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DISCRETE-TIME PI CONTROLLER BASED SPEED CONTROL OF DTC INTERIOR PERMANENT MAGNET SHYNCHRONOUS MOTOR

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ABSTRACT

Recently, interior permanent magnet synchronous motors (IPMSMs) are becoming more used due to the powerful magnetic characteristic of the rare earth, being used in different areas. Several researchers have proposed implementations combining the use of IPMSM with the direct torque control (DTC) technique offering a quick and precise control. However, DTC can provide only for torque and flux control, the speed controller is also needed to design for high performance of ac motor. The design of the speed controller greatly affects the performance of an electric motor. A common strategy to control an IPMSM is to use direct torque control combined with a PI speed controller. These schemes are not capable to fulfill the requirements of high performance because elimination of steady-state error and overshoot problems and the rejection of load disturbance cannot be achieved simultaneously. This paper proposed a discrete-Time PI (DTPI) controller to control the speed of DTC IPMSM to replace conventional PI controllers to improve the IPMSM performance. In order to obtain the stable performance of speed of IPMSM, the gains of designed DTPI controller are chosen by choosing the proper value of poles. Moreover, the chosen gains of DTPI controller confirm that the steady state error and the overshoot problems can be minimized and the controller becomes robust against the disturbance of load torque. The effectiveness of our propose DTIP controller to control speed of IPMSM incorporated with DTC method is verified by Matlab/Simulink software. It is seen from simulation works that the performance of DTPI controller is better as compared with the conventional proportional integral (PI) controller.

Key words: Direct Torque Control, Speed Control, PI Controller, Discrete-Time PI Controller, Interior Permanent Magnet Synchronous Motor.

I. INTRODUCTION

Interior Permanent Magnet Synchronous Motors (IPMSMs) have been used widely in the industry [1] to replace DC motors and induction machines. The main characteristics of these motors are low inertia, high torque to current ratio as well as high power to weight ratio, high efficiency, low noise, wider speed range, compact construction and robust operation [2]. Due these advantages, permanent magnet synchronous motors are ideal for the applications where a quick accurate torque control is required.

For different industrial applications which require high dynamic performance, field oriented control (FOC) is often employed in ac drives [2]-[4]. Recently, another high-performance control technique, named direct torque control (DTC) has also been investigated in ac drives [5]-[10]. The operating principles of these control strategies are different but their objectives are the same. The aim of both controllers is to control effectively the motor torque and flux in order to force the motor to accurately track the command trajectory regardless of the machine and load parameter variation or any extraneous disturbances. Both control strategies have been successfully implemented in industrial products [11]. The advantages of DTC over FOC are faster torque and flux regulation, elimination of current regulators and PWM generators, robustness to rotor parameters variation, no required the coordinate transformation and continuous rotor position information since all calculations are implemented in stationary reference frame and the structure of DTC is simple [12, 13].

A common strategy to control an IPMSM is to use direct torque control combined with a proportional-plus-integral (PI) speed controller to achieve high performance in industrial applications [14]. The conventional PI controllers are widely used in industrial control systems applications. They have a simple structure and can offer a satisfactory performance over a wide range of operation. In order to obtain the better performance from a PI controller, a lot of strategies have been proposed to tune the PI controller parameters. The most famous method, which is frequently used in industrial applications, is the Ziegler–Nichols method. Fixed gain PI controllers for speed control have been used in industry for a long time because of simplicity, satisfactory steady state performance and easier real-time implementation. However, conventional controllers such as PI, PID are not suitable for high performance variable speed drive because of their sensitivity to plant parameter variations, load disturbance and any other kinds of disturbances like temperature change, command speed change, etc. [15, 16]. Moreover, the overshoot and steady state error problem cannot be minimized using one fixed set of gains. These inherent disadvantages of the PI controller have encouraged the replacement of the conventional PI controller.

As replacement of a conventional PI controller the following controllers are used: fuzzy logic controller (FLC) [15], self-tuning PI controllers [16], sliding mode control (SMC) [17], fuzzy neural network [18], model reference adaptive control (MRAC) [19], and genetic algorithms (GA) [20]. All of these control techniques however increase the complexity of the ac drive systems due to the controller design complexity. Moreover, the design of intelligent control (such as fuzzy logic, artificial neural network) in ac drives is time consuming task since its performance depends on the expert knowledge and its need to tune a number of parameters.

