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FPGA based direct torque control with speed loop Pseudo derivative controller for PMSM drive

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Abstract
This paper presents a comprehensive evaluation of proposed speed loop pseudo derivative feedback (PDF) controller based DTC with speed loop PI based direct torque controller (DTC) for permanent magnet synchronous motor (PMSM) drive. The proposed PDF-DTC system significantly improves dynamic response i.e. completely eliminates overshoot in speed, reduces 50% overshoot in electromagnetic torque and has two times faster settling time compared to PI-DTC system during step changes in speed with load disturbance. The proposed controller is verified for different cases viz., speed variation at constant load and variation in the load torque at constant speed. The proposed controller is implemented for 1.5 kW laboratory prototype PMSM drive using FPGA ALTERA cyclone II. Experimental results demonstrates the efficacy of the proposed controller.

Keywords Permanent magnet synchronous motor · Speed control · Pseudo derivative feedback · Direct torque control

Nomenclature

v_{ds}, v_{qs}	*d-q* axes stator voltage component
i_{ds}, i_{qs}	*d-q* axes stator current component
R_s	Stator resistance
L_s	Stator inductance
ψ_m	PM flux linkage
P	Number of poles
T_L	Load torque
T_e	Electromagnetic torque
$\check{T}_e$	Estimated electromagnetic torque
ω_r	Rotor speed

1 Introduction

In recent years, PMSM drive has drawn significant importance from the research and industry due to its high efficiency, power factor and power density. In general, Field oriented control (FOC) and Direct Torque Control (DTC) are widely used to achieve high dynamic performance of PMSM drive. FOC scheme [1–3] consists of two loops i.e. inner current loop and outer speed loop. For current control primarily two controllers are widely used i.e. Hysteresis and PI based current control. Further in outer loop PI controller based speed control of PMSM drive are used for many applications. Though it has zero steady state error, it takes more time to settle. So, in order to reduce the settling time the gain values should be increased, which causes overshoot and oscillations of the system. Moreover, the presence of load disturbance also leads to overshoot and oscillations of the system. On the other hand DTC technique has become more popular due to improved performance of PMSM drive compared to FOC, as it eliminates coordinate transformation and less parameter dependence [4–11]. So, DTC is widely adopted control strategy and it is implemented to different types of machines such as induction motor, permanent magnet synchronous motor, synchronous reluctance machines [4]. DTC scheme does not involve pulse with modulation (PWM) and current regulators [5, 6]. It mainly concentrates on minimizing stator current and electromagnetic torque ripples compared to FOC [8]. The DTC achieve high torque performance under transient and steady-state conditions. DTC technique uses electromagnetic torque and flux as the control variable, where the feedback signal is obtained through flux and torque estimator [9]. Sliding mode control based speed control of PMSM drive

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presented in [12, 13], improves performance of drive under parameter uncertainty and load disturbance, but it suffers from chattering phenomenon. In [14–18], the DTC scheme based on duty cycle control strategy which depends on machine parameter, suffers during uncertainties. In [11], PI-DTC scheme is used to control actual speed, electromagnetic torque and stator flux where PI controller is used in outer speed loop to generate reference to the torque controller. As mentioned earlier PI based control exhibits overshoot and oscillation which are unavoidable. So in this paper, speed loop pseudo derivative feedback controller based direct torque controlled PMSM drive is presented to overcome the problems in PI controller based system. This paper is organized as follows, in section II mathematical model of PMSM is described. In section III the proposed speed loop PDF-DTC and PI-DTC for PMSM are discussed. Experimental results are presented in section IV.

2 Mathematical model of PMSM in the rotor reference frame

The stator voltage of surface mounted permanent magnet synchronous motor in the rotor reference frame can be expressed as [19]

$$v_{qs} = R_s i_{qs} + \omega_r (L_s i_{ds} + \psi_m) + \frac{d(L_s i_{qs})}{dt} \tag{1}$$

$$v_{ds} = R_s i_{ds} - \omega_r (L_s i_{qs}) + \frac{d(L_s i_{ds} + \psi_m)}{dt} \tag{2}$$

From (1) and (2), the stator *d*–*q* axes current can be described as

$$i_{qs} = \frac{1}{L_s} \int \{ v_{qs} - R_s i_{qs} - \omega_r L_s i_{ds} - \omega_r \psi_m \} \tag{3}$$

$$i_{ds} = \frac{1}{L_s} \int \{ v_{ds} - R_s i_{ds} + \omega_r L_s i_{qs} \} \tag{4}$$

