

Three-phase Induction Motor DTC-SVM Scheme with Self-Tuning PI-Type Fuzzy Controller

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Abstract—The Direct Torque Control (DTC) with Space Vector Modulation (SVM) and Self-Tuning PI-Type Fuzzy (STPIF) controller is proposed. This controller determines dynamically the load angle between stator and rotor flux vectors and in consequence the electromagnetic torque necessary to supply the motor load. The rule base for STPIF controller is defined in function of the error " e " and the change of the error " Δe " of the torque using a most natural and unbiased membership functions (MF). Constant switching frequency and low torque ripple are obtained using SVM. Performance of the proposed DTC-SVM with STPIF are compared with the performance of the same scheme but using PI controller in terms of several performance measures such as settling time, rise time and integral-of-time multiplied by the absolute magnitude of the error index (ITAE). The simulation results show that the proposed scheme can ensure fast torque response and low torque ripple in comparison with DTC-SVM with PI controller.

I. INTRODUCTION

Three-phase induction motors (IM) are used in a wide variety of industrial applications today due to its simple construction, reliability, robustness and low cost. In the last years DTC has become a popular technique for three-phase IM drives as it provides a fast dynamic torque response and robustness under machine parameter variations without the use of current regulators.

There are already some DTC based strategies, e.g., voltage-vector selection using switching table [1], direct self-control [2], an alternative approach to reduce the torque ripples based on SVM technique [3], [4] and in [5] it is presented a simple one step stator flux control algorithm which avoids coordinate rotation and predictive controllers. However, this scheme needs the adjustment of PI torque controller parameters to achieve good performance.

In general the use of fuzzy control does not require the accurate mathematic model of the process to be controlled. Instead, it uses the experience and knowledge of the involved professionals to construct its control rule base.

Fuzzy logic has been proved to be powerful in the motor control area, e.g., in [6] the PI and Fuzzy Logic Controllers (FLC) are used to control the load angle which simplifies the IM drive system. In [7] the FLC is used to obtain the voltage vector reference dynamically in terms of torque error, stator flux error and stator flux angle. In this case both torque and stator flux ripples are remarkably reduced. Another paper on fuzzy logic application in DTC-SVM shows that the fuzzy PI

(or PI-type fuzzy) speed controller has a better response for a wide range of motor speed [8]. Different type of adaptive FLC such as self-tuning and self-organizing controllers has also been developed and implemented [9]-[11].

In [12] it was used a self-tuning PI-type fuzzy controller to control a second-order linear and marginally stable system. This method requires three scaling factors (SF) or gains. The performance analysis of this controller was compared to the regular PI controller and the results were very encouraging. The same was done in [13] where the self-tuning PI-type fuzzy controller was used in an industrial weigh belt feeder control process successfully. In both cases only the output scaling factor was adjusted online depending on the process trend.

In this paper it was designed a STPIF for a DTC-SVM three-phase IM based in [5], where only the output controller gain (output SF) was adjusted continuously with the help of fuzzy rules considering that it is equivalent to the controller gain. It has been given the highest priority to the output SF tuning due to its strong influence on the performance and stability of the system.

In our scheme, the STPIF generates corrective control actions based on the real torque trend only. This controller was tuned dynamically online during the control operation by adjusting its output SF by a gain updating factor " α ". The value of " α " is determined from a fuzzy rule base defined in function of the control error " e " and in the variations of the control error " Δe " as shown in the tables provided in the paper body and derived from the knowledge of the control process.

According to the torque error " e " and to the change of torque error " Δe ", the required load angle is provide by a STPIF. With this angle the stator flux reference is calculated and the stator voltage vector necessary for tracking the torque reference is synthesized.

The simulation results show that the proposed STPIF controller for the DTC-SVM three-phase IM outperforms the same scheme with conventional PI [5].

The paper is organized as follows. In section II the basic control principles of the three-phase induction motor DTC is presented. In section III the topology of the proposed control scheme is analyzed and in section IV the proposed STPIF is described in details mentioning different aspects of its design consideration.

