly its reference speed is changed to negative 185 rad/sec. Table II, III and IV presents performance comparison during steady state operation, during transient operation and in time domain analysis respectively. The results shows better performance of NFC based IM drive as compare to conventional PI controller based IM drive under starting, load perturbation and speed reversal. It shows NFC based SVPWM-VCIM drive is robust for high performance IM drive.

TABLE II

Performance comparison during steady state operation

Controller	Speed Ripple (rad/sec)	Torque Ripple (Nm)
PI	0.1	0.0017
NFC	0.004	0.0003

TABLE III

PERFORMANCE COMPARISON DURING TRANSIENTS

Controller	Starting Time (sec.)	Reversal Time (sec.)	Dip in Speed (rad/sec)	Rise in Speed (rad/sec)
PI	0.04	0.145	4.9	4.8
NFC	0.03	0.08	4.7	4.6

TABLE IV

PERFORMANCE COMPARISON IN TIME DOMAIN ANALYSIS

Controller	Peak Over shoot	Peak Time (sec.)	Rise Time (sec.)	Settle Time (sec.)
PI	0.1351	0.06	0.03	0.13
NFC	0.0054	0.057	0.026	0.11

VI. CONCLUSION

A novel Neuro-fuzzy controller based SVPWM-VCIM drive has been presented in this paper. Some of the advantages of ANFIS are reduced number of rules, faster speed of operation and no need for modifications in membership function by conventional trial and error method for optimal response. This makes NFC a easy-build and robust controller. The performances of the proposed NFC based SVPWM-VCIM drive has been investigated at various operating conditions. A comparison of the performance between the proposed NFC based drive and PI based drive has also been presented. The proposed NFC based SVPWM-VCIM drive has been found to be robust for high performance drive application.

Figure.11 Performance Characteristics of Drive Scheme with PI-Speed controller (a) speed (rad/sec.) (b) current (amp.) (c) torque (Nm) (d) speed during loading cycle (e) speed ripples (f) torque ripples.

Figure.12 Performance Characteristics of Drive Scheme with ANFIS- Speed controller (a) speed (rad/sec.) (b) current (amp.) (c) torque (Nm) (d) speed during loading cycle (e) speed ripples (f) torque ripples.

APPENDIX

The parameters of induction motor are as follows:

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P	Nominal power	2.2KW
R_s	Stator resistance	1.77 ohms
R_r	Rotor resistance	1.34 ohms
X_{ls}	Stator leakage reactance	5.25 ohms
X_{lr}	Rotor leakage reactance	4.57 ohms
X_m	Mutual reactance	139 ohms
J	Rotor inertia	0.025 Kg.m ²
p	Number of pole	4

The parameters for SVPWM:

V_{dc}	DC-link voltage	700 volts
v_{sw}	Amplitude of v_{sw} voltage	5 volts
f_{sw}	Switching frequency	10 kHz

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Figure.8 Adaptive Neuro-Fuzzy speed controller based vector controlled induction motor drive.