SIMPLIFIED PREDICTIVE TORQUE CONTROL SCHEME FOR OPEN END WINDING INDUCTION MOTOR USING ANFIS CONTROLLER

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ABSTRACT

This paper presents a Simplified Predictive Torque Control Scheme for Open end winding induction motor drive with two inverters using ANFIS controller. The flux weighting factor can be removed and the reactive torque control is used in the place of flux control objective in simplified PTC. The two control objectives torque and flux are represented with same units and thus flux weighting factor can be eliminated in the cost function. It results minimum torque and flux ripple and transient current is reduced. The various performances using PI and ANFIS controller of simplified PTC for dual inverter fed OEWM is validated through MATLAB/SIMULINK.

KEYWORDS: Dual Inverter Fed OEWM, Predictive Torque Control, Reactive Torque Control, ANFIS Controller

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1. INTRODUCTION

Now a days for many industrial drive applications, Induction motor drives fed with voltage source inverter became more popular. By increasing number of voltage vectors the accurate control of motor drive is possible. With multilevel voltage source inverters (MLI) more number of voltage vectors are obtained. In [1], Different types of multi level inverters with reduced device count were presented. In [2], various topologies for multilevel Converters such as Neutral point clamped, cascaded H-bridge, flying capacitors and most widely used modulation methods are studied. While different types of multilevel inverters are available, we use dual inverter OEWM configuration as it provides more advantages such as: simple because of the absence of clamping diodes, easy accessibility of two-level VSIs for multilevel inversion. The drive dynamic performance can be enhanced through several control methods. There are some disadvantages in FOC like complicated control structure and reference frame transformations. The Field Oriented Control for OEWM is presented in [4]. The Direct torque control technique has overcome these limitations for the drive [5]. The limitations of DTC are presented in [6]-[8]. The Direct Torque Control technique for two inverters fed OEWM is presented in [9].

Model Predictive Control is used in control technique and is enforced for the different applications of drive [10]. Finite control set MPC and Continuous control set MPC are the two sections of MPC where Predictive Torque Control (PTC) is the section in FS-MPC. PTC becomes very famous due to the merits like straightforward structure, improved torque and flux regulation, simple control.

The PTC management mechanism is a minimization of cost functions. The cost function comprises torque and flux control objectives which has different units, hence a corresponding balance weighting factor is provided,

which determines the motor drive performance [11]. By replacing flux control objective with reactive torque control, the weighting factor can be eliminated in simplified PTC.

This paper contains modelling of OEWM with dual inverter and also the voltage space vector allocations. The simplified PTC scheme is enforced for the dual inverter fed OEWM drive, where the weighting element of the cost function is completely removed. Based on the selection of adjacent voltage vectors number of prediction voltage vectors is reduced, thereby decreasing calculating control mechanism stress. The simplified PTC scheme of OEWM is evaluated with PI and ANFIS controller through simulation. The paper structured as, Section II with the mathematical modelling of two inverters fed OEWM drive. Section III sets out specific details about the operation of simplified PTC. The section IV has simplified PTC with ANFIS controller is specified. The section V gives the effectiveness of simplified PTC with ANFIS controller over simplified PTC with PI controller through simulation. Section VI, represents the conclusions of this paper.

2. DUAL INVERTER FED OEWM MATHEMATICAL EQUATIONS

The pole voltages of voltage source inverters are characterized by equations (1) and (2) from Fig.1. The pole voltages can be calculated with negative rails of their corresponding VSIs. The dc link voltages of two inverters are managed as 2:1 ratio for achieving four level inversion. Thence, $C_1 V_{dc}$ is the input voltage provided to the VSI-1, where C_1 is $2/3$ and voltage across VSI-1 is $2 V_{dc}/3$. $C_2 V_{dc}$ is the voltage given to the VSI-2, where C_2 is $1/3$ and hence the voltage across VSI-2 is $V_{dc}/3$. The switching pulses like $S_a, S_b, S_c, S_a', S_b', S_c'$ are given to upper switches ($S_1, S_3, S_5, S_1', S_3', S_5'$) of dual inverter.