In this paper we proposed a discrete-time PI (DTPI) controller [21] to control the speed of IPMSM incorporated with DTC to overcome the problems of a conventional PI controller. The design and implementation of DTPI controller, which can be implemented most recent digital technique, is very simple like of those of PI controller. The designed DTIP controller is able to overcome the steady state error and overshoot problems and to reject the disturbance. The poles are selected to locate the eigenvalues of the transfer functions inside the unit circle of *z*-plane.

The effectiveness of our proposed DTPI controller to control speed of IPMSM incorporated with DTC method is verified by simulation results, which were carried out by Matlab/Simulink software. It is seen from simulation works that the performance of DTPI controller is better as compared with the conventional PI controller.

II. DYNAMIC MODEL OF IPMSM

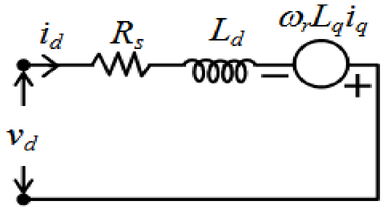
The dynamic model of IPMSM are a set of equations depending on rotor position. By representing the motor equations in rotor reference frame, there is a set of equations independent of rotor position. The *d* and *q* axis currents will be obtained from two transformations. The first part transfers the three phases (*a*, *b*, *c*) to two phases (α, β). The second part is the quantities at stationary frame to rotational frame [22]:

$$\begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} \tag{1}$$

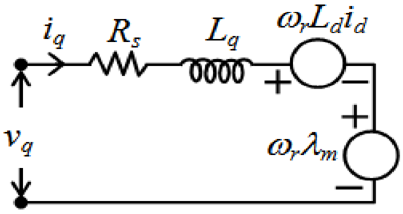
$$\begin{bmatrix} i_d \\ i_q \end{bmatrix} = \begin{bmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{bmatrix} \begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} \tag{2}$$

where, θ represents the rotor position, i_α and i_β are the stator currents at stationary reference frame, and i_d and i_q are the stator currents at synchronously rotating reference frame.

Fig. 1 shows the equivalent circuit of an IPMSM in a synchronously rotating reference frame. Electromechanical behavior of the IPMSM in the



(a) *d*-axis equivalent circuit



(b) *q*-axis equivalent circuit

Fig. 1 Equivalent circuit of IPMSM.

synchronously rotating reference frame is as follows [7]:

$$v_d = R_s i_d + p\lambda_d - \omega_r \lambda_q \tag{3}$$

$$v_q = R_s i_q + p\lambda_q + \omega_r \lambda_d \tag{4}$$

$$\lambda_d = L_d i_d + \lambda_m \tag{5}$$

$$\lambda_q = L_q i_q \tag{6}$$

$$T_e = P_n[\lambda_d i_q - \lambda_q i_d] \tag{7}$$

$$J_m p\omega_r = -B_m \omega_r + P_n(T_e - T_L) \tag{8}$$

where, v_d and v_q are the *d*-axis and *q*-axis components of terminal voltage, i_d and i_q are the *d*-axis and *q*-axis components of armature current, λ_d and λ_q are the *d*-axis and *q*-axis components of flux, L_d and L_q are the *d*-axis and *q*-axis components of armature self-inductance, R_s is the armature resistance, $p = d/dt$, P_n is the number of pole pairs, T_e is the electromagnetic torque, T_L is the load torque, B_m is friction coefficient, J_m is the inertia and λ_m is the rotor magnetic flux linkage.

The stator flux linkage and the torque can be estimated in the stationary (α-β) frame. The equations are as follows [21]:

$$\lambda_\alpha = \int (v_\alpha - R_s i_\alpha)dt \tag{9}$$

$$\lambda_\beta = \int (v_\beta - R_s i_\beta)dt \tag{10}$$

$$T_e = P_n[\lambda_\alpha i_\beta - \lambda_\beta i_\alpha] \tag{11}$$

The absolute value and the phase angle of stator flux are given by the following equation.

$$|\lambda_s| = \sqrt{\lambda_\alpha^2 + \lambda_\beta^2} \tag{12}$$

$$\theta = \tan^{-1}(\lambda_\beta / \lambda_\alpha) \tag{13}$$

The estimated flux and torque by means of using Eqs. (9) ~ (13) are used to calculate the difference between the desired quantities and actual quantities to apply in DTC.

