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Proposed Voltage Vector to Optimize Efficiency of Direct Torque Control

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ABSTRACT

Compared to field-oriented control (FOC) system, direct torque control (DTC) system has gained attractiveness in control drive system because of its simpler control structure and faster dynamic control. However, supplying the drive system with rated flux at light load will decrease the power factor and efficiency of the system. Thus, an optimal flux has been applied during steady-state in order to maximize the efficiency of drive system. But when a torque is suddenly needed, for example during acceleration, the dynamic of the torque response would be degraded and it is not suitable for electric vehicle (EV) applications. Therefore, a modification to the voltage vector as well as look-up table has been proposed in order to improve the performance of torque response.

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1. INTRODUCTION

A simple control structure of DTC that has been proposed by Takahashi [1] has gained popularity in industrial motor drive applications. Due to its simpler control structure and faster dynamic control compared to FOC system, the popularity of DTC system is increased rapidly in the past decades [1-3]. In FOC, the torque and flux are controlled based on stator current components whereas in DTC, the torque and flux are controlled directly and independently via an optimized selection of voltage vectors using look-up table.

As illustrated in Figure 1, the simple control structure of DTC consists of three-phase voltage source inverter (VSI), hysteresis comparators, stator flux and torque estimators, as well as look-up table. By using two-level and three-level hysteresis comparators, the stator flux and electromagnetic torque can be controlled independently. Based on look-up table, an appropriate voltage vector is selected to satisfy its flux and torque requirement. The selected voltage vector is then applied to activate the VSI in which it will in turn operate the induction machine.

A fast instantaneous control of torque and flux occurs because of de-coupled control of torque and flux, in which it leads to the faster dynamic control of DTC system compared to the FOC system. To achieve more accurate flux estimation, the current model is applied during low speed operations whereas the voltage model is employed in high speed operations. Only stator resistance and terminal quantities such as stator voltages and currents are required in the estimation of voltage model.

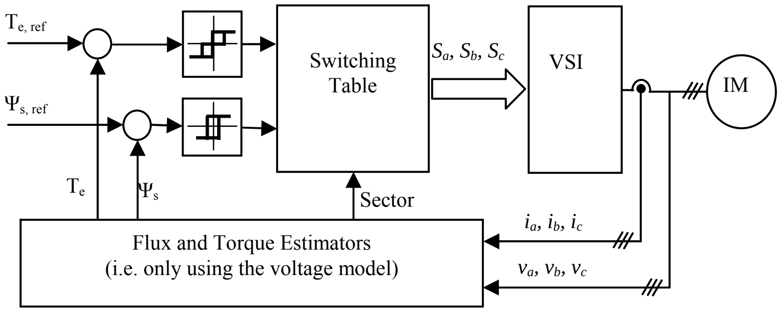


Figure 1. Simple Control Structure of DTC

In order to fully utilized the power and lengthen the life span of induction motor, an optimal efficiency of the drive system is an important factor to be implemented in EV applications. Usually, induction motors are operated at light load and thus, supplying the motor at its rated flux will decrease the power factor and efficiency of the drive [4]. Therefore, researchers have been working on the efficiency optimization of drive system in recent years but there is still no suitable method to achieve the fast instantaneous torque response of DTC drive.

Two main methods have been proposed to maximize efficiency in DTC drive system. These methods are known as flux search controller (SC) [4-12] and loss model controller (LMC) [13-16]. The former method measures input power or stator current of the system while decreasing the flux value in a consecutive step. When the input power or stator current is at its minimized value, the optimal flux is obtained. Meanwhile, by applying loss model equations, the optimal flux of latter method is determined. When copper losses are approximately equal to iron losses, the optimize efficiency of drive system is achieved.

Instead of just concentrated on searching for the optimal flux, improving the dynamic torque is also an essential factor to be considered in order to optimize the efficiency of DTC system. This is because supplying the drive system at its optimum flux will cause the torque response to be degraded when a rated torque is suddenly needed. Therefore, a modification to look-up table as well as DTC algorithm has been done so that the dynamic torque is achieved during transient state.