Figure 1: OEWM model

$$\begin{pmatrix} V_{ao} \\ V_{bo} \\ V_{co} \end{pmatrix} = \begin{pmatrix} S_a \\ S_b \\ S_c \end{pmatrix} * C_1 V_{dc} \quad (1)$$

$$\begin{pmatrix} V_{a'o'} \\ V_{b'o'} \\ V_{c'o'} \end{pmatrix} = \begin{pmatrix} S_{a'} \\ S_{b'} \\ S_{c'} \end{pmatrix} * C_2 V_{dc} \quad (2)$$

Where C_1 and C_2 are constants which are assigned as $C_1=2/3$ and $C_2=1/3$

The difference of dual inverter pole voltages is stated by equation (3). The voltage enforced to OEWM phases are given by (6).

$$\begin{pmatrix} \delta V_{aa'} \\ \delta V_{bb'} \\ \delta V_{cc'} \end{pmatrix} = \begin{pmatrix} V_{ao} - V_{a'o'} \\ V_{bo} - V_{b'o'} \\ V_{co} - V_{c'o'} \end{pmatrix} \quad (3)$$

$$\begin{pmatrix} \delta V_{aa'} \\ \delta V_{bb'} \\ \delta V_{cc'} \end{pmatrix} = \begin{pmatrix} V_{aa'} \\ V_{bb'} \\ V_{cc'} \end{pmatrix} + \begin{pmatrix} V_z \\ V_z \\ V_z \end{pmatrix} \quad (4)$$

$$V_z = \frac{1}{3}(\delta V_{aa'} + \delta V_{bb'} + \delta V_{cc'}) \quad (5)$$

$$\begin{pmatrix} V_{aa'} \\ V_{bb'} \\ V_{cc'} \end{pmatrix} = \begin{pmatrix} \frac{2}{3} & \frac{-1}{3} & \frac{-1}{3} \\ \frac{-1}{3} & \frac{2}{3} & \frac{-1}{3} \\ \frac{-1}{3} & \frac{-1}{3} & \frac{2}{3} \end{pmatrix} * \begin{pmatrix} \delta V_{aa'} \\ \delta V_{bb'} \\ \delta V_{cc'} \end{pmatrix} \quad (6)$$

The OEWM is modelled in stator reference frame. The voltage, flux linkage of rotor and stator are expressed in equations (7)-(10). Electromagnetic torque and motor-load torque are expressed by the equations (11)-(12).

$$V_s = R_s i_s + p \lambda_s \quad (7)$$

$$0 = R_r i_r + p \lambda_r - j \omega_r \lambda_r \quad (8)$$

$$\lambda_s = L_s i_s + L_m i_r \quad (9)$$

$$\lambda_r = L_m i_s + L_r i_r \quad (10)$$

$$T_m = \frac{3p}{2} \left(\text{imag}(\overline{\lambda_s} * i_s) \right) \quad (11)$$

$$T_m - T_l = J \frac{d\omega_m}{dt} \quad (12)$$

The rotor and stator terms are described with subscript “r” and “s” in equation (9) and (10). In a machine P represents the number of poles and moment of inertia is denoted by J. ω_m and ω_r represents motor mechanical and electrical speed. The flux space vector (λ_s) and current space vector (i_s) are called as state variables of machine. Stator flux vector and current vector is given by (13) and (14) equations respectively.

$$\frac{d\lambda_s}{dt} = V_s + R i_s \quad (13)$$

$$\frac{di_s}{dt} = R_1 \left(R_2 \lambda_s - R_3 i_s + K_r (V_s - j \omega_r \lambda_r) + K_r R i_s + \frac{j \omega_r i_s}{R_1} \right) \quad (14)$$

$$\text{Where } R = R_s, R_1 = \frac{L_m}{L_s L_r - L_m^2}, R_2 = \frac{R_r}{L_m}, R_3 = \frac{L_s R_r}{L_m}, P = \frac{d}{dt}, K_r = \frac{L_r}{L_m}, V_s = V_{s\alpha} + V_{s\beta}, i_s = i_{s\alpha} + i_{s\beta}, \lambda_s = \lambda_{s\alpha} + \lambda_{s\beta}$$