III. DIRECT TORQUE CONTROL

Fig. 2 shows the block diagram of the direct torque control system with the discrete-time PI controller based speed controller. In DTC control strategy includes two major loops: the torque control loop and the flux-control loop. It can be seen from Fig. 1

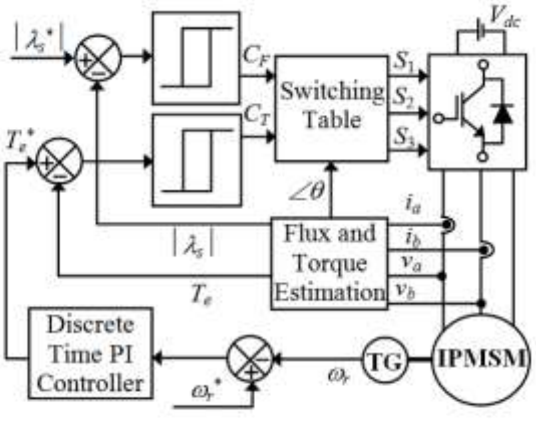


Fig. 2 Block diagram of direct torque control with discrete-time PI based speed controller.

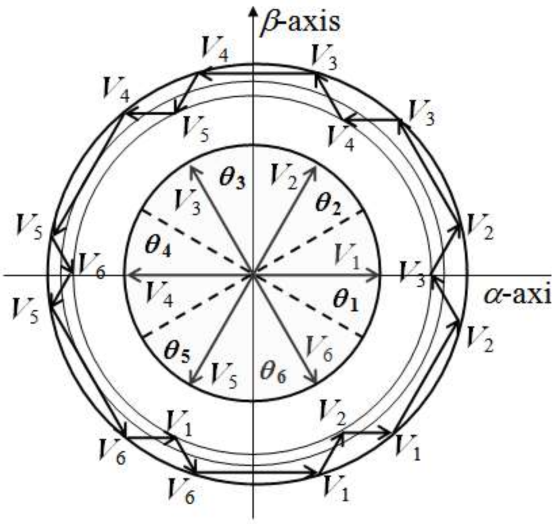


Fig. 3 Voltage Vectors for direct torque control.

that the flux and torque are directly controlled individually. The current-control loop, which is necessary for FOC, is not required here. Thus, the DTC departs from the vector control in which the coordinate transformation is crucially needed. The DTC control method relies on a bang-bang control instead of a decoupling control which is the characteristic of vector control. Their technique (bang-bang control) works very well with the on-off operation of inverter semiconductor power devices.

In Fig. 2, the estimating torque and flux can be obtained by measuring the *a*-phase and the *b*-phase voltages and currents. The torque error and flux error are calculated by using the reference value and estimated value of them. The basic principle of the direct torque control is to bind the torque error and the flux error in hysteresis bands by properly choosing the switching states of the inverter. To achieve this goal, the plan of the voltage vector is divided into six operating sectors as shown in Fig. 3, and a suitable switching state is associated to each sector. As a result, when the voltage vector rotates, the switching state can be automatically changed. For practical implementation, the switching procedure is determined by a state selector based on pre-calculated look up tables.

The look up table works based on the output of the hysteresis comparators. The output of the torque hysteresis comparator is denoted as C_T, the output of the flux hysteresis comparator as C_F and the flux linkage sector is denoted as θ. The torque hysteresis comparator is a three valued comparator. $C_T = -1$ means that the actual value of the torque is above the reference and out of the hysteresis limit, and $C_T = 1$ means that the actual value is below the reference and out of the hysteresis limit. $C_T = -1$ means that the difference between actual and reference values of the torque and inside the hysteresis limit. The flux hysteresis comparator is a two valued comparator. $C_F = 0$ means that the actual value of the flux linkage is above the reference and out of the hysteresis limit and $C_F = 1$ means that the actual value of the flux linkage is below the reference and out of the hysteresis limit [18]. All the possibilities can be tabulated into a switching table as shown in **Table 1** [6].