Section V presents the simulations results of STPIF con-

troller performance in comparison with the conventional PI controller. Both controllers were applied to three-phase induction motor DTC-SVM scheme. Finally, conclusion is given in Section VI.

II. BASIC CONTROL PRINCIPLES

A. Dynamic Equations of the Three-Phase Induction Motor

By utilizing the definitions of the fluxes, currents and voltages space vectors, the dynamic equations of the three-phase IM in stationary reference frame can be put into the following mathematical form [14]:

$$\vec{u}_s = R_s \vec{i}_s + \frac{d\vec{\psi}_s}{dt} \quad (1)$$

$$0 = R_r \vec{i}_r + \frac{d\vec{\psi}_r}{dt} - j\omega_r \vec{\psi}_r \quad (2)$$

$$\vec{\psi}_s = L_s \vec{i}_s + L_m \vec{i}_r \quad (3)$$

$$\vec{\psi}_r = L_r \vec{i}_r + L_m \vec{i}_s \quad (4)$$

Where \vec{u}_s is the stator voltage space vector, \vec{i}_s and \vec{i}_r are the stator and rotor current space vectors, respectively, $\vec{\psi}_s$ and $\vec{\psi}_r$ are the stator and rotor flux space vectors, ω_r is the rotor angular speed, R_s and R_r are the stator and rotor resistances, L_s , L_r and L_m are the stator, rotor and mutual inductance, respectively.

The electromagnetic torque is expressed in terms of the cross product of the stator and the rotor flux space vectors.

$$t_e = \frac{3}{2} P \frac{L_m}{L_r L_s \sigma} \vec{\psi}_r \times \vec{\psi}_s \quad (5)$$

$$t_e = \frac{3}{2} P \frac{L_m}{L_r L_s \sigma} |\vec{\psi}_r| |\vec{\psi}_s| \sin(\gamma) \quad (6)$$

Where γ is the load angle between stator and rotor flux space vectors, P is the number of pole pairs of the motor and $\sigma = 1 - L_m^2/(L_s L_r)$ is the dispersion factor.

B. Three-phase Induction Motor Direct Torque Control

If the sample time is short enough, such that the stator voltage space vector is imposed to the motor keeping the stator flux constant at the reference value, the rotor flux can be considered constant because it changes slower than the stator flux. The electromagnetic torque (6) can be quickly changed by changing the angle γ in the desired direction. This angle γ can be easily changed when choosing the appropriate stator voltage space vector.

For simplicity, let us assume that the stator phase ohmic drop could be neglected in (1). Therefore $d\vec{\psi}_s/dt = \vec{u}_s$. During a short time Δt , when the voltage space vector is applied, it has:

$$\Delta \vec{\psi}_s \approx \vec{u}_s \cdot \Delta t \quad (7)$$

Thus the stator flux space vector moves by $\Delta \vec{\psi}_s$ in the direction of the stator voltage space vector at a speed which is proportional to the magnitude of the stator voltage space

vector. By selecting step-by-step the appropriate stator voltage vector, it is possible to change the stator flux in the required direction.

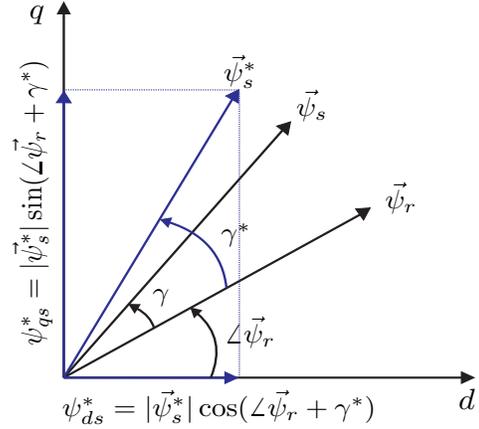


Fig. 1. Load angle γ^* between stator flux reference $\vec{\psi}_s^*$ and rotor flux $\vec{\psi}_r$ in stationary reference frame.

