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Performance Evaluation of DTC, MPDTC and DDTC Methods for Drive of a SPMSM

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Abstract— This paper investigates three different direct torque control strategies for permanent magnet synchronous machines (PMSM), namely direct torque control (DTC), model predictive torque control (MPTC), and duty ratio modulated direct torque control (DDTC). The basic principle of the mentioned control strategies are presented. Then, using a PMSM fed by a two level voltage source inverter, all of the control strategies are simulated. Based on the obtained results, their performance are compared.

I. INTRODUCTION

Permanent magnet synchronous motors (PMSM) have several distinctive features such as high torque and power density, efficiency, and good dynamic response, which renders them suitable for drive applications. As the name of PMSM suggests, it is composed of an iron rotor with permanent magnets attached to it. The permanent magnets can be mounted on the rotor surface or inside the rotor core [1]-[4]. In this way, the magnetic field is fixed to the rotor position. So, the stator frequency can determine the speed of rotor. For changing the stator frequency or having variable speed operation, a voltage source inverter can be utilized.

Direct torque control (DTC) is a popular method employed in variable frequency drives of AC electric motors to control the torque, and consequently their speed. To this end, the motor's torque and magnetic flux should be estimated based on the voltage and current measurement of the motor stator [5]- [7]. In spite of simple structure of DTC, high torque and flux ripples and variable switching frequency can be its main drawbacks [12], [8].

To overcome some problems of DTC, model predictive DTC (MPDTC) has been proposed. The main principle of MPC is to predict some future machine states based on a discrete model of the system. After prediction of machine states, based on minimizing a cost function, the best voltage vector for inverter is determined. The main optimization goals in cost functions are usually torque, flux or switching frequency [9]- [11].

Another approach is to apply duty ratio modulation (DRM) to conventional DTC [13]-[15]. The main idea is to calculate duty ratio of active voltage vector so that in addition to achieving the required torque, some variables such as, torque ripple, stator flux ripple and switching frequency are decreased.

In this paper, primarily, the basic model of PMSM is presented. In Section III, conventional DTC strategy is reviewed. MPDTC and DDTC are presented in Section IV and V, respectively. In Section VI, simulations of permanent magnet synchronous machine based on DTC, MPDTC and DDTC are conducted and the results thus obtained are compared with each other. The summary of the paper is brought in Section VII.

II. PMSM MODEL

Since sinusoidal quantities of PMSM in rotor reference frame (RRF) and under steady-state condition are constant, the state equations of a PMSM are written in dq reference frame as follows

$$\mathbf{u}_{s,dq} = R_s \mathbf{i}_{s,dq} + \frac{d}{dt} \boldsymbol{\psi}_{s,dq} + \mathbf{F} \boldsymbol{\psi}_{s,dq} \quad (1)$$

where R_s is the stator resistance, $\boldsymbol{\psi}_{s,dq} = [\psi_{sd} \ \psi_{sq}]^T$ is the vector of stator flux, $\mathbf{u}_{s,dq} = [u_{sd} \ u_{sq}]^T$ and $\mathbf{i}_{s,dq} = [i_{sd} \ i_{sq}]^T$ are the vectors of stator voltage and current, respectively, and

$$\mathbf{F} = \begin{bmatrix} 0 & -\omega_r \\ \omega_r & 0 \end{bmatrix} \quad (2)$$

here, ω_r is the electrical rotor angular speed and the stator flux vector is

$$\boldsymbol{\psi}_{s,dq} = \mathbf{G} \mathbf{i}_{s,dq} + \boldsymbol{\psi}_{r,dq} \quad (3)$$

where $\boldsymbol{\psi}_{r,dq} = [\psi_f \ 0]^T$ with ψ_f denotes the permanent magnet flux and

$$\mathbf{G} = \begin{bmatrix} L_d & 0 \\ 0 & L_q \end{bmatrix} \quad (4)$$

L_d and L_q are the direct axis and quadrature axis stator inductances, respectively. The generated electromagnetic torque by the machine is

$$T_e = \frac{3}{2} p(\psi_d i_q - \psi_q i_d) \quad (5)$$

where p is the number of pole pairs.