3.SIMPLIFIED PTC USING PI CONTROLLER

The required inputs for the simplified PTC are stator current, real and reactive torque, sensed motor speed. Speed PI controller generate real torque by comparing the reference speed with sensed speed, giving error to the PI controller. It will maintain the speed of motor nearer to the mention speed. By using equations (13)-(14) the machine model can be characterized in a discrete manner by implementing Forward Euler's method.

Figure 2: Simplified PTC using PI controller

This can be illustrated as

$$\frac{dz}{dt} = \frac{z(k+1) - z(k)}{T_s} \quad (15)$$

Where: 'k' is present sampling state, 'Ts' is sampling period and 'Z' is any state variable

The basic steps in this simplified PTC are given as follows

Step1: The Measure and Estimation

The motor speed and dc link voltage are precisely measured and with the motor phases stator currents i_a , i_b and i_c are obtained directly. The 3-Ø currents are transformed into 2-Ø currents (i_α, i_β) by using Clarke's transformation for reducing the complexity. All the measured variables voltage, speed, current are given to the PTC algorithm. The stator flux is obtained by knowing instant sample state (k) and previous sample state (k-1) variables, which is given as

$$\lambda_s(k) = \lambda_s(k-1) + T_s((V_s(k-1) + R i_s(k-1))) \quad (16)$$

Step2: The Prediction

In a given dual inverter configuration for all the active voltage space vectors, the stator current and flux can be forecasted with one step ahead [k+1]. Both inverters are fed with unequal voltages and from VSI-1, VSI-2 the voltage space vectors produced (V_{s1} and V_{s2}). The effective voltage space vector applied for the machine will be given by (19).

$$V_{s1} = \left(\frac{2}{3}\right) (C_1 * V_{dc}) \left(S_a + S_b e^{j2\pi/3} + S_c e^{j4\pi/3}\right) \quad (17)$$

$$V_{s2} = \left(\frac{2}{3}\right) (C_2 * V_{dc}) \left(S'_a + S'_b e^{j2\pi/3} + S'_c e^{j4\pi/3}\right) \quad (18)$$

$$V_s = V_{s1} - V_{s2} \quad (19)$$

They are 64 possible dual inverter switching states. Among these states, there are 37 effective states which are grouped into small, medium, and large group. Voltage vector (V_1 - V_6) is small group, (V_7 - V_{18}) is medium group and (V_{19} - V_{36}) is large group.

The table shown below gives the realisation in stationary reference frame and effective switching states. For the 37 voltage space vector, the stator current and flux can be forecasted using sample state variable. The forecasted stator flux

and current are given by (20) and (21).

$$\lambda_s(k+1)_n = \lambda_s(k) + T_s((V_s(k))_n + Ri_s(k)) \quad (20)$$

$$i_s(k+1)_n = i_s(k) + T_s(R_1(R_2\lambda_s(k) - R_3 i_s(k) + k_r \left((V_s(k))_n + Ri_s(k) - j\omega_r \lambda_s(k) \right) + \frac{j\omega_r i_s(k)}{R_1}) \quad (21)$$

Where, n denotes voltage vector (i.e. 0 to 36)

By forecasting flux and current for all voltage vectors, we can forecast torque for all the active voltage vector by using (22)

$$(T_m(k+1))_n = \frac{3P}{2} (\text{imag}(\overline{\lambda_s(k+1)}_n * i_s(k+1)_n)) \quad (22)$$

