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Reducing torque ripple of induction motor control via direct torque control

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ABSTRACT

The induction motor is extremely well known and used as an alternating current (AC) machine. Therefore, torque and speed regulations are very essential for this type of machine. This paper presents direct torque control (DTC) based on induction motors (IM). The mathematical model of IM is reported, and the machine is modeled in a synchronous coordinate farm. Classic DTC is applied to IM with two bandwidths of hysteresis controller for electromagnetic torque and stator flux. The system is simulated and investigated via MATLAB/Simulink and the results carry out a high ripple on the torque. There are numerous of improving torque response, one of them is adding a new loop for speed with proportional, integral, and derivative (PID) controllers. IM model with PID based on DTC is simulated through MATLAB. A contrast performance of IM is presented between traditional DTC and DTC with PID. As result, the new DTC with PID carries out improvement in the speed response as well reduces the ripples of torque.

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1. INTRODUCTION

Induction motor (IM) is very commonly utilized in residential and industrial plants. As a result of its properties such as simpler construction, unexpansive, high efficiency, and low maintenance [1]–[4]. Therefore, IM has been controlled (torque or speed) and experimented in early time, in competing with DC spritely excited motor [1]. The need for regulating speed and torque, as increasing in IM industrial applications and rapidly developed semiconductors, is demanded with high performance at steady state, starting, as well transient condition [5], [6]. There are several technics which can ache torque/speed control for example direct torque control (DTC) technique. The DTC technic was introduced by Depenbrock [7] and Takahashi and Ohmori [8]. It can achieve high performance for the dynamic application of machines with improved starting. It directly controls the electromagnetic torque and stator flux by electing the suitable switching state of the inverter. Takahashi and Noguchi first demonstrated DTC over 30 years. The approach was utilized for 3-phase alternating current (AC) motor drives in order to control the stator flux and torque. DTC may be performed by computing an electric motor's flux and torque using just quantifiable stator parameters such as the current and voltage of the stator of the motor drive [9]–[11]. Classic DTC involves two hysteresis comparators, one for calculating the error of stator flux coupled with another one for estimating torque error [12]–[14]. In comparison with field-oriented control of vector control [15], DTC is easier to apply since it does not need a complex block of parameters. Moreover, DTC could gain very acceptable and precise responses [16], [17].

The purpose of this paper is to compare conventional DTC and enhanced DTC with proportional, integral, and derivative (PID) controllers as well as reduce the torque ripples. Classic or conventional DTC is applied to control three phase induction machine via a flux reference that compares to the actual measured flux feedback to yield an error. Flux error feeds into two levels of hysteresis comparator. Also, actual measured electromagnetic torque is compare to reference to carry out errors that feeds into three-level hysteresis [18].

Conventional DTC is capable of controlling the torque of the induction motor. However, this technique of control has drawbacks such as flux droop at lower speeds, the inverter having variable losses of switching, and high ripples in current and torque [19]. Hence, adding a new loop for speed with PID controller in order to minimize the torque ripples as well enhancing overall performance [20], [21].

2. METHOD

Modeling of 3-phase IM is exhibited in the paper, the switching state vector, Lookup table, as well direct torque control. The model is based on [22]. Performance of the IM via DTC is analyzed during no load, steady state, and transient by using MATLAB/Simulink. In addition, the IM model is tested under various disturbance loads via DTC with PID closed loop. Modeling of the IM motor is based on the equivalent circuit in the direct quadrature rotating frame [23], [24]. Figure 1 is shown the pre-phase of the IM equivalent circuit model in the synchronous frame, which has been used for modeling the IM. Figure 1(a) depicts the direct equivalent circuit model of IM, while Figure 1(b) shows the quadrature equivalent circuit model of IM.

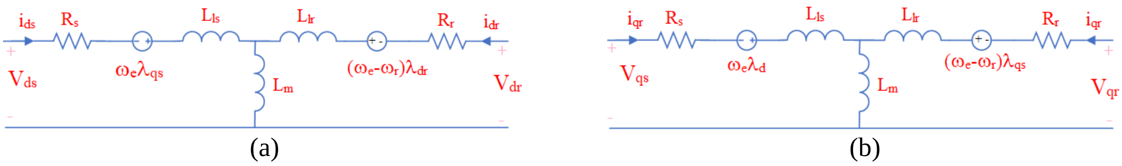


Figure 1. Modeling of induction motor in the synchronous rotating frame (a) direct equivalent circuit model of IM and (b) quadrature equivalent circuit model of IM