Electromagnetic torque is given as

$$T_e = \left(\frac{3}{2}\right)\left(\frac{P}{2}\right)\{\psi_m i_{qs}\} \tag{5}$$

The mechanical speed and position is expressed as

$$T_e - T_l = J\frac{d\omega_r}{dt} + B\omega_r \tag{6}$$

3 Speed loop PDF controller based DTC for PMSM

The block diagram of PI based speed control for direct torque controlled PMSM drive is shown in Fig. 1. The reference electromagnetic torque is generated using speed loop PI controller. Further the desired stator flux and reference electromagnetic torque are compared with instantaneous estimated stator flux and electromagnetic torque respectively which are obtained from the electromagnetic torque and stator flux estimator. The flux and torque error signals are passed through hysteresis comparator thereby to generate switching logic using switching table of the DTC. The block diagram of proposed speed loop PDF-DTC for PMSM drive is shown in Fig. 2. The overall performance of DTC depends on reference electromagnetic torque, accurate estimation of electromagnetic torque and stator flux. In the proposed method, the reference electromagnetic torque is computed through speed PDF controller. PI controller is widely used speed controller where overshoot in speed is unavoidable during changes in the system dynamics. The proposed PDF controller eliminates overshoot and oscillation in the speed. Further the estimated stator flux and electromagnetic torque is computed using (9) and (11) respectively. The rated stator flux is considered as reference to the flux controller. The reference electromagnetic torque and stator flux are compared with estimated flux and electromagnetic torque values to generate the error signal. The instantaneous torque and flux error signals are passed through direct torque controller which generates switching pulse to the voltage source inverter. Table 1 shows the switching table for the DTC.

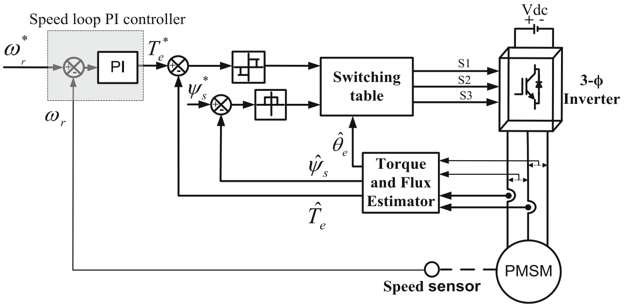


Fig. 1 Block diagram of speed loop PI-DTC for PMSM drive

Estimated stator flux linkages in the αβ reference frame are

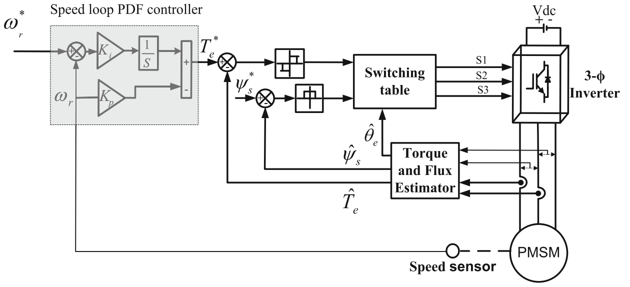


Fig. 2 Block diagram of proposed speed loop PDF-DTC for PMSM drive

Table 1 Switching table of the DTC

ψ	T	Θ					
		Θ_1	Θ_2	Θ_3	Θ_4	Θ_5	Θ_6
1	1	110 (V$_2$)	010 (V$_3$)	011 (V$_4$)	001 (V$_5$)	101 (V$_6$)	100 (V$_1$)
	0	111 (V$_7$)	000 (V$_0$)	111 (V$_7$)	000 (V$_0$)	111 (V$_7$)	000 (V$_0$)
	− 1	101 (V$_6$)	100 (V$_1$)	110 (V$_2$)	010 (V$_3$)	011 (V$_4$)	001 (V$_5$
0	1	010 (V$_3$)	011 (V$_4$)	001 (V$_5$)	101 (V$_6$)	100 (V$_1$)	110 (V$_2$)
	0	000 (V$_0$)	111 (V$_7$)	000 (V$_0$)	111 (V$_7$)	000 (V$_0$)	111 (V$_7$)
	− 1	001 (V$_5$)	101 (V$_6$)	100 (V$_1$)	110 (V$_2$)	010 (V$_3$)	011 (V$_4$)

$$\hat{\psi}_{\alpha s} = \int \left(v_{\alpha s} - R_s i_{\alpha s}\right) dt \tag{7}$$

$$\hat{\psi}_{\beta s} = \int \left(v_{\beta s} - R_s i_{\beta s}\right) dt \tag{8}$$