III. CONVECTIONAL DTC

DTC is mainly based on producing adequate torque based on applying appropriate voltage vectors to inverter. Fig. 1 shows the scheme of DTC strategy. In the first stage, voltages and currents of PMSM stator are measured and torque and flux of machine are estimated based on an observer. Control performance of DTC depends on accurate estimation of the stator flux, which is achieved using stator voltages and currents. They are expressed using the following sets of equations

$$\psi_{s,dq} = \int (u_{s,dq} - R_s i_{s,dq}) dt \quad (6)$$

$$\psi_{s,dq} = G i_{s,dq} + \psi_{r,dq} \quad (7)$$

where (6) and (7) are in stationary and rotor reference frame, respectively. After obtaining the stator flux, the torque can be calculated using (5).

Then, the estimated variables are compared with their corresponding reference values. By using speed control loop, the torque reference can be obtained. Afterwards, torque and flux error go to a three-level and two-level hysteresis controller, respectively. According to output of hysteresis controllers and the position of stator flux, the optimal voltage vector, which can minimize the torque and flux error, can be obtained with reference to Table I.

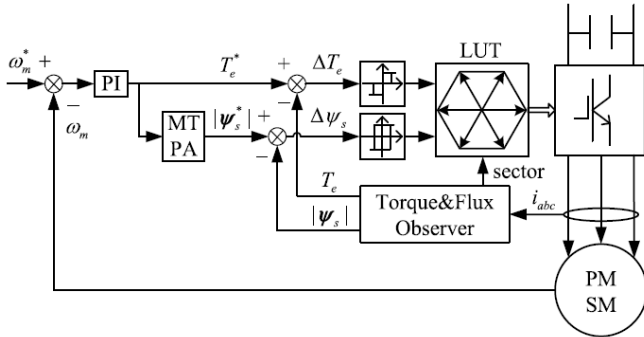


Fig. 1. Block diagram of direct torque control (DTC) [13]

TABLE I. VECTOR VOLTAGE LOOK UP TABLE OF DTC [13]

$\Delta\psi_s$	ΔT_e	Sector					
		①	②	③	④	⑤	⑥
1	1	u_{s2}	u_{s3}	u_{s4}	u_{s5}	u_{s6}	u_{s1}
	0	u_{s0}	u_{s7}	u_{s0}	u_{s7}	u_{s0}	u_{s7}
	-1	u_{s6}	u_{s1}	u_{s2}	u_{s3}	u_{s4}	u_{s5}
-1	1	u_{s3}	u_{s4}	u_{s5}	u_{s6}	u_{s1}	u_{s2}
	0	u_{s7}	u_{s0}	u_{s7}	u_{s0}	u_{s7}	u_{s0}
	1	u_{s5}	u_{s6}	u_{s1}	u_{s2}	u_{s3}	u_{s4}

With DTC we can obtain adequate torque control performance under dynamic and steady state conditions at high speeds. However, at low speed we observe reduced controllability, variable switching frequency and high torque ripple.

IV. MODEL PREDICTIVE DIRECT TORQUE CONTROL

The main principle of predictive model control is to predict the future behavior of the variables over a time frame based on the model of the system [13]. Fig. 2 depicts the block diagram of MPDTC strategy. The predictive controller takes torque and flux references, the measured rotor speed, and the predicted torque and stator flux as its inputs.

At each sample, the values of stator flux and torque for the next sample can be obtained based on the future values of direct and quadrature stator currents. Using (1), the PMSM machine model can be rewritten in terms of state space equations:

$$\frac{di_{sd}}{dt} = \frac{-R_s i_{sd} + \omega_r L_q i_q + v_{sd}}{L_d} \quad (8)$$

$$\frac{di_{sq}}{dt} = \frac{-R_s i_{sq} - \omega_r L_d i_d + v_{sq} - \omega_r \psi_f}{L_q} \quad (9)$$

By discretizing the above equations, the predicted currents can be expressed as

$$i_{sd}^{k+1} = i_{sd}^k + \frac{1}{L_d} (-R_s i_{sd}^k + \omega_r L_q i_q^k + v_{sd}^k) T_s \quad (10)$$

$$i_{sq}^{k+1} = i_{sq}^k + \frac{1}{L_q} (-R_s i_{sq}^k - \omega_r L_d i_d^k + v_{sq}^k - \omega_r \psi_f) T_s \quad (11)$$

where T_s is sampling time and variables with superscript $(k+1)$ show the $(k+1)$ st instant of that variable. Now, by substituting (10) and (11) in (3), the $(k+1)$ st for stator flux can be derived. Finally, using (5), the predicted torque can be calculated.