Equations of induction motor in d-q model are given by (1)-(4);

$$V_{ds} = R_s\, i_{ds} + \frac{d\lambda_{ds}}{dt} \tag{1}$$

$$V_{qs} = R_s\, i_{qs} + \frac{d\lambda_{qs}}{dt} \tag{2}$$

$$V_{dr} = R_r\, i_{dr} + \frac{d\lambda_{dr}}{dt} - (\omega_e - \omega_r)\lambda_{qr} \tag{3}$$

$$V_{qr} = R_r\, i_{qr} + \frac{d\lambda_{qr}}{dt} - (\omega_e - \omega_r)\lambda_{dr} \tag{4}$$

where V_{ds} direct stator voltage, V_{dr} direct rotor voltage, R_r and R_s are the resistance of rotor and stator, respectively. As well, i_{ds} is current of stator in direct axis, i_{dr} is the current of the rotor in the direct axis, i_{qs} is the quadrature stator current, i_{qr} is the quadrature rotor current. Also, ω_r and ω_e are the angular speed of the rotor and d-q reference frame, correspondingly. The flux linkage of the indication motor in both stator and rotor and d-q axes are λ_{ds}, λ_{dr}, λ_{qs}, *and* λ_{dqr}. The indication motor is a squirrel cage rotor which has a voltage of rotor zero in (3) and (4). The flux equation can be written as (5)-(7):

$$\lambda_{ds} = L_s\, i_{ds} + L_m\, i_{ds} \tag{5}$$

$$\lambda_{dr} = L_r\, i_{dr} + L_m\, i_{dr} \tag{6}$$

$$\lambda_{qs} = L_s\, i_{qs} + L_m\, i_{qs} \tag{7}$$

$$\lambda_{qr} = L_q\, i_{qr} + L_m\, i_{qr} \tag{8}$$

where L , and L_r are the self-inductance of the stator and rotor, respectively, and the magnetizing inductance is L_m. Also, the self-inductance can be written as (9), (10).

$$L_s = L_{ls} + L_m \tag{9}$$

$$L_r = L_{lr} + L_m \tag{10}$$

The develop electromagnetic torque and speed of rotor are given by (11)-(13),

$$T_e = \frac{3}{2}\frac{P}{2} L_m(i_{qs}i_{dr} - i_{ds}i_{qr}) \tag{11}$$

$$T_e = \frac{3}{2}\frac{P}{2} (\lambda_{dm}i_{qr} - \lambda_{qm}i_{dr}) \tag{12}$$

$$\frac{d\omega}{dt} = \frac{P}{2J} (T_e - T_L) \tag{13}$$

where P, J, T_e, and T_L are poles number, the inertia of the rotor, electromagnetic torque, and torque of load, respectively.

2.1. Direct torque control principle

Takahashi and Noguchi [8] freshly presented DTC, which was applied for the control induction motor. The basic principle of DTC is to regulate stator flux magnitude and electromagnetic torque in real-time in the interior of relevant bands of error by electing the accurate vector of stator voltage. Figure 2 depicts a classical DTC block diagram for an inverter-fed three-phase IM. Where the Block diagram contains an estimator of flux and Torque, a voltage source inverter, a switching table, hysteresis comparator of torque and flux. The basic principle of DTC is constructed on a voltage source inverter with 8 vectors of stator voltage, 6 vectors are not zero vector states, whereas the lasting 2 are zero vectors. Thus, keeping developed torque and stator flux within the appropriate hysteresis band. The lookup table [16], [25] determines the reference of the voltage vector. Classic DTC implies two hysteresis controllers that use two signals of feedback. One is the flux of the stator, and another is the developed torque, in order to evaluate the flux of the stator and developed torque error by contrasting the signal of feedback to control or reference value. Then, error signals are fed to the hysteresis comparator or controller.