$$\hat{\psi}_s = \sqrt{(\hat{\psi}_{\alpha s}^2 + \hat{\psi}_{\beta s}^2)} \tag{9}$$

$$\hat{\theta}_s = \sin^{-1}\left(\frac{\hat{\psi}_{\beta s}}{\hat{\psi}_s}\right) \tag{10}$$

where $\hat{\psi}_{\alpha s}$ and $\hat{\psi}_{\beta s}$ are the estimated stator flux in the α–β axes.Estimated electromagnetic torque can be expressed as

$$\hat{T}_e = \left(\frac{3}{2}\right)\left(\frac{P}{2}\right)\left(\hat{\psi}_{\alpha s} i_{\beta s} - \hat{\psi}_{\beta s} i_{\alpha s}\right) \tag{11}$$

where $i_{\alpha s}$ and $i_{\beta s}$ are the stator current in the α–β axes. Figure 3 shows the stator flux linkage regions and inverter voltage vectors.

3.1 Performance analysis of proposed speed loop PDF and PI controller for PMSM drive

In this section, to analyze the performance of proposed PDF-DTC and PI-DTC schemes, the outer speed loop is considered. The general structure of PI and PDF controller are discussed in [20]. Simulation results for speed control of PMSM drive based on the proposed method shows an improvement in dynamic performance i.e. the proposed controller completely eliminates overshoot and has two times faster settling time than that of PI controller. The block diagrams of speed loop PDF and PI controller based speed control of PMSM drive are shown in Figs. 4 and 5.

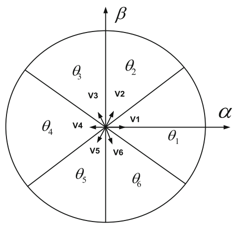


Fig. 3 Stator flux linkage regions Θ_1–Θ_6

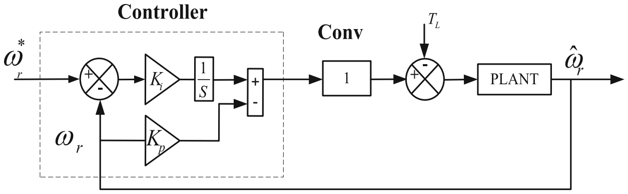


Fig. 4 The structure of speed loop PDF controller

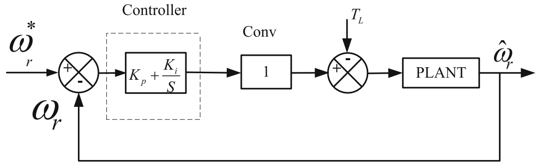


Fig. 5 The structure of speed loop PI controller

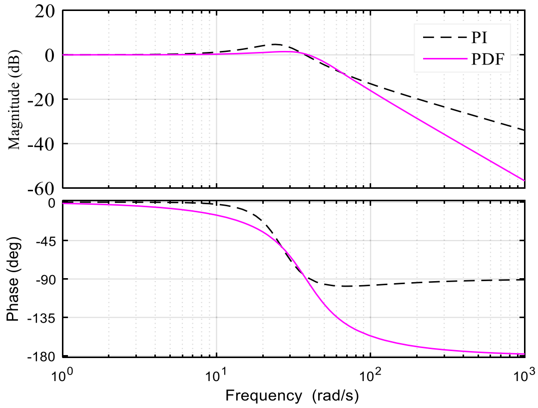


Fig. 6 Bode diagram for the closed loop transfer function of speed loop PI-DTC and PDF-DTC

The speed loop PDF controller based PMSM drive eliminates oscillation, overshoot of the system. Figure 6 shows the bode diagram of the closed loop transfer function of speed loop PI and PDF controller. It is seen that the magnitude gain of the PDF controller is much lower than PI controller, which results in the improvement of the transient response and disturbance rejection ability of the system. To validate the robustness and ability of the PDF controller based speed control of PMSM drive, the