IV. DISCRETE-TIME PI SPEED CONTROLLER DESIGN

To perform the DTC strategies with the speed control of IPMSM, the reference torque is generated by the speed controller as shown in Fig.2. Using Eq. (8) the dynamics equation of speed yield:

$$p\omega_r = -A_\omega \omega_r + B_\omega T_e - D_\omega T_L \tag{14}$$

where, $A_\omega = B_m / J_m$, $B_\omega = P_n / J_m$, $D_\omega = P_n / J_m$

The state equations of Eq. (14) can be written as follows:

$$px(t) = -A_\omega x(t) + B_\omega u(t) - D_\omega d(t) \tag{15}$$

where, $x(t) = \omega_r$, $u(t) = T_e$, $d(t) = T_L$

Using the Euler approximation, the discrete time form of Eq. (33) can be written as follows:

$$x(k+1) = A_k x(k) + B_k u(k) + D_k d(k) \tag{16}$$

where, $A_k = 1 - A_\omega T_s$, $B_k = B_\omega T_s$, $D_k = D_\omega T_s$, T_s is sampling time.

Table 1: Vector selection of DTC

θ, C_T, C_F		θ6	θ6	θ6	θ6	θ6	θ6
C_T =1	C_T =1	$\boldsymbol{V}_2$	$\boldsymbol{V}_3$	$\boldsymbol{V}_4$	$\boldsymbol{V}_5$	$\boldsymbol{V}_6$	$\boldsymbol{V}_1$
	C_T =0	$\boldsymbol{V}_7$	$\boldsymbol{V}_0$	$\boldsymbol{V}_7$	$\boldsymbol{V}_0$	$\boldsymbol{V}_7$	$\boldsymbol{V}_0$
	C_T =-1	$\boldsymbol{V}_6$	$\boldsymbol{V}_1$	$\boldsymbol{V}_2$	$\boldsymbol{V}_3$	$\boldsymbol{V}_4$	$\boldsymbol{V}_5$
C_F =0	C_T =1	$\boldsymbol{V}_3$	$\boldsymbol{V}_4$	$\boldsymbol{V}_5$	$\boldsymbol{V}_6$	$\boldsymbol{V}_1$	$\boldsymbol{V}_2$
	C_T =0	$\boldsymbol{V}_0$	$\boldsymbol{V}_7$	$\boldsymbol{V}_0$	$\boldsymbol{V}_7$	$\boldsymbol{V}_0$	$\boldsymbol{V}_7$
	C_T =-1	$\boldsymbol{V}_5$	$\boldsymbol{V}_6$	$\boldsymbol{V}_1$	$\boldsymbol{V}_2$	$\boldsymbol{V}_3$	$\boldsymbol{V}_4$

The error between reference values $r(k) = \omega_r^*(k)$ and actual values $x(k)$ can be written as:

$$e(k) = r(k) - x(k) \tag{17}$$

Considering the reference signal and the disturbance are step function, an augmented state space dynamics, that includes the error $\boldsymbol{e}(k)$, the incremental state vector $\Delta\boldsymbol{x}(k)$ and the incremental input $\Delta\boldsymbol{u}(k)$, can be expressed as

$$\boldsymbol{X}(k+1) = \boldsymbol{L}\boldsymbol{X}(k) + \boldsymbol{M}\Delta u(k) \tag{18}$$

where,

$$\boldsymbol{X}(k) = \begin{bmatrix} e(k) \\ \Delta x(k) \end{bmatrix}, \quad \boldsymbol{L} = \begin{bmatrix} 1 & -A_k \\ 0 & A_k \end{bmatrix}, \quad \boldsymbol{M} = \begin{bmatrix} -B_k \\ B_k \end{bmatrix}$$

The first difference of input voltage is obtained as follows

$$\Delta u(k) = \boldsymbol{KX}(k) \tag{19}$$

where, $\boldsymbol{K} = [K_e \quad K_x]$

To realize the control system by the simple block diagram, the Eq. (37) can be decomposed as follows:

$$u(k) = K_e \sum_{i=0}^{k} e(i) + K_x x(k) - K_x x(0) + u(0) \tag{20}$$

The first term represents the integral controller, the second term represents the proportional controller, and the third and fourth terms represent the initial values. The integral term helps to minimize the steady state error. The control system will be stable under the variation of disturbance $d(t)$ if the controller gains are chosen by placing the poles inside the unit circle of z-plane. The block diagram of the speed control based DTPI controller is drawn according to Eq. (19) as shown in **Fig. 4**.