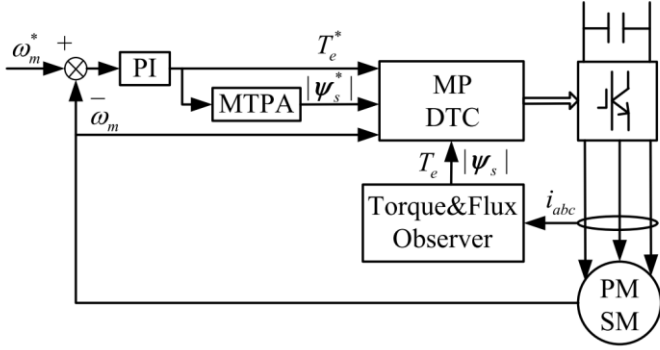


Fig. 2. Block diagram of model predictive direct torque control (MPDTC) [13]

The above equations allow predictions of the torque and stator flux to be calculated for one of the eight voltage vectors generated by the inverter. After obtaining the predicted stator flux and torque, the optimum voltage vector can be derived by evaluating a cost function. A cost function can be designed to fulfill different goals. The cost function in this report is chosen as follows

$$g = k_1 |T^* - T_e^{k+1}| + k_2 |\psi_s^* - \psi_s^{k+1}| \quad (12)$$

where, the first term represents the minimization of electromagnetic torque, and the second term is defined for minimizing stator flux. k_1 and k_2 are weighting factors and can be chosen based on the importance of torque or stator flux. After replacing the predicted torque and stator flux of eight voltage vectors in (12), the voltage vector leading to minimum g would be the optimum voltage vector and is imposed to the inverter.

V. DUTY RATIO MODULATED DIRECT TORQUE CONTROL

In DDTC, two or three voltage vectors are applied at intervals of the control period in order to achieve the control requirements of stator flux and torque. DDTC usually uses one non-zero voltage vector, which has a time duration ranging from zero to the entire control period. The goal of any DDTC method is the calculation of this time duration. In the remaining time for each control cycle, zero voltage vector is applied to maintain stator flux and torque. This results in a reduced switching frequency which is a positive consequential effect; however, this engenders a slight reduction in control performance [16].

With the aim of reducing switching frequency, the nonzero voltage vector $us1$ (1 0 0), $us3$ (0 1 0), $us5$ (0 0 1) are followed by zero voltage vector $us0$ (0 0 0), while the other three nonzero voltage vectors are followed by zero voltage vector $us7$ (1 1 1). As such, only one phase leg changes status during one control period.

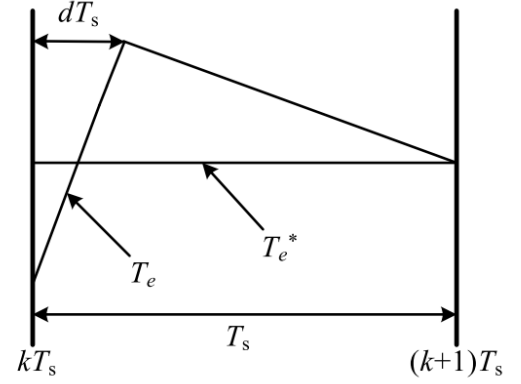


Fig. 3. Duty decision in DDTC [16]

A. Control Scheme

In control of PMSM, the most important criterion is torque ripple. On the other hand, in the voltage source converters, the voltage vector is the single controllable input. So, duty ratio determination can be implemented based on the relationship between torque variation and the voltage. Due to (1) - (5), the torque derivative under different non zero voltage vectors can be calculated as

$$\begin{aligned} \frac{dT_e}{dt} = & \frac{3p}{2} \left(\frac{1}{L_q} - \frac{1}{L_d} \right) \left(\text{Im}(u_s \psi_s) - \omega_r \text{Re}(\psi_s^2) \right) \\ & + \frac{3pR_s}{4} \left(\frac{1}{L_d^2} - \frac{1}{L_q^2} \right) \text{Im}(\psi_s^2) \\ & - \frac{3p}{2L_d} \left(\frac{R_s}{L_d} \text{Im}(\psi_s \psi_r) + \omega \text{Re}(\psi_s \psi_r - \text{Im} u_s \psi_r) \right) \end{aligned} \quad (13)$$