III. DIRECT TORQUE CONTROL WITH SPACE VECTOR MODULATION

Fuzzy logic control has been proved to be powerful and able to solve many IM control problems. In Fig. 2, we show the block diagram for the DTC-SVM scheme with STPIF controller based in [5]. The scheme [5] is an alternative to the classical DTC schemes [1], [2] and [3]. In this scheme, the load angle γ^* is not prefixed but it is determinate by the STPIF controller. Equation (6) shows that the angle γ^* determines the electromagnetic torque which is necessary to supply the load. The proposed STPIF determines this angle from the torque error "e" and the change of torque error " Δe ". Details about this controller is going to be presented in the next section.

In Fig. 3, it can be seen the scheme of the power electronics drive used in our simulation. The control signals for three-phase, two-level inverter is generated by the DTC-SVM block shown in Fig. 2.

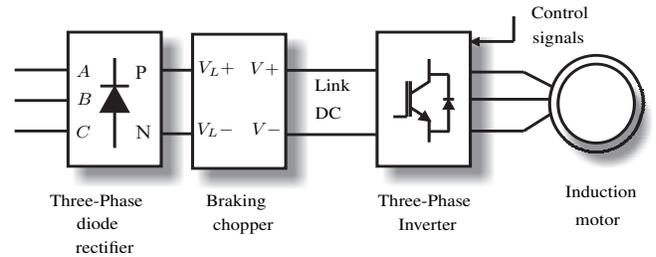


Fig. 3. Scheme of power electronics drive.

A. Flux Reference Calculator Block

As shown in Fig. 1, in stationary reference frame, the stator flux reference $\vec{\psi}_s^*$ can be decomposed in two perpendicular

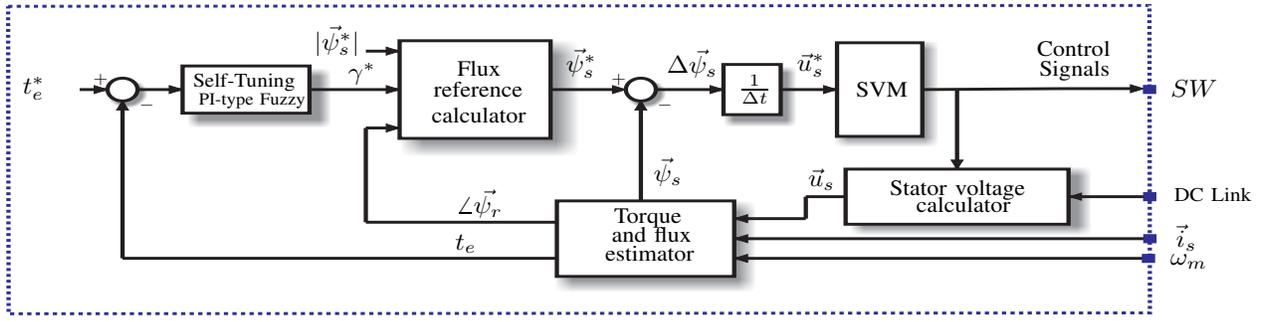


Fig. 2. Direct torque control with space vector modulation and self tuning PI-type fuzzy controller.

components ψ_{ds}^* and ψ_{qs}^* . The addition of the angle determinates " γ^* ", which is the output of the STPIF, to the estimated rotor flux angle " $\angle \vec{\psi}_r$ " permits to estimate the next value of the angle of the stator flux reference.

In this paper, the magnitude of stator flux reference is considered constant. We use the relation, presented in (8), to calculate the stator flux reference vector.

$$\vec{\psi}_s^* = |\vec{\psi}_s^*| \cos(\gamma^* + \angle \vec{\psi}_r) + j|\vec{\psi}_s^*| \sin(\gamma^* + \angle \vec{\psi}_r) \quad (8)$$

With the application of the stator voltage \vec{u}_s during a short time Δt it is possible to reproduce a flux variation $\Delta \vec{\psi}_s$. Notice that the stator flux variation is nearly proportional to the stator voltage space vector as seen in the equation (7).

B. Stator Voltage Calculator Block

The inputs for the stator voltage calculator block in Fig. 2 are the DC link voltage U_{dc} and the inverter switch state (S_a, S_b, S_c).