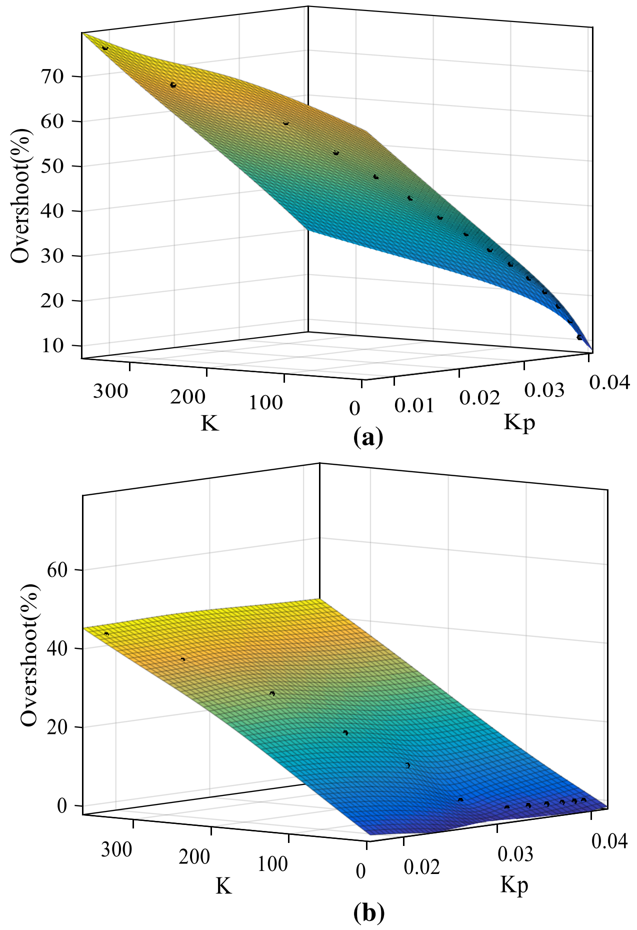


Fig. 7 Overshoot of PI and PDF controller with different Kp and K(Ki/Kp) values **a** PI controller **b** PDF controller

different controller gain values are considered as shown in Fig. 7. It can be seen that, the overshoot produced by the PI controller ranges from 76.5 to 10.5% and the overshoot generated by the PDF controller ranges from 43.4 to 0%. It is also observed that overshoot of the PDF system is much smaller than that of the PI system.

Figure 8a and b the step response for speed loop PDF and PDF controller for PMSM drive. It is observed that, The step response for speed loop PDF controller has a maximum overshoot of 33.3% at $\zeta = 0.3$ and eliminates overshoot at $\zeta = 1$. The speed loop PI controller has a maximum overshoot of 36.6% at $\zeta = 0.3$ and minimum overshoot of 16.3% at $\zeta = 1$. Further it is observed from Fig. 8a and b, the speed loop PI controller has 16.3% overshoot with settling time of 220 ms ($\zeta = 1$) and speed loop PDF controller based system eliminates overshoot with settling time of 120 ms ($\zeta = 1$), which is two times faster than that of speed loop PI controller.