where $u_s = u_{sd} + ju_{sq}$ is the nonzero voltage vector. Under the condition that zero state is applied to the PMSM, the torque derivative can be as follows

$$\begin{aligned} \frac{dT_e}{dt} = & \frac{-3p}{2} \left(\frac{1}{L_q} - \frac{1}{L_d} \right) \left(\omega_r \text{Re}(\psi_s^2) \right) \\ & + \frac{3pR_s}{4} \left(\frac{1}{L_d^2} - \frac{1}{L_q^2} \right) \text{Im}(\psi_s^2) \\ & - \frac{3p}{2L_d} \left(\frac{R_s}{L_d} \text{Im}(\psi_s \psi_r) + \omega \text{Re}(\psi_s \psi_r) \right) \end{aligned} \quad (14)$$

Considering (14), someone can note that the torque derivative is negative when zero voltage vector is applied, which can be inferred that applying the zero voltage vector will continuously reduce the torque.

B. Control Objectives for DDTC

The goal of DDTC control, in this report, is to force the actual torque to be equal to the desired torque at the end of each control period. Fig. 3 illustrates the DDTC procedure in this report. Therefore the torque error at the end of each control cycle can be shown as

$$E_T = \left| T_e^c + s_1 d T_s + s_2 (1-d) T_s \right| \quad (15)$$

where s_1 and s_2 are torque slopes under nonzero and zero vector respectively, $T_e^e = T_{e0} - T_e^*$ is the initial torque error of each control period, T_{e0} and T_e^* are the initial and desired torque respectively, with d being the duty ratio.

If $E_T = 0$, the duty ratio of nonzero voltage vector is defined as

$$d = -\frac{(s_2 T_s + T_e^e)}{(s_1 - s_2) T_e} \quad (16)$$

Duty ratio d is limited within $[0,1]$. It is a constant with little variation during steady state operation, but in dynamic mode of operation it is seen that d becomes close to one because the nonzero voltage vector is applied for the whole control period in order to quickly achieve the desired torque.

As it is clear from (14) to (16), the equations are sophisticated and parameter dependent. In [16], the authors proposed a method to calculate duty cycle of non-zero voltage vector independent of parameter of machine. It can be shown that the duty cycle can be rewritten torque and stator flux error as follows

$$d = \left| \frac{T_e^* - T_{e0}}{C_T} \right| + \left| \frac{\psi_s^* - \psi_0}{C_\psi} \right| \quad (17)$$

where ψ_s^* and ψ_0 are reference value and the k th sampling instant of stator flux, respectively.

VI. SIMULATION RESULTS AND DISCUSSION

The PMSM simulation for DTC, MPDTC and DTC are carried out in Matlab/Simulink. The simulation model is composed mainly of

- Reference speed generation
- Proportional and integral (PI) controller
- Two-level inverter model
- Coordinate transformations
- Permanent magnet synchronous model
- Torque and stator flux observer
- Control algorithm (DTC, predictive control or DDTC)