V. SIMULATION RESULTS AND ANALYSIS

In order to verify the performance of proposed DTPI controller based speed control of IPMSM incorporated with DTC, computer simulations were performed using Matlab/Simulink. In the simulation studies different operating conditions are observed for DTC and the speed controller strategies. The simulation has done like the overall block diagram is shown in **Fig. 2**. The structure of DTPI controller of Fig. 4 is used in the block of discrete-time PI controller of Fig. 2. The rating and the parameters values of used IPMSM in the simulation are given in **Table 2**. The sampling time and dc voltage of inverter for this simulation is considered 50 μsec, and 350 V, respectively.

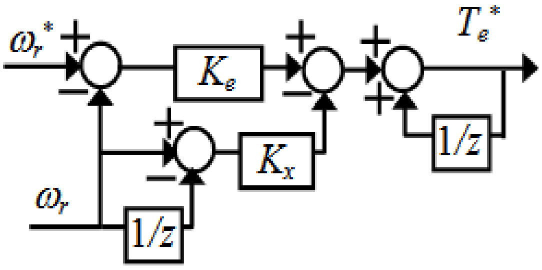
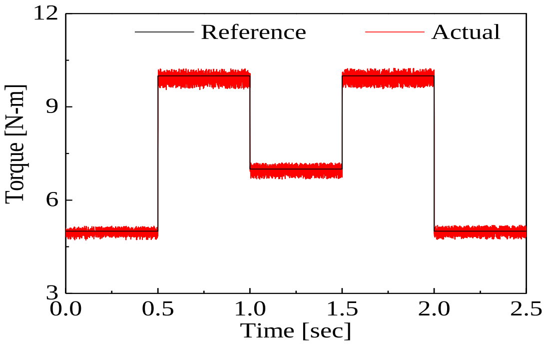


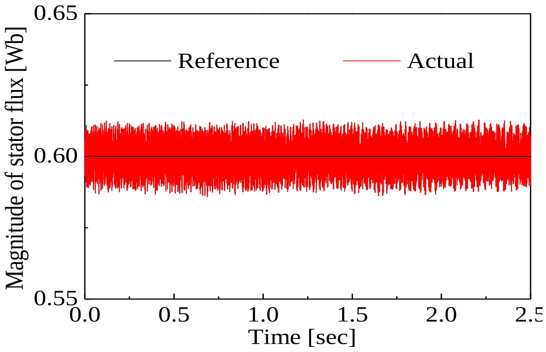
Fig. 4 Structure of discrete-time PI.

Table 2: Ratings and Parameters of IPMSM

Stator resistance, R_s	5.8 Ω
d-axis self inductance, L_d	44.8 mH
q-axis self inductance, L_q	102.7 mH
Rotor flux constant, λ_s	0.533 Wb
Moment of Inertia, J_m	0.00529 kg-m^2
Damping coefficient, B_m	0.00006 kg-m^2/s
Number of pole pairs, P_n	2
Mechanical torque, T_m	10 Nm



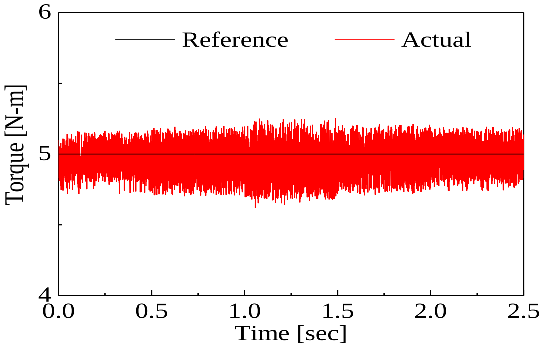
(a) Torque



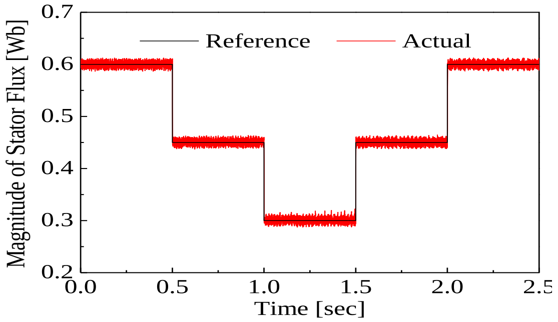
(b) Magnitude of stator flux

Fig. 5 Performance of DTC of IPMSM due to the step change of torque.