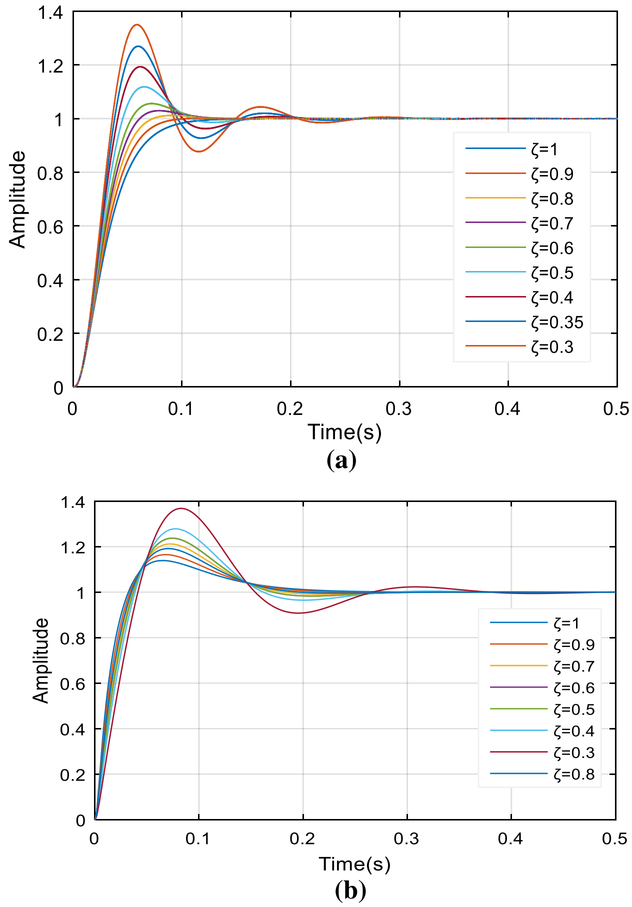
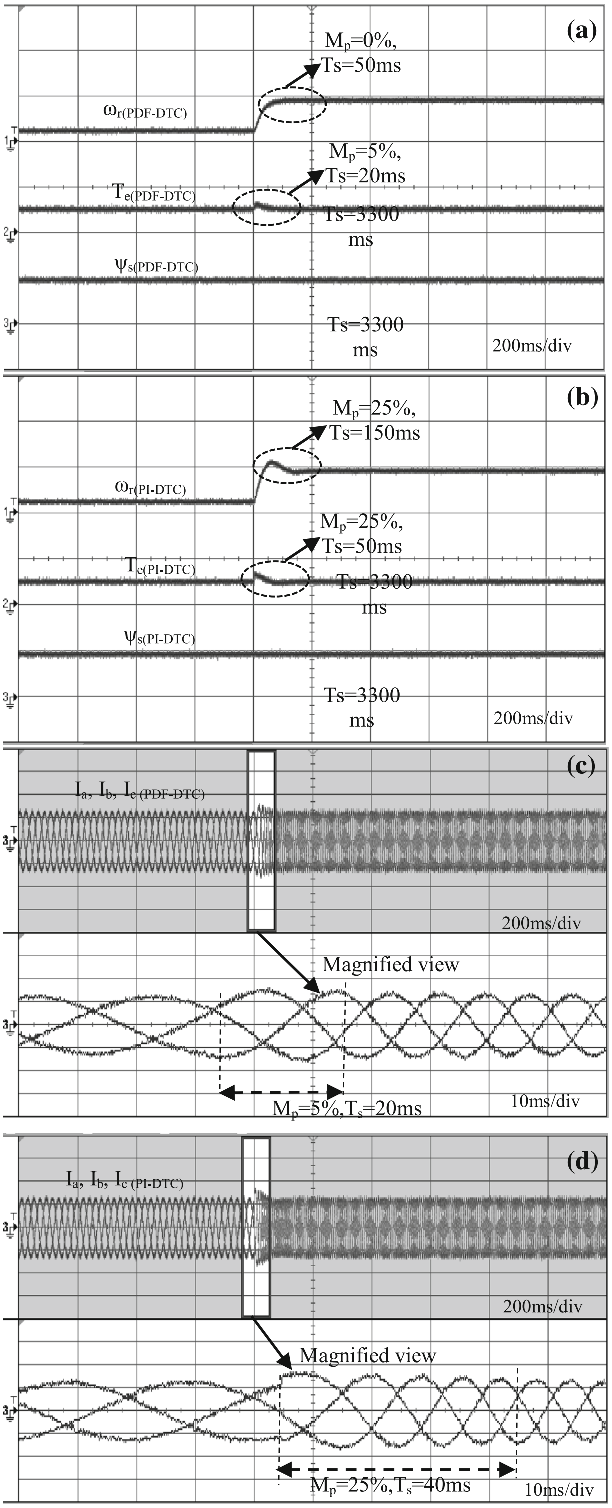


Fig. 8 Time response analysis for controller. **a** speed loop PDF controller based system for zeta variation. **b** speed loop PI controller based system for zeta variation

4 Experimental results and discussion

Experimental results for proposed speed loop PDF-DTC and PI-DTC system are presented in this section. The proposed scheme is implemented on 1.5 kW PMSM drive using ALTERA Cyclone II FPGA controller. The Experimental block diagram, experimental setup and machine parameters are given in appendix. Three phase IGBT inverter (SEMIKRON make, 750 V, 30A, 20 kHz) is used for control of PMSM. The switching pulses are generated based on DTC technique. The switching frequency of VSI is 5 kHz and sampling time for control is 100 µs. The motor voltage, current are sensed through LV-25P, LAH 25-NP respectively and it is given to signal conditioning circuit using OP-AMP (OPA 227P). The actual rotor speed is obtained by differential line encoder (1024 PPR).