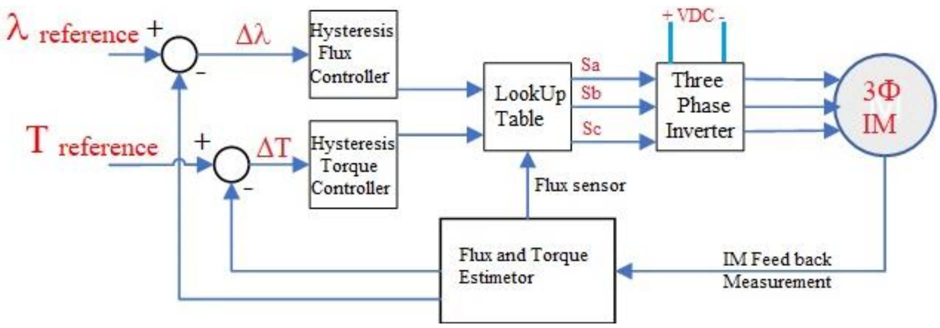


Figure 2. Block diagram of direct torque control induction motor

2.2. Torque and flux hysteresis comparators

The principle of traditional DTC is two control loops: one for torque and the second for the flux of the stator, where the control value is compared to the feedback signals. The stator flux error signal is controlled by two levels of hysteresis comparator, whereas the torque error signal is controlled by a three-level of hysteresis comparator. Figure 3 depicts the hysteresis controller band. Figure 3(a) shows two-level bands of the hysteresis controller while Figure 3(b) depicts three-level bands of the hysteresis controller.

2.3. Switching table

The conventional DTC technique selects the proper voltage vector using a lookup table of voltage vector to accomplish DTC of torque and flux linkage [7], limiting it to a given range of errors. When a vector of voltage is employed, the flux of the stator promotions a shaft angle between the flux vector of the rotor and the stator, resulting in electromagnetic torque escalations. There are six sectors (S) in the traditional DTC technique for voltage vectors. To enhance the magnitude of the stator vector increasing, as shown in S1 in Figure 4, vectors V6, V2, and V1 might be implanted. On the other hand, choosing V5, V4, and V3 can reduce flux vector magnitude. By utilizing one of vectors V7 or V0, the developed torque decreases, while the vector of stator flux remains almost unchanged. As result, selecting voltage vectors V2, V3, and V4 can increase the torque of the motor, whereas voltage vectors V1, V5, and V6 can decrease the torque. Table 1 presents the lookup table of voltage.

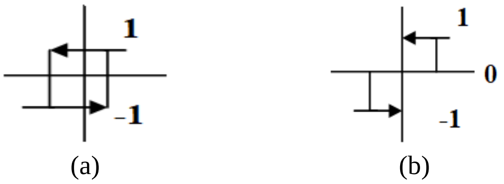


Figure 3. Hysteresis controller band: (a) two level and (b) three level of hysteresis

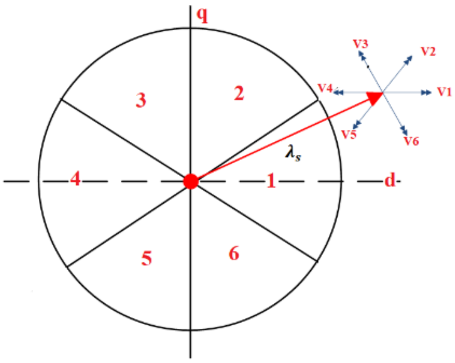


Figure 4. Election of required vector of voltage stator flux vector on sector 1 (S1)

Table 1. Lookup table

Δλ	ΔTe	S1	S2	S3	S4	S5	S6
	1	v2	v3	v4	v5	v6	v1
1	0	v7	v0	v7	v0	v7	v0
	-1	v6	v1	v2	v3	v4	v5
	1	v3	v4	v5	v6	v1	v2
-1	0	v0	v7	v0	v7	v0	v7
	-1	v5	v6	v1	v2	v3	v4

2.4. PID controller

By using classic DTC results in an uncontrol speed, a new control loop with PID control is utilized to control the speed and become the reference of the torque. PID controller is widely implied in recent system control [25]. The controllers entirely include necessary features such as fast response on changing the input reference, lower ripples on the torque [26], [27] an increase in the control signal to reduce the error to zero, and acceptable activity inside the control blunder zone to eliminate motions.

The subsidiary method improves the model system's soundness and allows for an increase in *Kp* gain, which increases the reaction time of the controller. PID controller output is made up of three terms: blunder flag, blunder vital, and blunder subsidiary. The equation of PID controller is given as (14) [28],

$$\frac{U(s)}{E(s)} = K_p + \frac{K_i}{S} + K_d S \quad (14)$$

where k_p, k_i, and k_d are proportional gain, derivative gain, and integral gains, respectively. U(s) is output control, which is referred to the control signal of electromagnetic torque of DTC. Figure 5 shows the PID controller with DTC which has a new loop of speed.

