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Direct Torque Control of PMSM using Space Vector Modulation

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Abstract: The direct torque control of permanent magnet synchronous motor using space vector pulse width modulation technique and fuzzy controller is presented in this paper. It is compared with the conventional DTC. In PMSM the electromagnetic torque is directly proportional to the angle between stator and rotor flux linkages. This angle can be controlled by controlling the stator flux linkages. The stator flux linkages can be controlled by controlling the stator voltage vector, which can be controlled by controlling the switching frequency of the inverter. The DTC-SVM and DTC-Fuzzy controller is implemented in MATLAB / simulation.

Keywords: DTC, SVM, Fuzzy, PMSM

I. INTRODUCTION

The main features of the PMSM are High torque / weight ratio, and negligible maintenance. The advances in the recent technology improve the magnetic and thermal capabilities of permanent magnet material, so that it is possible to design permanent magnets with high residual flux densities.

The direct torque control scheme is first proposed for induction motor [1] and it is next implemented to the synchronous motor [4]. The difference between DTC and vector control is, the later involves the current controller and park's transformation, whereas in DTC there is no need of axis of transformation and current control. The DTC scheme is simple, robust control technique and gives fast dynamic response.

However DTC suffers from variable switching frequency, violation of polarity consistency rules and high ripples in the torque and current due to sector changes. All the above difficulties can be eliminated by employing the voltage modulator with predictive controller, in which the torque error, flux reference, stator flux vector (λ_S), position of the stator flux and current vector (i_{dq}) are the inputs for the predictive controller. The predictive controller determines the stator voltage and its phase, which are the inputs for the space vector voltage modulator. It generates the necessary switching pulses for the inverter.

Also, fuzzy logic controller has been used instead of PI controller with DTC-SVM to reduce the ripple content in the current, Torque and flux.A complete simulation of the DTC-SVM with PI controller and with fuzzy controller fed to PMSM is tested using MATLAB / SimuLink.

II. MODEL OF PMSM

The voltage and flux equations for a PMSM in the rotor oriented coordinates d-q can be expressed as:

$$V_{ds} = R_S\, i_{ds} + \rho\, \lambda_{ds} - p\, \omega_m\, \lambda_{qs} \qquad (1)$$

$$V_{qs} = R_S\, i_{qs} + \rho\, \lambda q_s + p\, \omega_m\, \lambda_{ds} \qquad (2)$$

$$\lambda_{ds} = L_d\, i_{ds} + \lambda_{PM} \qquad (3)$$

$$\lambda_{qs} = L_d\, i_{qs} \qquad (4)$$

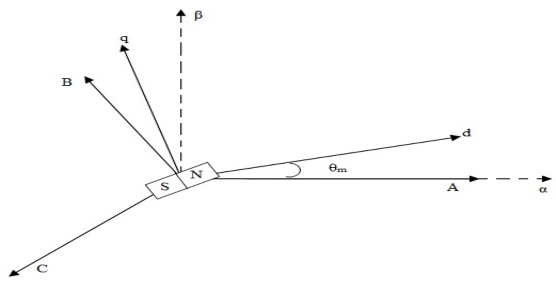
and the electromagnetic torque equation

$$T_e = 1.5\, p\, [\lambda_{ds}\, i_{qs} - \lambda_{qs}\, i_{ds}] = 1.5\, p\, [\lambda_{PM}\, i_{qs} - (L_d - L_q)\, i_{qs}\, i_{ds}] \qquad (5)$$

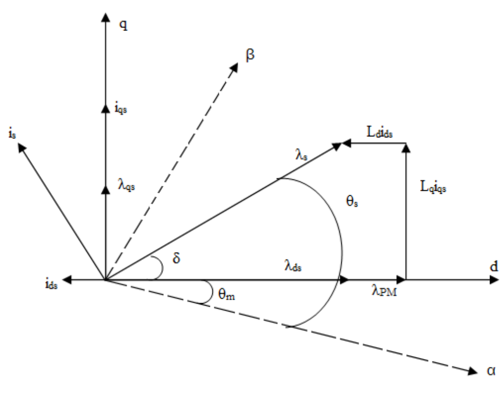
where ρ is the differential operator, p is the number pair of poles, R_S is the stator winding resistance, ω_m is the angular frequency, V_{ds} , V_{qs} and i_{ds} , i_{qs} are d, q components of voltage and current, λ_{ds} , λ_{qs} are d, q components of the stator flux linkage, L_d , L_q are d, q axis inductances, and λ_{PM} is the permanent magnet rotor flux linkage. The dynamics of motion equation is given by

$$\rho\, \omega_m = (1/J) * (T_e - T_l - k\, \omega_m) \qquad (6)$$

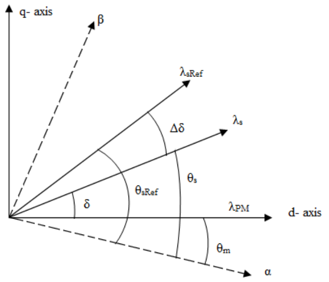
where J is the moment of inertia, T_l motor torque and k is the damping constant. The phasor diagrams of the PMSM are shown in figures (1a), (1b), (1c).