At first the results are observed for the DTC to control the torque and flux. Fig. 5 shows the transient responses of torque and flux for the step change of reference torque while the reference value of magnitude of stator flux is kept constant at 0.6 Wb. The reference torque is step-changed among 5 N-m, 10 N-m and 7 N-m. It is observed from Fig. 5(a) the actual torque follows the reference torque quickly using the DTC strategy by using the switching Table 1. The actual magnitude of flux can also follow the reference of magnitude of stator flux as shown if Fig. 5(b).



(a) Torque



(b) Magnitude of stator flux

Fig. 6 Performance of DTC of IPMSM due to the step change of magnitude of stator flux.

The results obtained by conventional DTC for the step change of magnitude of stator flux are represented in **Fig. 6**. The reference of magnitude of stator flux is stepped-changed among 0.6 Wb, 0.45 Wb and 0.3 Wb. It is observed from Fig. 6(b) the actual magnitude of flux follows the reference of magnitude of flux quickly. The actual torque can also follow the reference of torque as shown in Fig. 6(a). From Figs. 5 and 6 it is clear that the torque and magnitude of stator flux can be control with the DTC strategy.

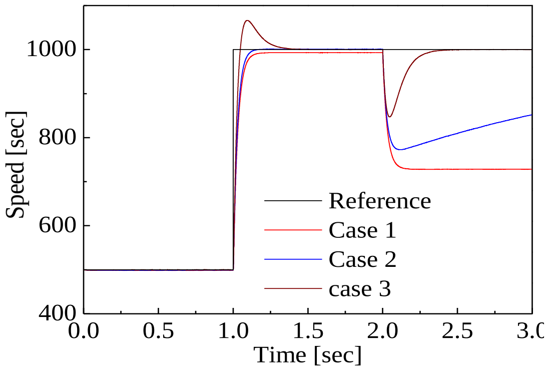
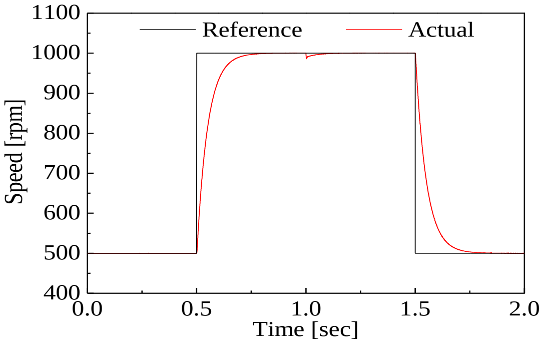
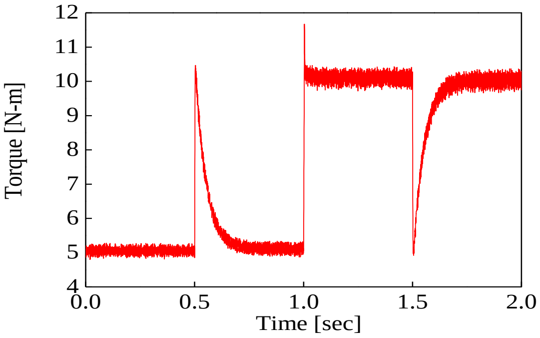


Fig. 7 Transient response of speed control based on PI controller with DTC.

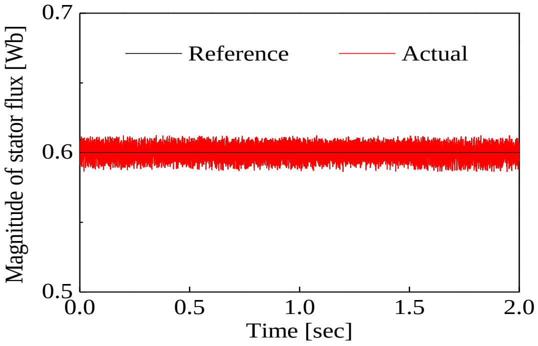
In order to control of speed of IPMSM with DTC, in this paper we design a DTPI controller. From the DTPI controller, the reference torque, which is used a reference torque of DTC, is obtained. Moreover, the simulation has done using the PI controller for different gains of its to clarify the problems of a conventional PI controller. **Fig. 7** shows the transient response of IPMSM due to the step change of speed and load torque based on the PI controller. In this work, three different cases of