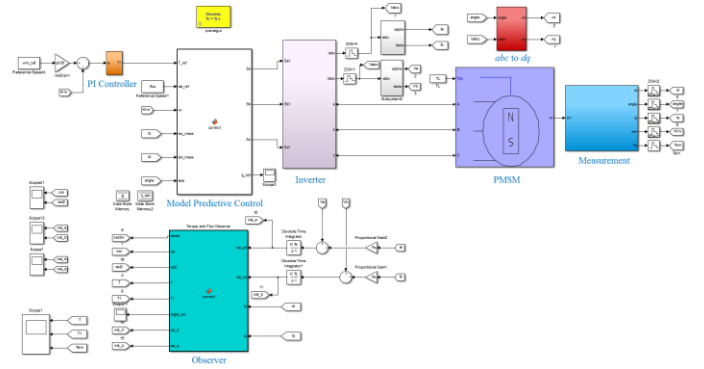


Fig. 4. Scheme of MPDTC in Simulink

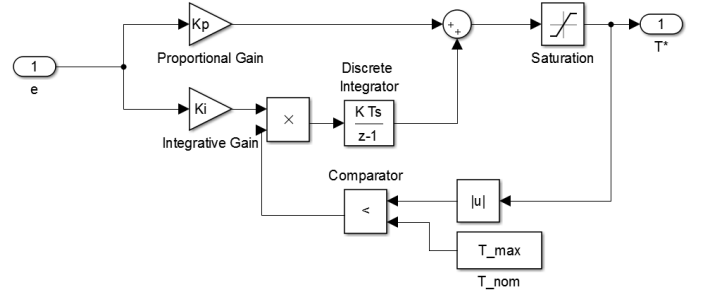


Fig. 5. PI controller

Fig. 4 shows the scheme of MPDTC in Matlab/Simulink. In DTC and DDTC the model predictive control block are replaced with DTC and DDTC block. Each of blocks will be discussed in the rest of the report.

A. PMSM Model

PMSM is modeled based on (1) to (5). The PMSM used in simulation is a salient 2 poles machine. The parameters of machine are summarized in Table II.

B. PI Controller

The reference speed in the simulation layout is constant and set at 1000 rpm. The error of reference speed and rotor speed goes to a PI controller [17]- [19]. The PI controller receives the error signal and computes the reference torque for the machine controllers using two tuning parameters, proportional gain K_p and integral gain K_i . The saturation block is included at the output of the PI controller in order to keep the amplitude of the torque reference within the limits of the simulated machine. The scheme of PI controller is shown in Fig. 5.

C. Two-Level Inverter

After evaluation of the cost function and determination of switching states, the gate signals of switches go to the inverter [20]. The inverter converts gates and generates the required 3 phase voltage (V_a, V_b, V_c) and currents (i_{abc}). Fig. 6 depicts the structure of the inverter.

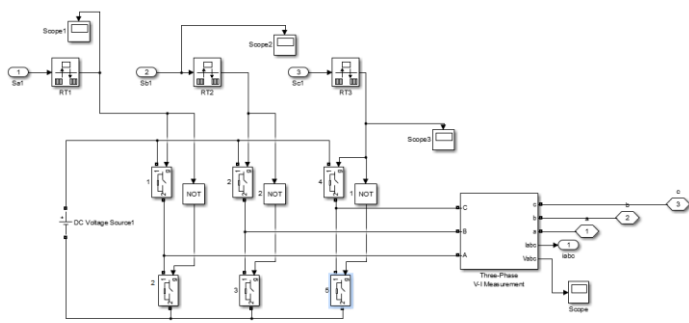


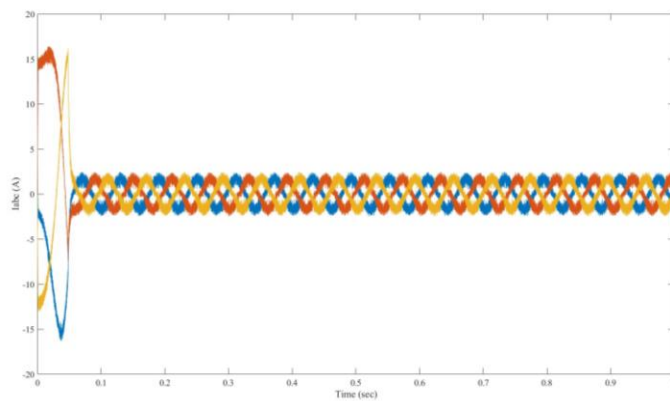
Fig. 6. Inverter layout

TABLE II. SIMULATION PARAMETERS

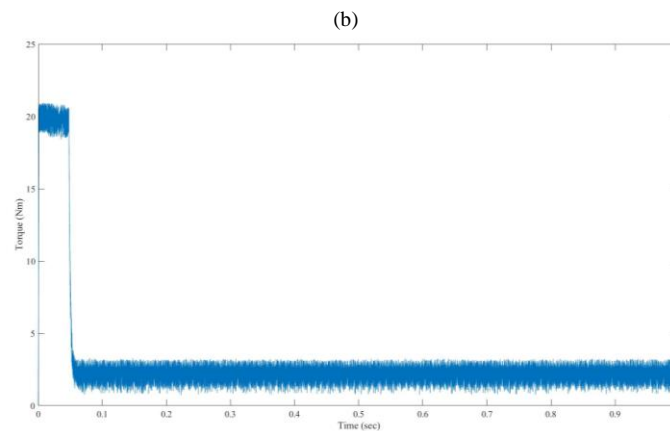
Parameter	Value
Rotor flux (Wb)	0.862
R_s (ohm)	1.96
$L_d=L_q$ (mH)	0.01607
Sampling time (s)	5e-5
K_p	4
K_i	0.1
Motor rating torque (Nm)	5
Load Torque (Nm)	2
Rated speed (rpm)	2000
Poles pair	1
J (kg.m ²)	0.0084
Inverter DC voltage (V)	450