a: Different coordinates of PMSM



b: Flux and Voltage vectors



c:Vector diagram of illustrating torque control conditions
Fig 1: Phasor diagrams of PMSM

III. DIRECT TORQUE CONTROL – SPACE VECTOR MODULATION (DTC-SVM)

A predictive controller is used for which the torque error signal (eT_e) and reference stator flux (λ_{sRef}), position of stator flux vector (θ_s), and measured current are the inputs and the outputs of it are the stator voltage and its phase (v_{Ref} = [V_{Ref} , φ_{Ref}]). These are the inputs for the space vector voltage modulator, which generates the switching pulses S_A, S_B, $S_C$for the inverter.

Sampled torque error (eT_e) and reference stator flux amplitude (λ_{sRef}) are delivered to the predictive controller. The relation between error of torque and increment of load angle Δδ is non linear. Therefore PI controller, which generates the load angle increment, required minimizing the instantaneous error between reference torque and actual torque has been applied. The reference values of the stator voltage vector v_{Ref} = [V_{Ref} , φ_{Ref}] is calculated based on stator resistance R_s , Δδ signal, actual stator current vector i_S, actual stator flux amplitude λ_S and position θ_S as follows

$$V_{Ref} = (v_{S\alpha Ref}^{2} + v_{S\beta Ref}^{2})^{0.5},\ \varphi_{Ref} = \arctan (v_{S\beta Ref} / v_{S\alpha Ref}) \quad (7)$$

Where $$v_{S\alpha Ref} = \{ (\lambda_{Sref} \cos (\theta_s + \Delta\delta) - \lambda_S \cos\theta_s) / T_s \} + R_S i_{s\alpha} \quad (8)$$

$$v_{S\beta Ref} = \{ (\lambda_{Sref} \sin (\theta_s + \Delta\delta) - \lambda_S \sin \theta_s) / T_s \} + R_S i_{s\beta} \quad (9)$$

and T_s is the sampling time.
For constant flux operating region, the reference value of stator flux amplitude λ_{sRef} is equal to the flux amplitude produced by permanent magnet λ_{PM}.
The block diagram of the DTC-SVM controlled PMSM is shown in fig (2).

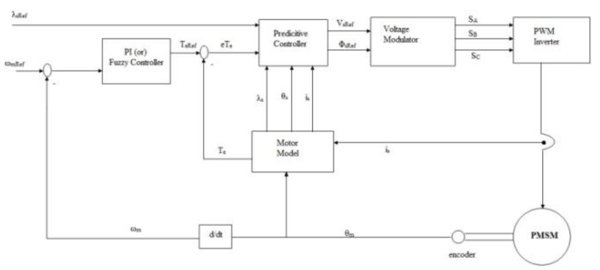


Fig 2: Block diagram of the DTC-SVM controlled PMSM

IV. FUZZY CONTROLLER

The Fuzzy logic controller (FLC) uses a set of fuzzy rules representing a control decision mechanism to adjust the effect of certain system stimuli. Therefore, the aim of using FLC is to replace a skilled human operator with a fuzzy rules-based system. The fuzzy input vectors are the motor speed deviation Δω and the acceleration Δώ. The fuzzy set for inputs and output membership functions are shown in Fig. (4). Seven linguistic variables (*LV*) are used for each input variables. These are PL (Positive Large), PM (Positive Medium), PS (Positive Small), Z (Zero), NS (Negative Small), NM (Negative Medium) and NL (Negative Large). The fuzzy output is the change in reference torque (Δ*Tref* {*k*}) which is to be added to the previous value of reference torque (*Tref*{*k*-1}). The output fuzzy sets have the same linguistic variables used for input except T is added to indicate the fuzzy sets are used for torque. For example T-PL means Torque Positive Large. A look-up table given in table 1, in which the relation between the input variables, Δω and Δώ, are defined and the output variable of the fuzzy logic controller was developed and used in the simulation. The maximum of minimum method has been used to find the output fuzzy rules stage, as

$$\Delta T(K) = (\int y^{*}\mu(y)^{*}dy) / (\int \mu(y)^{*}dy \quad (10)$$

The fuzzy logic controller is implemented and simulated to determine the desired torque reference (T_{Ref})for the system shown in fig 3. The FLC output is added to the previous torque reference T_{Ref} (k-1) to calculate the present T_{Ref} (k) by using the following equation.