(a) Speed



(b) Torque

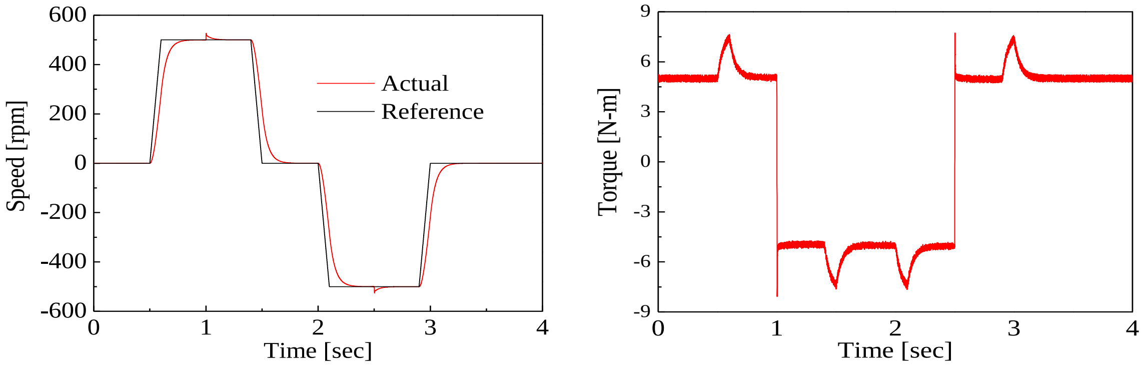


(c) Magnitude of stator flux

Fig. 8 Transient response of speed control based on DTPI with DTC gains of PI controller are considered. The gains, which are used this simulation, are as follows: (i) *Case 1*: K_P=0.09; K_I=1.0e-06, (ii) *Case 2*: K_P=0.1; K_I=5.0e-02, and (iii) *Case 3*: K_P=0.12; K_I=1.17.

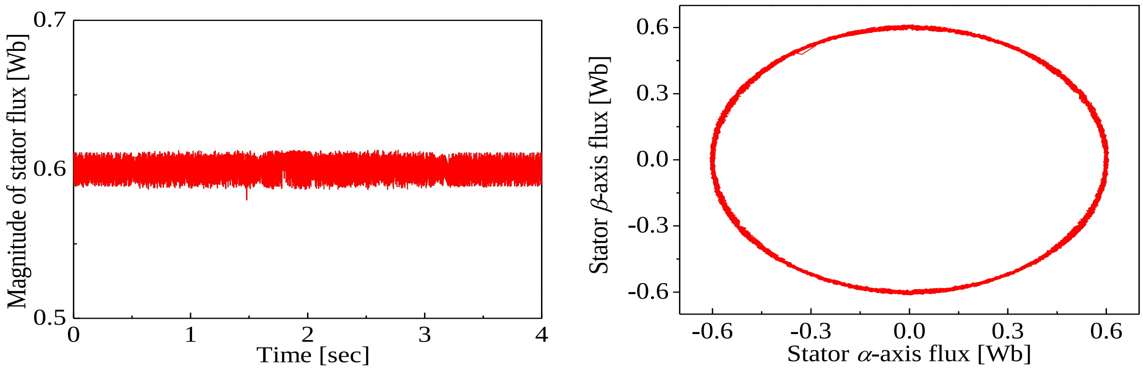
It is observed from Fig. 7 that the steady-state error problem, the overshoot problem, and the stable performance under the variation of load disturbance cannot be eliminated by using a one fixed set of gains of a PI controller.

The effectiveness of the designed of DTPI controller is also verified by simulation results. **Fig. 8** shows the responses of speed, torque and flux for the step change of speed and the load torque. The reference speed stepped-up from 500 rpm to 1000 rpm at t=0.5 sec and again stepped-down from 1000 rpm to 500 rpm at t=1.5 sec. At t = 1.0 sec the load torque is changed from 5 N-m to 10 N-m. In this simulation, the gains are chosen as follows: K_e = 2.3327×10^{-4} and K_x = -0.2351. Using these gains the poles are obtained as [0.9985, 0.9970] which are inside the unit-circle of z-plane.