The stator voltage vector \vec{u}_s is determined as in [15] by:

$$\vec{u}_s = \frac{2}{3} \left[\left(S_a - \frac{S_b + S_c}{2} \right) + j \frac{\sqrt{3}}{2} (S_b - S_c) \right] U_{dc} \quad (9)$$

C. Torque and Flux Estimator Block

In Fig.2 the torque and the stator flux estimator block depends on the stator voltage and on the stator current space vectors, therefore:

$$\vec{\psi}_s = \int (\vec{u}_s - R_s \cdot \vec{i}_s) dt \quad (10)$$

On the other hand, the rotor flux depends on the estimated stator flux and stator current space vectors. From the equations (3) and (4) it can estimate the rotor flux space vector:

$$\vec{\psi}_r = \frac{L_r}{L_m} \vec{\psi}_s - \frac{L_s L_r}{L_m} \sigma \vec{i}_s \quad (11)$$

With the components of $\vec{\psi}_r$ we can obtain the angle of the rotor flux:

$$\angle \vec{\psi}_r = \tan^{-1} \left(\frac{\psi_{rq}}{\psi_{rd}} \right) \quad (12)$$

The fluxes given by the equations (10) and (11) substituted in (5) it is possible to estimate the motor electromagnetic torque.

IV. DESIGN OF SELF-TUNING PI-TYPE FUZZY CONTROLLER

The STPIF controller block which is depicted in Fig. 4 is composed by a PI-type fuzzy (PIF) and a gain tuning fuzzy (GTF) controllers, as well as two input scale factors " $G_e, G_{\Delta e}$ " and one output scale factor " G_{γ^*} ". Finally it has the saturation block to limit the output and create nonlinearity.

This controller has only a single input variable, which is the torque error " e " and one output variable which is the motor load angle " γ^* " given by:

$$\gamma^*(k) = \gamma^*(k+1) + \Delta \gamma^*(k) \quad (13)$$

In (13), k is the sampling time and $\Delta \gamma^*(k)$ represents the incremental change of the controller output. It is emphasized here that this accumulation (13) of the controller output takes place out of the fuzzy part of the controller and it does not influences the fuzzy rules.

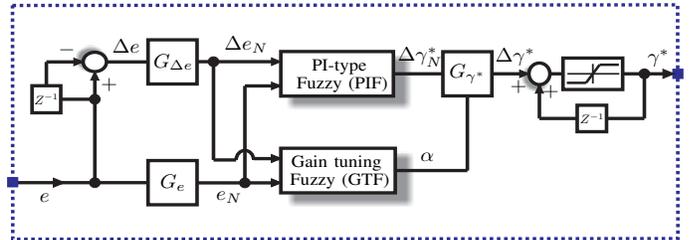


Fig. 4. Self-tuning PI-type fuzzy (STPIF) controller.

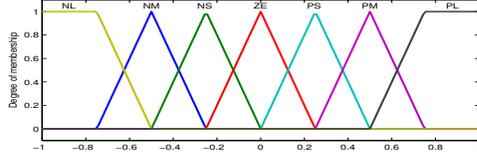
A. Membership Functions (MF)

The MF for PIF controller are shown in Fig. 5(a). This MF for input variables " $e_N, \Delta e_N$ " and output variable " $\Delta \gamma_N^*$ " are normalized in the closed interval $[-1,1]$.

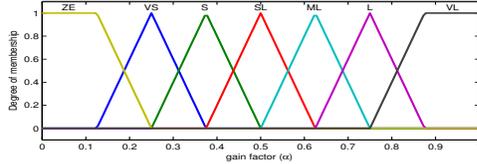
The MF for GTF controller are shown in Fig. 5(a) and in Fig. 5(b) for input and output variables respectively. This MF for input variables " $e_N, \Delta e_N$ " are defined in the closed

interval $[-1,1]$ and for output variable " α " are defined in the closed interval $[0,1]$.

All MF have triangular form [Fig. 5] with 50% overlapping neighbor functions, except the extremes which are trapezoidal. The linguistic variables are referred to as: NL-Negative Large, NM-Negative Medium, NS-Negative Small, ZE-Zero, VS-Very Small, S-Small, SL-Small Large and so on as shown in Tab. I and in Tab. II.