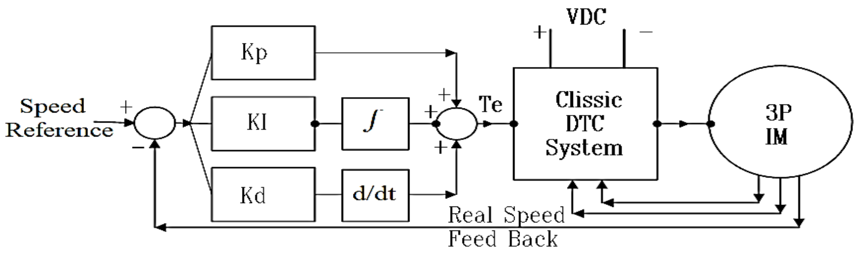


Figure 5. Block diagram of PID controller with DTC

Induction motor controls via DTC with PID and switching table for electing the right voltage in order to produce the required speed or torque with minimum ripples and enhance the performing of classic DTC vector control system. Hence, the drawback of DTC, which are ripples or distortions in electromagnetic torque output as well as current because of electing sector, speed lack at low rpm and starting, is carried away [29].

3. RESULTS AND DISCUSSION

In this section, PID with DTC of IM is simulated and utilizing simulation in a MATLAB program. There are many experiments which applied to the system model in the paper for examining performing characteristics for both classical systems of DTC and using PID controller. A compering between the two systems of DTC for control IM simulation under the same load condition. Table 2 presents the load torque disturbance with time.

Table 2. Display the load torque

Time Sec	Load Torque (N.m)
0	0
0.2	8
0.5	10
0.8	6

Figure 6 shows the three-phase current of the stator of induction with zooming depicts the change in the current as a response to rising the torque load. Figure 7 shows both the torque of the induction motor via classic DTC in Figure 7(a) and PID with DTC in Figure 7(b), where the performance of motor torque and speed are examined under load and some different torque loads in both classic DTC and PID with DTC using a new loop with PID for speed control reduces the ripples in the torque.

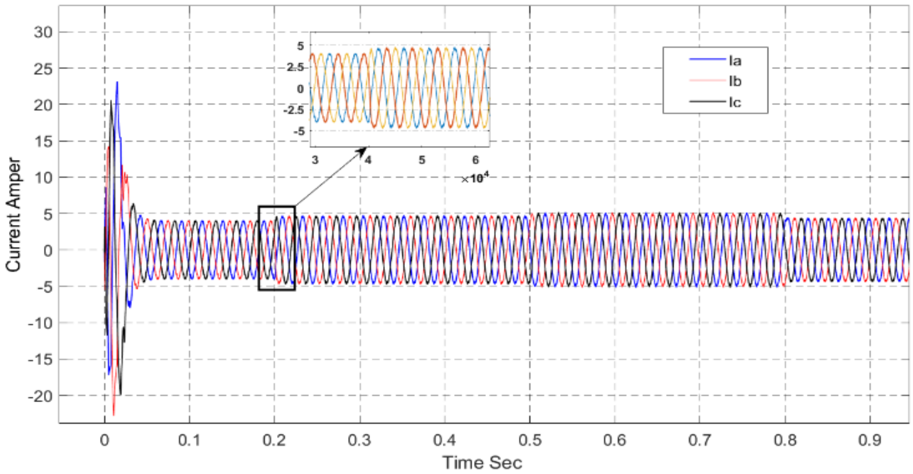
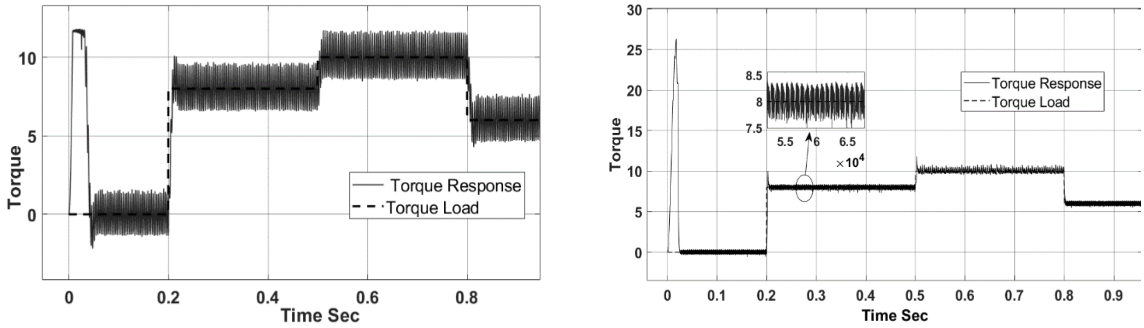