D. Simulation Results

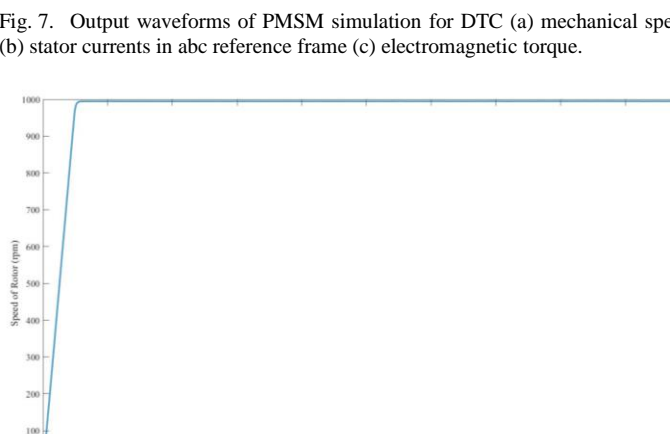
The simulation results for DTC, MPDTC and DDTC are shown in Fig.7, Fig. 8 and Fig. 9, respectively. The output waveforms include rotor speed, stator current (dq) and electromagnetic torque.



(a)

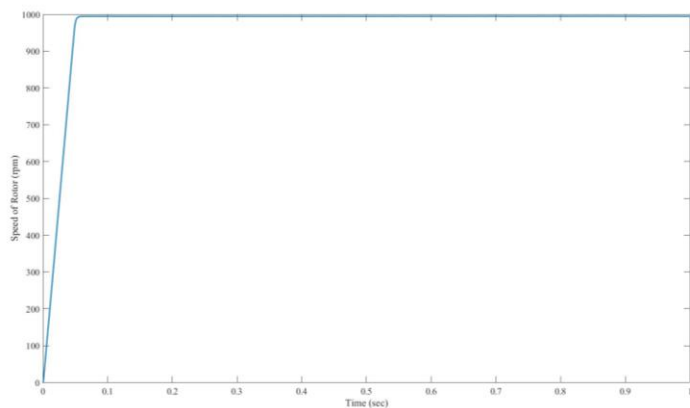


(b)

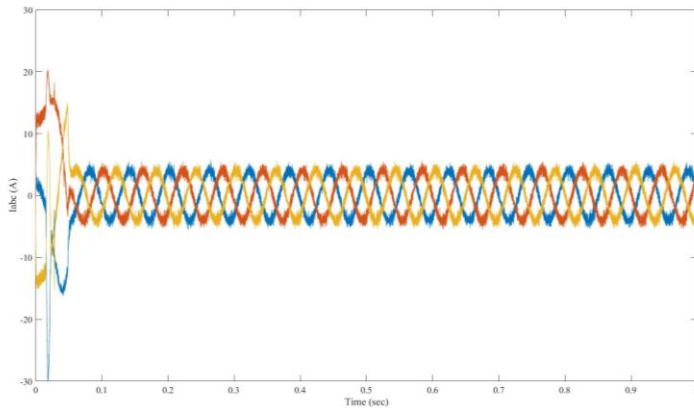


(c)

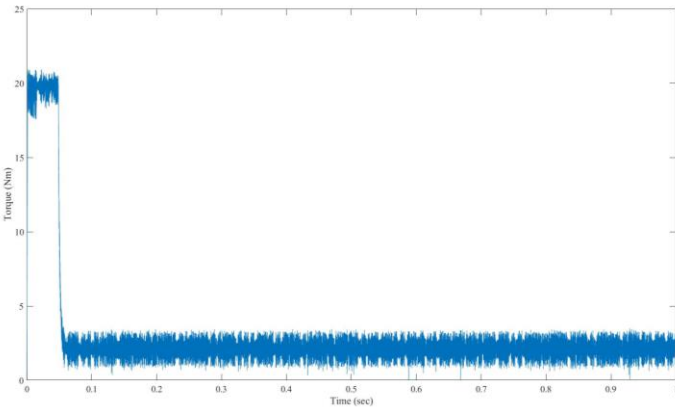
Fig. 7. Output waveforms of PMSM simulation for DTC (a) mechanical speed (b) stator currents in abc reference frame (c) electromagnetic torque.