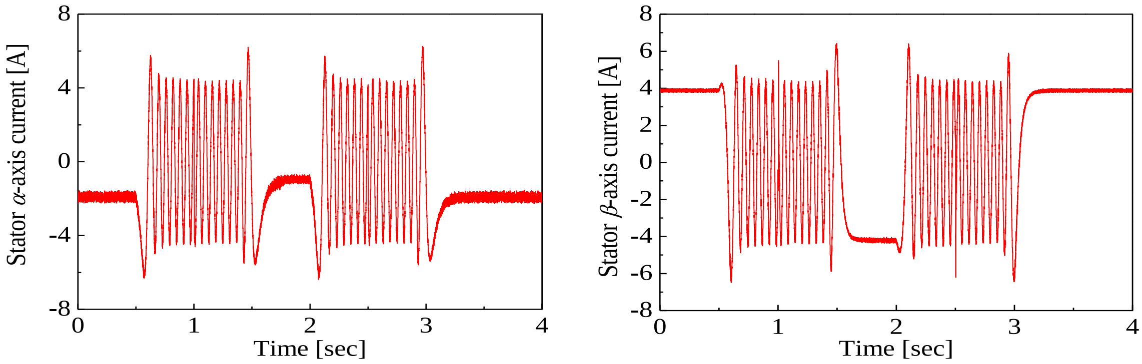
(a) Speed

(b) Torque



(c) Magnitude of stator flux

(d) Stator α-β axes fluxes



(e) Stator α axis current

(f) Stator β axes current

Fig. 9 Transient response of four quadrant operation of speed and torque based on the DTPI controller.

The response of speed is obtained without steady-state error and overshoot problems as shown in Fig. 8 (a). T Since the poles are inside the unit-circle of *z*-plane, the designed DTPI is stable under the variations of load torque which is confirmed from Fig. 8(b). The actual flux can follow the reference flux as shown in Fig. 8(c) even the change of speed and load torque. The compensation of change of load torque is possible by electromagnetic torque is shown in Fig. 8(b).

The effectiveness of proposed DTPI is also verified for the four quadrant operation of IPMSM with DTC. **Fig. 9** shows the responses for the four quadrant operation of speed and torque. It is seen from Figs. 9(a) and 9(a) as follows: (i) *Forward motoring*: during time 0 to 1 sec the speed and the torque both are positive, (ii) *Forward regenerating*: during time 1 to 1.5 sec the speed is positive and the torque is negative, (iii) *Reverse motoring*: during time 2 to 2.5 sec the speed and the torque are both negative, and (iv) *Reverse regenerating:* during time 2.5 to 3 sec the speed is negative and the torque is positive. So the actual flux can follow the reference flux as shown in Fig. 9(c) even the change of speed and load torque. The stator flux is always kept constant in its rated value as shown in Fig. 9(d).

Fig. 9(e) and 9(f) shows the α-axis and β-axis stator current of IPMSM. It is seen from the current response, the magnitude of current will not be changed due to change of speed but the frequency is changed to reach to the desired value. The magnitude of stator current is increased as increases the load torque. From the observation of simulation results it is cleared the performance of DTPI controller is better as compared with those of PI controller.

VI. CONCLUSION

This paper has presented a DTPI controller to control the speed of IPMSM incorporated with DTC to achieve the high performance response of speed. According to the requirements of high performance the speed response by using the designed DTPI controller is obtained without steady-state error and overshoot problems of conventional PI controller. The gains of DTPI controller has chosen based on the pole-placement technique, thus the designed DTPI controller is capable to show the stable performance under the variations of load disturbance torque. The high performance of the DTPI speed controller has been verified using Matlab/Simulink software. The presented shows the excellent performance for the step change of speed, step change of load torque and the four quadrant operation of IPMSM. With the help of simulation results, it has cleared the performances of DTPI controller is better than those of conventional PI controller. The simulation results confirmed that the proposed DTPI controller to control the speed of IPMSM with DTC is suitable to fulfill the requirements of high performance.

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