Table 1: Active Switching States and realization

VSI-1	VSI-2	Voltage space Vector	Realization	
(S _a , S _b , S _c)	(S _a ', S _b ', S _c ')	V _s	V _α	V _β
(0,0,0)	(0,0,0)	V ₀	0	0
(1,0,0)	(1,0,0)	V ₁	V _{dc} (2/9)	0
(1,1,0)	(1,1,0)	V ₂	V _{dc} (1/9)	(1.732/9)V _{dc}
(0,1,0)	(0,1,0)	V ₃	V _{dc} (-1/9)	(1.732/9)V _{dc}
(0,1,1)	(0,1,1)	V ₄	V _{dc} (-2/9)	0
(0,0,1)	(0,0,1)	V ₅	V _{dc} (-1/9)	(-1.732/9)V _{dc}
(1,0,1)	(1,0,1)	V ₆	V _{dc} (1/9)	(-1.732/9)V _{dc}
(1,0,0)	(1,1,1)	V ₇	V _{dc} (4/9)	0
(1,0,0)	(1,0,1)	V ₈	V _{dc} (1/3)	(1.732/9)V _{dc}
(1,1,0)	(1,1,1)	V ₉	V _{dc} (2/9)	(3.464/9)V _{dc}
(0,1,0)	(0,1,1)	V ₁₀	0	(3.464/9)V _{dc}
(0,1,0)	(1,1,1)	V ₁₁	V _{dc} (-2/9)	(3.464/9)V _{dc}
(0,1,0)	(1,1,0)	V ₁₂	V _{dc} (-1/3)	(1.732/9)V _{dc}
(0,1,1)	(1,1,1)	V ₁₃	V _{dc} (-4/9)	0
(0,0,1)	(1,0,1)	V ₁₄	V _{dc} (-1/3)	(-1.732/9)V _{dc}
(0,0,1)	(1,1,1)	V ₁₅	V _{dc} (-2/9)	(-3.464/9)V _{dc}
(0,0,1)	(0,1,1)	V ₁₆	0	(-3.464/9)V _{dc}
(1,0,1)	(1,1,1)	V ₁₇	V _{dc} (2/9)	(-3.464/9)V _{dc}
(1,0,0)	(1,1,0)	V ₁₈	V _{dc} (1/3)	(-1.732/9)V _{dc}
(1,0,0)	(0,1,1)	V ₁₉	V _{dc} (2/3)	0
(1,0,0)	(0,0,1)	V ₂₀	V _{dc} (5/9)	(1.732/9)V _{dc}
(1,1,0)	(0,1,1)	V ₂₁	V _{dc} (4/9)	(3.464/9)V _{dc}
(1,1,0)	(0,0,1)	V ₂₂	V _{dc} (1/3)	(1.732/3)V _{dc}
(1,1,0)	(1,0,1)	V ₂₃	V _{dc} (1/9)	(1.732/3)V _{dc}
(0,1,0)	(0,0,1)	V ₂₄	V _{dc} (-1/3)	(1.732/3)V _{dc}

			1/9)	
(0,1,0)	(1,0,1)	V ₂₅	V _{dc} (-1/3)	(1.732/3)V _{dc}
(0,1,0)	(1,0,0)	V ₂₆	V _{dc} (-4/9)	(3.464/9)V _{dc}
(0,1,1)	(1,0,1)	V ₂₇	V _{dc} (-5/9)	(1.732/9)V _{dc}
(0,1,1)	(1,0,0)	V ₂₈	V _{dc} (-2/3)	0
(0,1,1)	(1,1,0)	V ₂₉	V _{dc} (-5/9)	(-1.732/9)V _{dc}
(0,0,1)	(1,0,0)	V ₃₀	V _{dc} (-4/9)	(-3.464/9)V _{dc}
(0,0,1)	(1,1,0)	V ₃₁	V _{dc} (-1/3)	(-1.732/3)V _{dc}
(0,0,1)	(0,1,0)	V ₃₂	V _{dc} (-1/9)	(-1.732/3)V _{dc}
(1,0,1)	(1,1,0)	V ₃₃	V _{dc} (1/9)	(-1.732/3)V _{dc}
(1,0,1)	(0,1,0)	V ₃₄	V _{dc} (1/3)	(-1.732/3)V _{dc}
(1,0,1)	(0,1,1)	V ₃₅	V _{dc} (4/9)	(-3.464/9)V _{dc}
(1,0,0)	(0,1,0)	V ₃₆	V _{dc} (5/9)	(-1.732/9)V _{dc}