(a) Membership function for e_N , Δe_N and $\Delta\gamma_N^*$.



(b) Membership function for α for GTF controller output

Fig. 5. Membership functions for: (a) error e_N and change of error Δe_N is the same for PIF and GTF controllers as well as for the output $\Delta\gamma_N^*$ of the PIF controller. (b) the gain updating factor α

B. Scaling Factors

In this paper it is adopted fixed values for the two inputs SF " $G_{\Delta e}$, G_e " and the output SF " G_{γ^*} " can be adjusted dynamically through updating the scaling factor " α ". " α " is computed online by using a model independent fuzzy rules defined in terms of " e , Δe ". The relationship between the SF and the input/output variables of the STPIF controller are shown below:

$$e_N = G_e \cdot e \quad (14)$$

$$\Delta e_N = G_{\Delta e} \cdot \Delta e \quad (15)$$

$$\Delta\gamma^* = (\alpha \cdot G_{\gamma^*}) \cdot \Delta\gamma_N^* \quad (16)$$

C. The Rule Bases

The incremental change in the controller output $\Delta\gamma_N^*$ for the PIF controller is determined by the rules of the form:

$$R_x : \text{if } e_N \text{ is } E \text{ and } \Delta e_N \text{ is } \Delta E \text{ then } \Delta\gamma_N^* \text{ is } \Delta\Gamma_N^* \quad (17)$$

Where $E = \Delta E = \Delta\Gamma_N^* = \{NL, NM, NS, ZE, PS, PM, PL\}$. The output α for the GTF controller is determined by the rules of the form:

$$R_x : \text{if } e_N \text{ is } E \text{ and } \Delta e_N \text{ is } \Delta E \text{ then } \alpha \text{ is } \chi \quad (18)$$

Where $E = \Delta E = \{NL, NM, NS, ZE, PS, PM, PL\}$ and $\chi = \{ZE, VS, S, SL, ML, L, VL\}$. The rule bases to calculate $\Delta\gamma_N^*$ and α are shown in Tab. I and in Tab. II respectively.

TABLE I
FUZZY RULES FOR COMPUTATION OF $\Delta\gamma_N^*$

$\Delta e_N / e_N$	NL	NM	NS	ZE	PS	PM	PL
NL	NL	NL	NL	NM	NS	NS	ZE
NM	NL	NM	NM	NM	NS	ZE	PS
NS	NL	NM	NS	NS	ZE	PS	PM
ZE	NL	NM	NS	ZE	PS	PM	PL
PS	NM	NS	ZE	PS	PS	PM	PL
PM	NS	ZE	PS	PM	PM	PM	PL
PL	ZE	PS	PS	PM	PL	PL	PL

TABLE II
FUZZY RULES FOR COMPUTATION OF α

$\Delta e_N / e_N$	NL	NM	NS	ZE	PS	PM	PL
NL	VL	VL	VL	L	SL	S	ZE
NM	VL	VL	L	L	ML	S	VS
NS	VL	ML	L	VL	VS	S	VS
ZE	S	SL	ML	ZE	ML	SL	S
PS	VS	S	VS	VL	L	ML	VL
PM	VS	S	ML	L	L	VL	VL
PL	ZE	S	SL	L	VL	VL	VL

D. Gain Tuning Fuzzy

The target of the GTF controller is online continuous update the value of α in every sample time. This α value is necessary to control the percentage of the output SF " G_{γ^*} " to calculate the new " $\Delta\gamma^*$ " with the equation (16).

The GTF controller rule base is based on the knowledge about the three-phase IM control, using a DTC type control according to the scheme proposed in [5], in order to avoid large overshoot and undershoot, e.g., when e and Δe have different signs, it means that the torque estimate t_e is approaching to the torque reference t_e^* , the output SF G_{γ^*} must be reduced to a small value by α , for instance, if e is PM and Δe is NM then α is S .

On the other hand, when e and Δe have the same sign, it means that the torque estimate t_e is moving away from the torque reference t_e^* , the output SF G_{γ^*} must be increased to a large value by α in order to avoid that the torque departs from the torque reference, e.g., if e is PM and Δe is PM then α is VL .