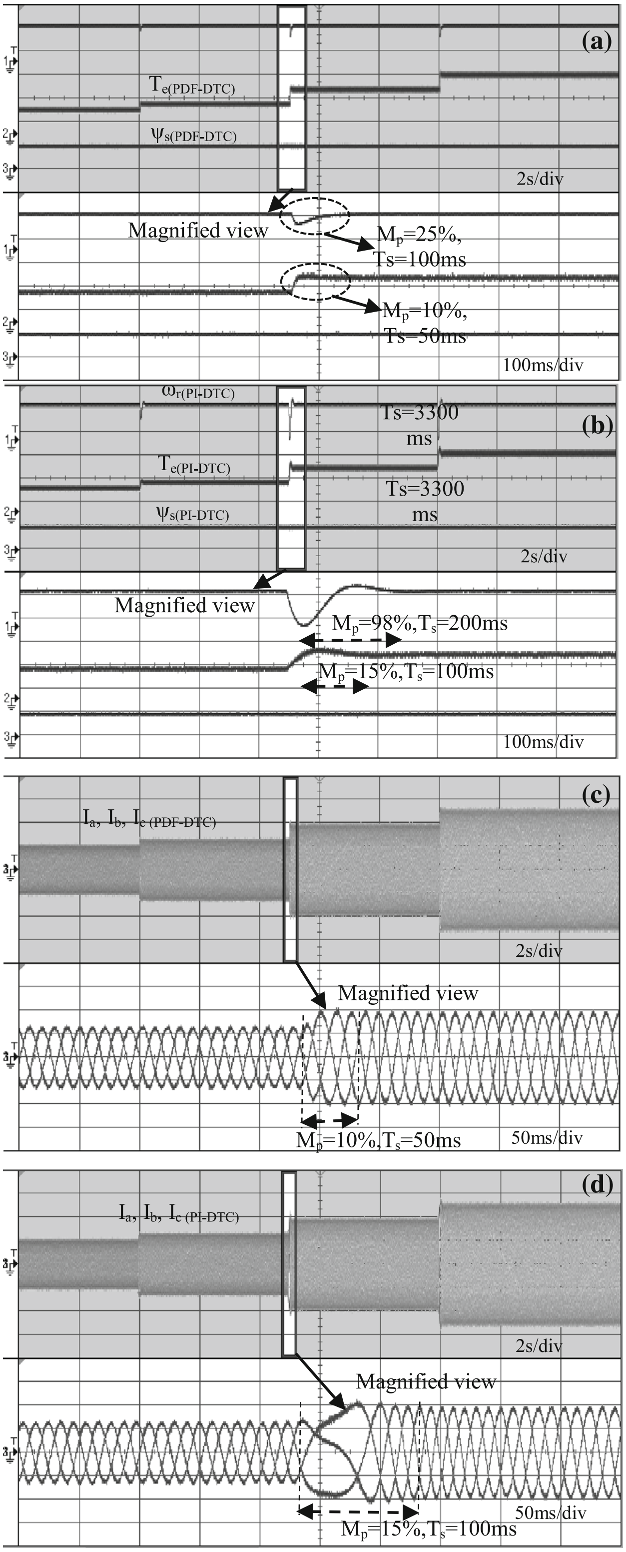
◀ **Fig. 9** Speed variation at constant load. **a** actual rotor speed, estimated electromagnetic torque and stator flux $_{\text{(PDF-DTC)}}$. Scale: ($\omega_{r(\text{aut})}$ = 157 rad/s/div) ($T_{e(\text{PDF})}$ = 10 Nm/div) ($\psi_{s(\text{PDF})}$ = 2 wb/div) **b** actual rotor speed, electromagnetic torque, stator flux $_{\text{(PI-DTC)}}$. Scale: ($\omega_{r(\text{aut})}$ = 157 rad/s/div) ($T_{e(\text{PDF})}$ = 10 Nm/div) ($\psi_{s(\text{PDF})}$ = 2 wb/div). **c** Three phase stator current $_{\text{(PDF-DTC)}}$. Scale: (I_a, I_b, $I_{c\ (\text{PI})}$ = 2 A/div) ($T_{e(\text{PI})}$ = 10 Nm/div). **d** Three phase stator current $_{\text{(PI-DTC)}}$. Scale: (I_{as}, I_{bs}, $I_{cs\ (\text{PDF})}$ = 2 A/div), Scale: (I_{as}, I_{bs}, $I_{cs\ (\text{PI})}$ = 2 A/div) ($T_{e(\text{PI})}$ = 10 Nm/div)

4.1 Case—1 speed variation at constant load

Figure 9 shows transient response for the PMSM drive during speed variation (50 to 157 rad/s) at half load torque (4.5 Nm). Figure 9a and b demonstrates the transient response of actual speed, electromagnetic torque and stator flux for the proposed speed loop PDF-DTC and PI-DTC based system. It is observed that, the proposed PDF-DTC system takes 50 ms to follow speed reference and completely eliminates overshoot in the actual speed where as PI-DTC system has an overshoot of 24.3% and it takes 120 ms to reach steady state. Further it is clearly seen that, the proposed PDF-DTC system has 5% overshoot in electromagnetic torque and it takes 20 ms to reach steady state where as PI-DTC system has 15% overshoot and it has settling time of 50 ms during variation in the speed. Figure 9c and d shows the three phase stator current response for PDF-DTC and PI-DTC system. It is observed that, the stator current of proposed PDF-DTC system has smooth transient response (overshoot is 5% & settling time is 20 ms) whereas the PI-DTC system has overshoot and oscillations(overshoot is 15% & settling time is 50 ms).