Step 3: The Formulation of Cost Function

In this simplified PTC, the costfunction is given with active and reactive torque control objectives. The Reactive torque control objective is similar to flux control and the cost function is given by (23).

$$G_n = |T_m^* - T_m(k+1)_n| + |T_r^* - T_r(k+1)_n| \quad (23)$$

In this reactive torque is obtained from the flux PI controller and flux in the machine is analogous to reactive torque. The reactive torque is given by

$$T_r = \frac{3P}{2} (\text{real}(\bar{\lambda}_s * i_s)) \quad (24)$$

Reactive torque can be forecasted one step ahead for all the active voltage vectors

$$(T_r(k+1))_n = \frac{3P}{2} (\text{real}(\bar{\lambda}_s(k+1)_n * i_s(k+1)_n)) \quad (25)$$

From (23), the first control objective serve as electromagnetic torque and second control objective serve as reactive torque control which represents flux control. So the two control objectives are in same units, the weighting factor in cost function is completely removed.

Step 4: Nearest Voltage Vector Selection

In simplified PTC of OEWIM drive, the most advantageous voltage vector is the one which gives small cost function value. For selecting optimal voltage vector, the cost function (23) should be resolved for the selected 37 vectors in each period. In the control process calculated burden can be reduced by limiting the number of forecasted voltage vectors, which is obtained by selecting the vector atmost to optimum voltage vector. This is done by selecting minimum one from small vector group and four from medium vector and four from large vector group. With this only 12 vectors are forecasted including null vector.

Figure 3: Available limited forecasting voltage vectors selection for later sample interval when the instant optimal voltage vector is V_{21}

The overall control steps involved in predicting voltage vectors is represented in flow graph

Figure 4: Simplified PTC Flow graph

4. SIMPLIFIED PTC USING ANFIS CONTROLLER

The adaptive neuro-fuzzy inference system (ANFIS) is the ANN (artificial neural network) which is the sequence of Fuzzy Systems and Neural Networks. The fuzzy inference system constitutes a fuzzy model which was given by Takagi-Sugeno to formalize a precise access to spawn the fuzzy rules from the input - output dataset. ANFIS block diagram is shown in Fig5.

Figure 5: ANFIS block diagram for generating torque

In this paper consider two inputs and 3 fuzzified values. The fuzzified values are positive, zero and negative. With three fuzzified values, 9 rules are framed in fuzzy system. Among 9 rules, the optimum one is fired and de-fuzzified output becomes the output neuron. The two inputs are speed error and change in speed error. The following figure shows the input membership functions.

a) Input-1

b) Input-2

c) Output

Figure 6: Membership functions of ANFIS

a) Input-1 is the speed error b) Input-2 is change in speed error c) output

Figure 8: Flux, speed, torque and current response of OEWM drive by simplified PTC with PI controller

Figure 9: Flux, speed torque and current response of OEWM drive by using simplified PTC with ANFIS controller

6. CONCLUSIONS

This paper introduces simplified PTC for dual inverter fed OEWM using ANFIS controller providing improved torque and flux response. The number of forecasting voltage vectors are limited based on the selection of nearby voltage vector to optimum voltage vector. Due to the selection of nearby voltage vector computational burden is reduced. Due to the sudden change in load, the transient current will be high in the simplified PTC fed OEWM drive with PI controller compared to the ANFIS controller. The torque and flux ripples will be minimum with ANFIS controller. The smooth variation in speed and time taken to reach steady state speed will be less with the ANFIS controller.

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