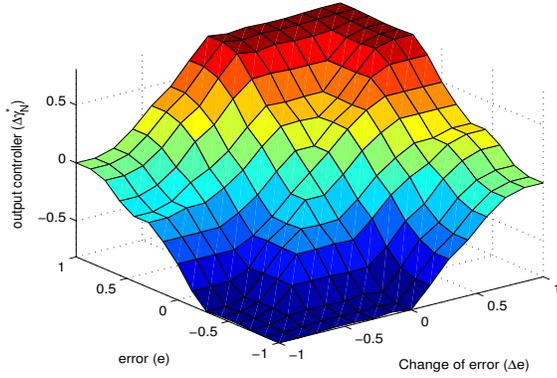
The nonlinear relationship between " e , Δe , $\Delta\gamma_N^*$ " and " e , Δe , α " are shown in Fig. 6.

The inference method used in this paper is the Mandani's implication based on max-min aggregation. Center of area method is used for defuzzification.

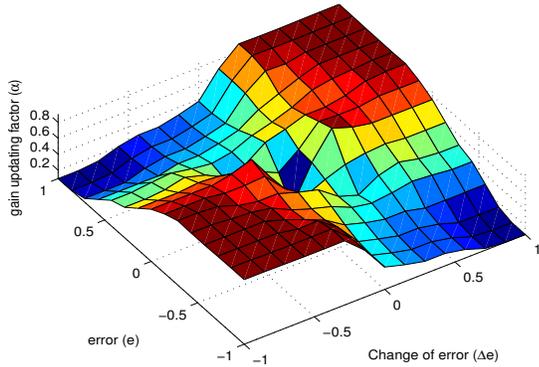
V. SIMULATION RESULTS

The simulations were performed using MATLAB Simulink/SimPowerSystem simulation package which include fuzzy logic toolbox. The switching frequency of PWM inverter is $10kHz$. Motor parameter's are given in Table III and the stator flux reference considered is 0.47 Wb which is the rated stator flux.

In order to investigate the effectiveness of the proposed control system and in order to check the closed-loop stability of the complete system, it was performed several tests.



(a) Surface of PIF controller output ($\Delta\gamma_N^*$).



(b) Surface of GTF controller output (α).

Fig. 6. Surface of: (a) PIF controller output and (b) GTF controller output

It was used different dynamic operating conditions such as step change in the motor load (from 0 to 1.0 pu) at 90 percent of rated speed, no load sudden change in the speed reference (from 0.5 pu to -0.5 pu) and the application of a specific load torque profile at 90 percent of rated speed.

The Fig. 7 and Fig. 8 show similar behaviors of the torque, current and the motor speed when it is imposed a speed reference step change from 0.5 pu to -0.5 pu in the DTC-SVM scheme with STPIF and PI controllers respectively. The sinusoidal shape of the current shows that this control technique leads also to a good current control in other words this means that the current control is inherent to the algorithm control presented in this paper.

Fig. 9 presents the results when the same torque profile is imposed to DTC-SVM scheme with STPIF and PI controllers. In both cases the controllers follow the torque reference.

Fig. 10 illustrates that the DTC-SVM scheme with PI controller and the proposed scheme have similar dynamic response to step change in the motor load. In Tab. IV it can be seen that the rise time t_r , the settling time t_s and the integral of time multiplied by the absolute magnitude of the error

index (ITAE) were relatively smaller in the proposed scheme when compared to the scheme with PI, very well adjusted, controller. It could be seen that the DTC-SVM scheme with STPIF controller is faster than the DTC-SVM scheme with PI.

This results show the good performance of the proposed scheme shown in Fig. 2.

VI. CONCLUSION

In this paper it was presented the DTC-SVM scheme to control a three-phase IM proposed by [5] using a STPIF controller. This scheme was used in order to determinate dynamically and online the load angle between stator and rotor flux space vectors. This load angle and the rotor flux estimated angle determine the stator flux reference and in consequence it was synthesized the stator voltage space vector necessary to track the torque reference.