4.2 Case—2 load torque variation at constant speed

Figure 10 shows transient response of PMSM drive during variation in the load torque (25 to 100%) at constant speed (100 rad/s). Figure 10a and b shows the responce of actual speed, electromagnetic torque and stator flux for the proposed PDF-DTC and PI-DTC system respectively during variation in the load torque at constant speed. It is observed that when load is varied from 25 to 50% at 100 rad/s the PI-DTC system exhibits dip (98%) in the actual rotor speed and settling time is 200 ms whereas the PDF-DTC system significantly reduces the undershoot (24%) in the actual rotor speed and it takes 100 ms to reach steady state as shown in Fig. 10a and b. Further It is observed that with the existing PDF-DTC system, electromagnetic torque has an overshoot of 15% and it takes 100 ms to reach the steady state during variation in the load torque whereas the proposed system completely has an overshoot of 10% in the electromagnetic torque and system settles with a faster



◀**Fig. 10** Load torque variation at constant speed. **a** actual rotor speed, estimated electromagnetic torque and stator flux $_{(\text{PDF-DTC})}$. Scale:($\omega_{r(\text{aut})}$ = 60 rad/s/div) ($T_{e(\text{PDF})}$ = 10 Nm/div) ($\psi_{s(\text{PDF})=}$ 2 wb/div). **b** actual rotor speed, electromagnetic torque, stator flux (PI-DTC). Scale: ($\omega_{r(\text{aut})}$ = 60 rad/s/div) ($T_{e(\text{PDF})}$ = 10 Nm/div) ($\psi_{s(\text{PDF})}$ = 2 wb/div). **c** Three phase stator current $_{(\text{PDF-DTC})}$. Scale: (I_{as}, I_{bs}, $I_{cs(\text{PDF})}$ = 2 A/div), Scale: (I_{as}, I_{bs}, $I_{cs(\text{PDF})}$ = 2 A/div) ($T_{e(\text{PI})}$ = 10 Nm/div). **d** Three phase stator current $_{(\text{PI-DTC})}$. Scale: (I_{as}, I_{bs}, $I_{cs(\text{PDF})}$ = 2 A/div), Scale: (I_{as}, I_{bs}, $I_{cs(\text{PI})}$ = 2A/div) ($T_{e(\text{PI})-}$ = 10 Nm/div)

settling time of 50 ms thereby the proposed controller has two times faster settling time than existing controller. Further the stator flux is maintained constant in both control schemes. Figure 10c and d shows the three phase stator current response for PDF-DTC and PI-DTC system for better clarity. It is observed that, the proposed PDF-DTC system has smooth stator current response compared to PI-DTC system. Table 2 shows the transient and steady state electromagnetic torque ripple when the speed is varied from 0 to 157 rad/s for different values of constant load torque. It is found that, the proposed speed loop PDF-DTC has reduced overshoot during transient conditions compared with speed loop PI-DTC. At rated torque (9.5 Nm), PI-DTC system has an overshoot of approximately 100% wheres the proposed PDF-DTC has an overshoot of 53% which is less compared with speed loop PI-DTC. Table 3 shows the performance analysis of proposed PDF-DTC and PI-DTC system during variation in the speed at rated load. It is observed that the proposed controller completely eliminates overshoot in speed for the entire speed range considered. Further the proposed PDF-DTC system has two times faster settling time in speed characteristic than PI-DTC system. The overall performance of PMSM dive for both PDF-DTC and PI-DTC is shown in Fig. 11a and b when the rotor speed is varied from standstill to rated speed with full load, it is observed that the proposed PDF-DTC system eliminates overshoot (0%) and further improves settling time i.e. two times faster than that of PI-DTC system.