$$T_{Ref}(K) = T_{Ref}(K-1) - \Delta T(K) \quad (11)$$

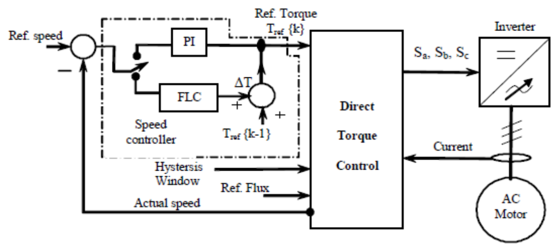


Fig 3: DTC System with PI and FLC for speed loop

Table 1 : Look-up Table which defines the relationshipbetween input and output variable in a fuzzy

Speed Change (Δω)	Speed Deviation Change (Δω')						
	NL	NM	NS	Z	PS	PM	PL
NL	T-NL	T-NL	T-NL	T-NL	T-NM	T-NS	T-Z
NM	T-NL	T-NL	T-NL	T-NM	T-NS	T-NS	T-NS
NS	T-NL	T-NL	T-NM	T-NS	T-NS	T-NS	T-NS
Z	T-NM	T-NM	T-NS	T-Z	T-PS	T-PM	T-PL
PS	T-PM	T-PM	T-PM	T-PM	T-PM	T-PL	T-PL
PM	T-NS	T-Z	T-	T-	T-	T-	T-
PL	T-Z	T-	T-	T-	T-	T-	T-

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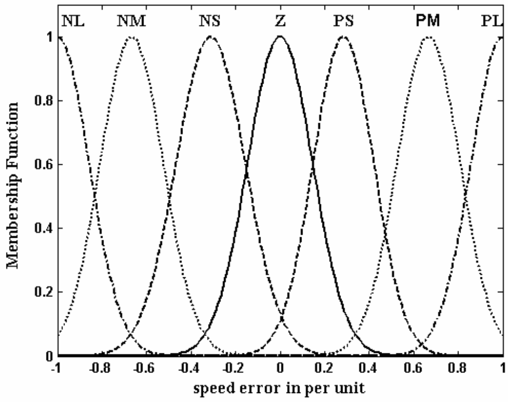
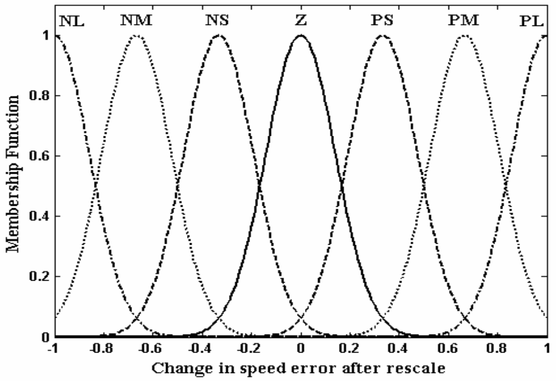
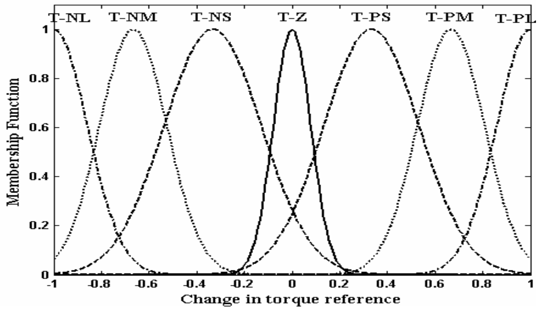


a: Input fuzzy set (speed error in p.u.)



b: Input fuzzy set (change in speed error.)



c: Output fuzzy set

Fig 4:Input and Output Fuzzy Memberships

The output surface of the FLC is shown in figure (5).

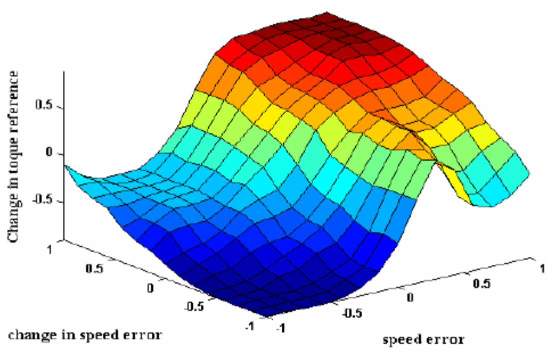


Fig 5: Output surface of FLC

V. SIMULATION RESULTS

The simulation results of the DTC – SVM fed PMSM are shown below. The torque tracking response is shown in fig 6a, 6b. The flux tracking response is shown in fig 7a, 7b. The torque ripple is shown in torque response alone in fig 8a, 8b.