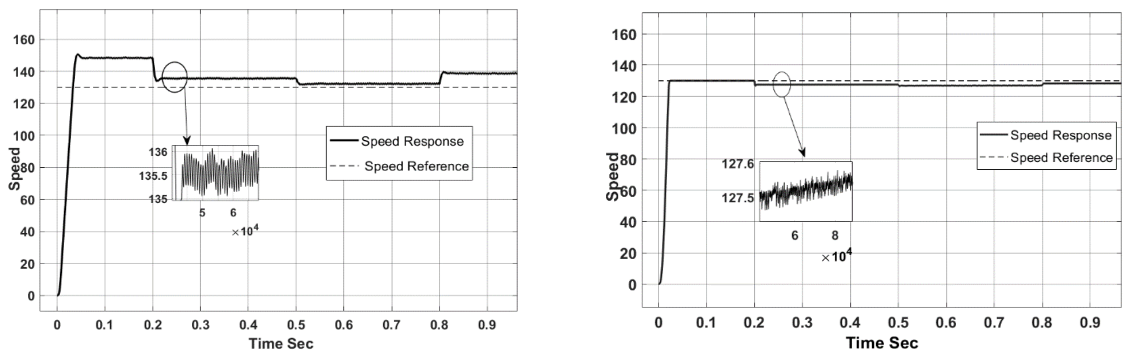
Figure 6. Three phase current of stator of IM

Figure 8 shows the response of speed with classic DTC in Figure 8(a) as well PID with DTC in Figure 8(b). Additionally, the ripples in the estimated speed are decreased and enhance the speed of rotor response of DTC with PID. Figure 9 displays the flux of IM; Figure 9(a) displays the flux without the PID controller whereas Figure 9(b) shows it with PID. Additionally, the estimated flux is enhanced of IM via DTC with PID.



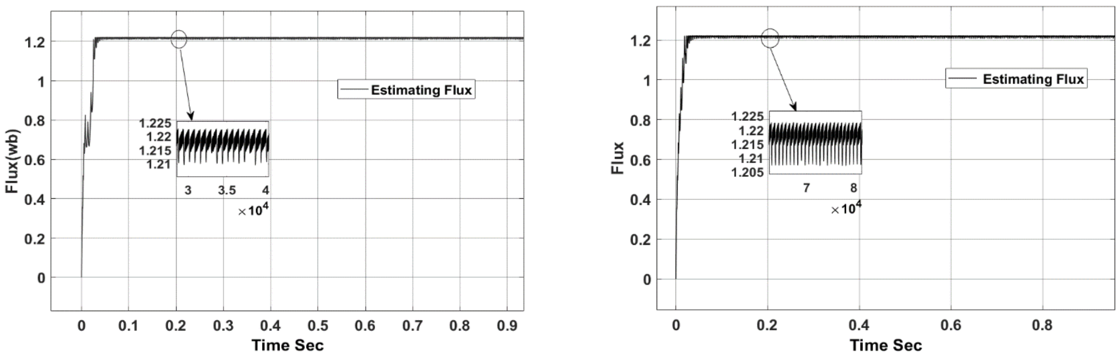
(a) (b)

Figure 7. Comparing simulation results of IM torque performance (a) classic DTC and (b) DTC with PID



(a) (b)

Figure 8. Speed comparing simulation results of IM performance (a) classic DTC and (b) DTC with PID



(a) (b)

Figure 9. Comparing of IM flux (a) estimated flux of classic DTC (b) estimated flux DTC with PID

The system demonstrates that PID controller with DTC is better outperforms than typical DTC in terms of output performance, electromagnetic torque, flux, and speed response in the same conduction of load disturbance. The simulation carries out reduction in the torque ripples as shown in Figure 7. As well as very satisfactory speed response.

4. CONCLUSION

The paper exhibits the model of IM. Classic direct torque control is illustrated with a hysteresis controller for both the control loop, torque loop, and flux loop. PID controller utilized for speed loop to improve overall the performance of induction motor. In comparison, the response of torque is better and more satisfactory via using a PID controller with a typical DTC. Moreover, it produces less ripple in torque. As result, applying a new loop with a PID controller on the speed loop that produces torque reference further the functioning characteristic of DTC for induction motor that solves the drawback of traditional direct torque control.

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