5 Conclusion

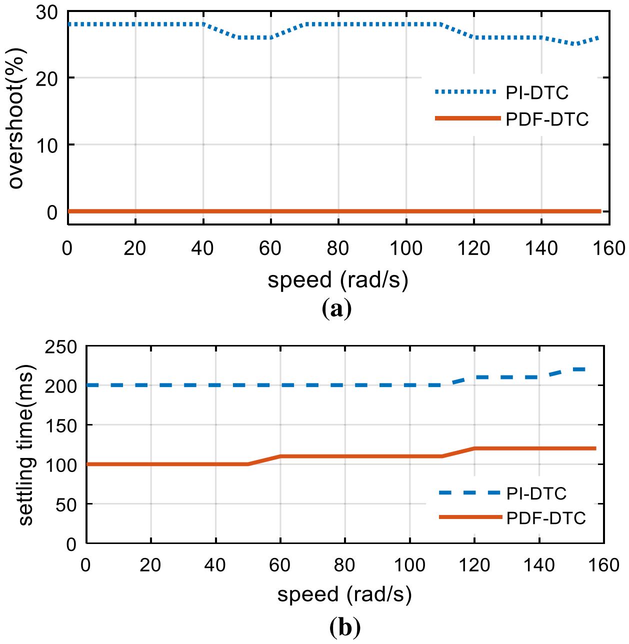
In this paper, the speed loop Pseudo derivative feedback controller based direct torque controlled PMSM drive has been presented. A comparative analysis is performed between PDF-DTC and PI-DTC for PMSM drive. It is found that the proposed controller reduces 50% overshoot in electromagnetic torque and completely eliminates overshoot in the speed. Further proposed controller improves the settling time of the system i.e. two times faster than that of PI-DTC system. The proposed speed

Table 2 Transient and steady state electromagnetic torque ripple of PDF-DTC and PI-DTC system

T_L (Nm)	Te ripple (transient/steady state in Nm), speed varied between 0 to 157 rad/s	
	Speed loop PDF with DTC	Speed loop PI with DTC
0	2.7/0.1	6.2/0.1
2	6/0.12	12/0.1
4	9.4/0.12	14.1/0.12
6	11.5/0.12	16.2/0.14
8	13.5/0.18	17.5/0.2
9.5	14.5/0.18	18.7/.18

Table 3 Performance of PDF-DTC and PI-DTC system at rated load

Speed variation	Overshoot in speed (%)		Settling of speed (ms)	
	PDF-DTC	PI-DTC	PDF-DTC	PI-DTC
0 → 20 rad/s (low speed)	0	28	100	200
0 → 50 rad/s (low speed)	0	28	100	200
0 → 100 rad/s (medium speed)	0	26	110	220
0 → 157 rad/s (wide speed)	0	25	120	220



(a)

(b)

Fig. 11 Time response analysis for the proposed PDF-DTC and existing PI-DTC system. **a** overshoot versus rotor speed. **b** setting time versus rotor speed

loop PDF-DTC performs well in different test conditions viz., speed variation at constant load and variation in the load torque at constant speed. Experimental results demonstrate the efficacy of the proposed speed loop PDF controller based direct torque controlled PMSM drive.

Appendix

Figures 12 and 13 shows the block diagram of experimental setup and photograph of the laboratory setup. Further the machine parameters are given in Table 4.

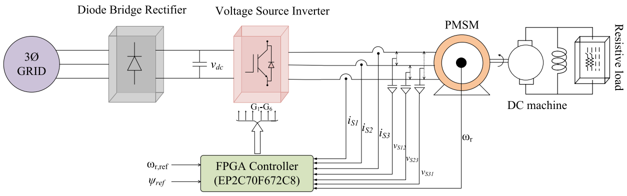


Fig. 12 The block diagram for the experimental setup

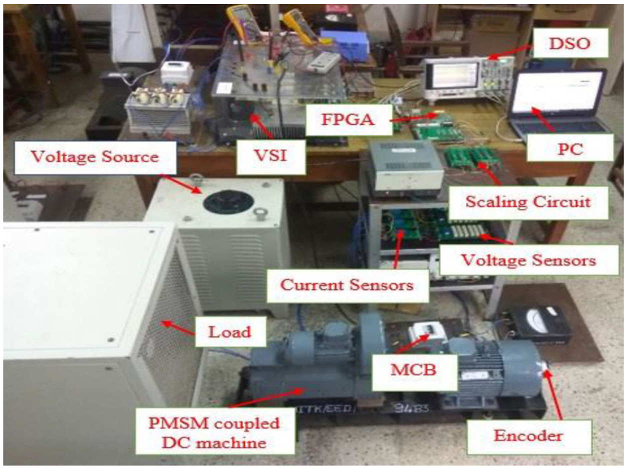


Fig. 13 Photograph of laboratory setup

Table 4 PMSM rating and parameters

Parameter	Measured value in SI units
R_s	1.15 Ω
L_s	24.3mH
λ_m	0.9426 Wbturns
J	0.0145 kg m^2
B	0.00029 kg m^2/s

Stator: 1.5 kW, 360 V, 1500 Rpm, 50 Hz, 4 pole, 3Φ, 9.5 Nm

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