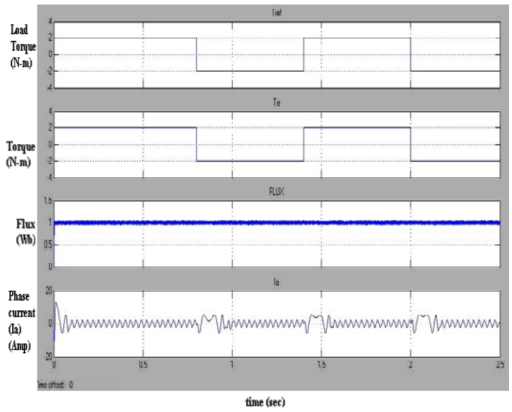


Fig. 6a Torque Tracking Response with PI controller

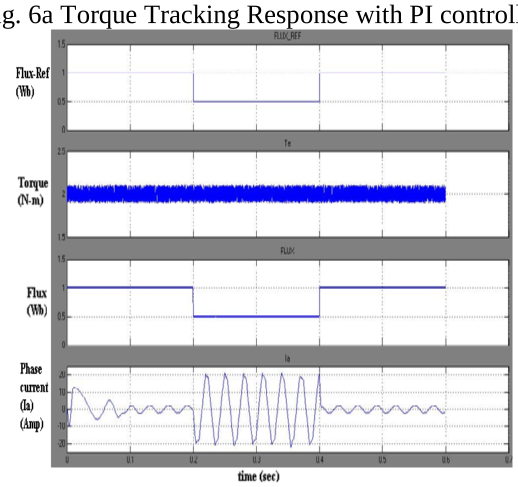


Fig.6b Torque Tracking Response with Fuzzy controller

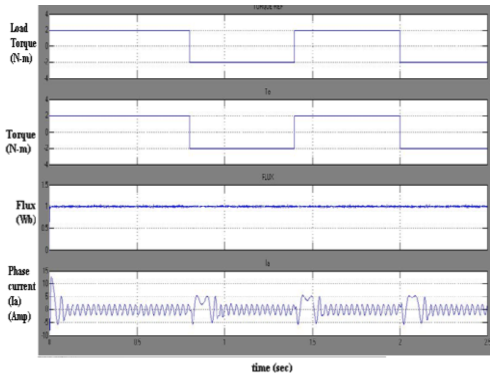


Fig. 7a Flux Tracking response with PI controller

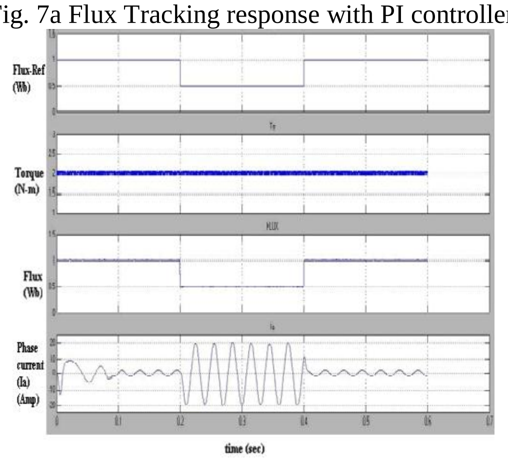


Fig. 7b Flux Tracking response with Fuzzy controller

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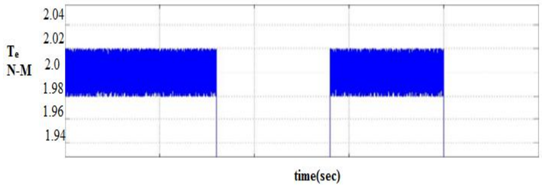

Fig. 8a Torque response with PI controller

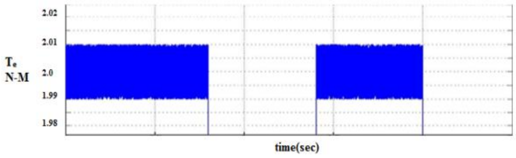

Fig. 8bTorque responsewith Fuzzy controller

VI. CONCLUSION

From the paper the following conclusions are made
DTC – SVM with PI controller ensures

i) Constant switching frequency of the inverter
ii) Low sampling frequency
iii) Good dynamic response.

DTC – SVM with Fuzzy controller ensures
Along with the above merits the fuzzy controller further reduces the ripple in the current, flux and torque and also improves the dynamic response.

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