Simulations at different operating conditions have been carried out. The simulation results verify that the proposed DTC-SVM scheme with STPIF controller achieves a fast torque response and low torque ripple, in comparison to the DTC-SVM scheme with PI, in a wide range of condition variations such as sudden change in the command speed, reverse operation and step change of the load.

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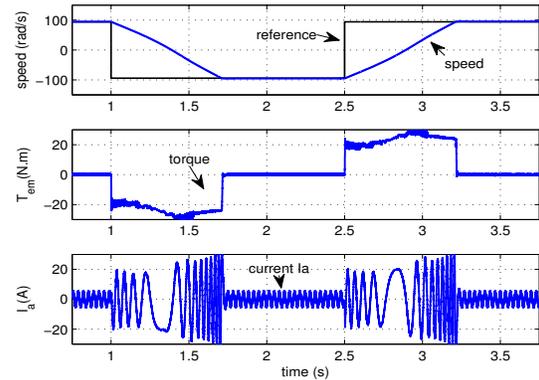


Fig. 7. Step change to speed for DTC-SVM with STPIF

TABLE III
INDUCTION MOTOR PARAMETER [16]

Rated voltage (V)	220/60Hz
Rated Power (W)	2238
Rated Torque (Nm)	11.9
Rated Speed (rad/s)	179
R_s, R_r (Ω)	0.435, 0.816
L_{ls}, L_{lr} (H)	0.002, 0.002
L_m (H)	0.0693
J (Kgm^2)	0.089
P	2

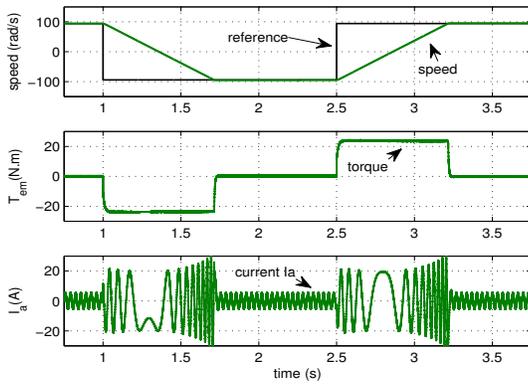


Fig. 8. Step change to speed for DTC-SVM with PI

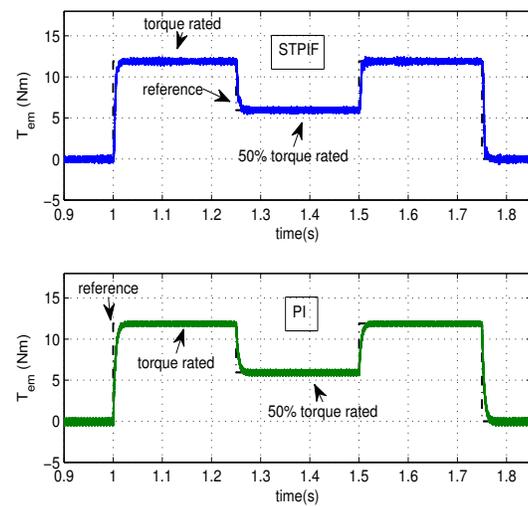


Fig. 9. Torque profile for DTC-SVM with STPIF and PI

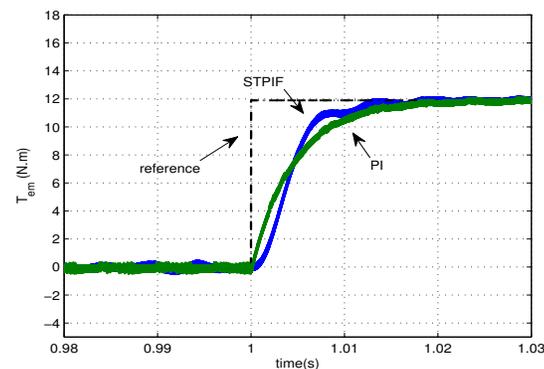


Fig. 10. Step change in torque for DTC-SVM scheme with STPIF and PI

TABLE IV
PERFORMANCE MEASURES

	t_r (s)	t_s (s)	ITAE
DTC-SVM PI	0.00953	1.016	212.8
DTC-SVM STPIF	0.00549	1.012	199.5

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