(a)

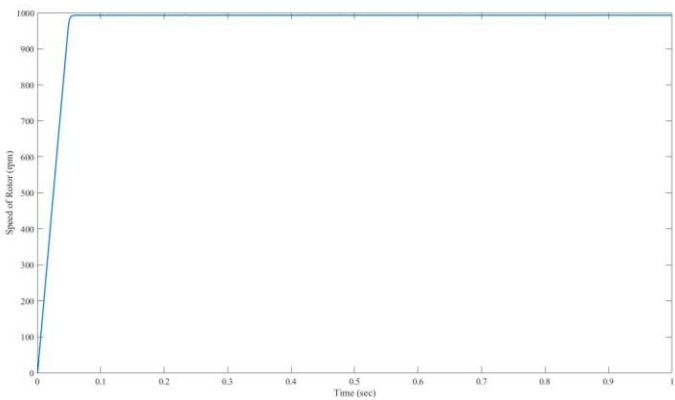


(a)

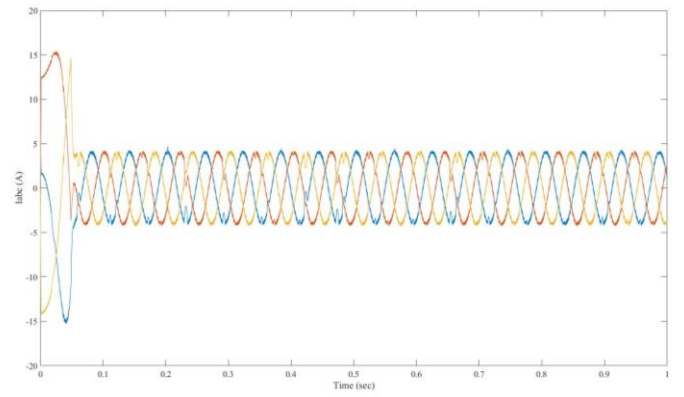


(b)

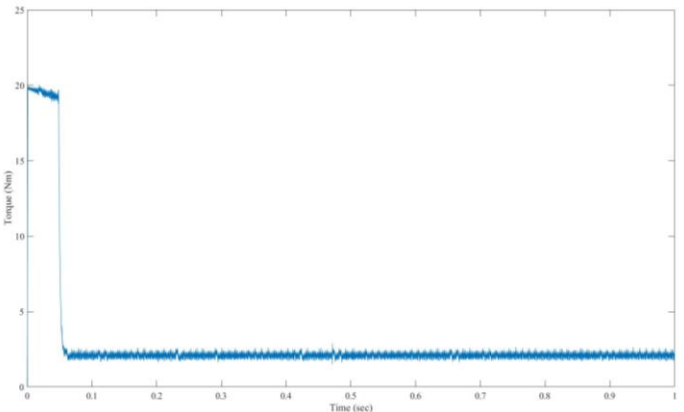
Fig. 8. Output waveforms of PMSM simulation for MPDTC (a) mechanical speed (b) stator currents in abc reference frame (c) electromagnetic torque.



(c)



(a)



(b)

Fig. 9. Output waveforms of PMSM simulation for DDTC (a) mechanical speed (b) stator currents in abc reference frame (c) electromagnetic torque.

Having compared the results obtained from three different approaches, someone can see that DDTC has the best performance in term of torque and stator current. Regarding the speed, all of the methods show the good performance. Although DDTC can be chosen as the best method, however, different simulations demonstrate that DDTC proposed in [16], is so dependent to the operating point of PMSM. Also, the tuning the parameters is time-consuming task.

VII. CONCLUSION

In this paper three different direct torque control strategies including direct torque control (DTC), model predictive torque control (MPTC), and duty ratio modulated direct torque control (DDTC) for drive of permanent magnet synchronous machines (PMSM) were reviewed and investigated. Then, using Matlab/Simulink, the performance of all control strategies to drive a PMSM fed by a two level voltage source inverter are assessed.

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