2. EFFECTS OF VOLTAGE VECTOR

The effect of voltage vector on torque response has been studied in order to improve the performance of torque response, as shown in Figure 2. Based on Figure 2 (b), in sector 4, the voltage vectors, $\boldsymbol{v}_{s,5}$ and $\boldsymbol{v}_{s,6}$, are applied to increase and decrease the stator flux, respectively. In Figure 2 (a), $\boldsymbol{v}_{s,5}$ is activated to increase the stator flux and at the same time, it is capable to increase the output torque dynamically. But activating $\boldsymbol{v}_{s,6}$ to decrease the flux causes the output torque to increase slightly, and thus, it degraded the torque performance. This case is worsening when the flux is set to its optimized value for efficiency purposes.

In sector 4, $\boldsymbol{v}_{s,5}$ is considered as the most optimized voltage vector compared to $\boldsymbol{v}_{s,6}$ because it has larger tangential to the stator flux and consequently, it can produce dynamically torque. Note that, at the very beginning of sector 4, the response of torque is more dynamic when $\boldsymbol{v}_{s,5}$ is activated for a longer time because this voltage vector is tangential to stator flux. Therefore, the voltage vector that is applied to decrease the stator flux has to be modified so that the proposed voltage vector can produce larger tangential to stator flux in order to improve torque performance.

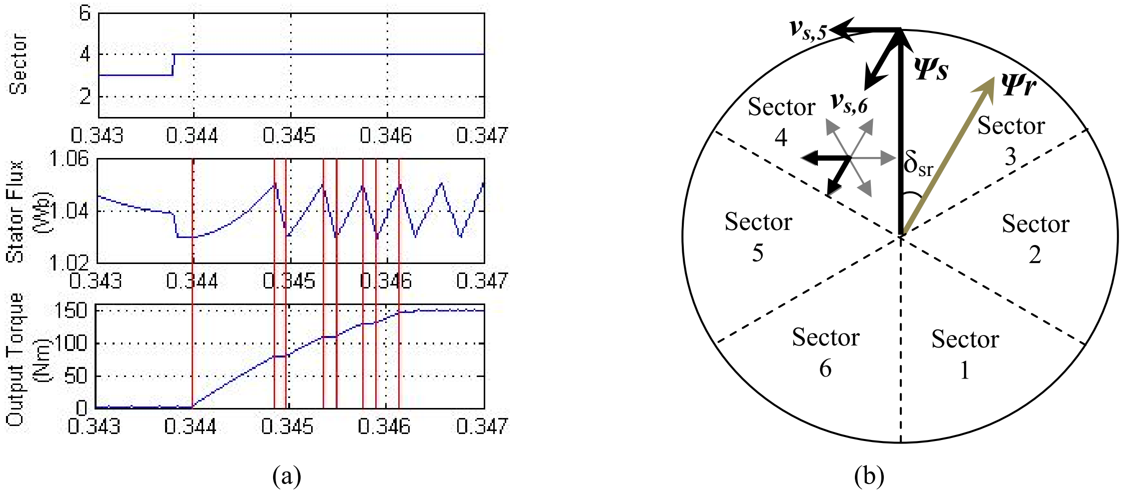


Figure 2. Voltage Vector (a) Effects on Torque Response, and (b) Controlling Stator Flux

3. RESEARCH METHOD

A proposed voltage vector is produced between two conventional voltage vectors by applying vector's parallelogram law. Compared to the conventional voltage vector, the proposed voltage vector has longer amplitude and an angle of 30° adjacent to the conventional voltage vector. For instance, addition of $\boldsymbol{v_{s,5}}$ to $\boldsymbol{v_{s,6}}$ will obtain $\boldsymbol{v_{s,5\text{-}6}}$, as shown in Figure 3, and their respective equations are calculated in (1).

$$\boldsymbol{v_{s,5-6}} = [(\boldsymbol{v_{sd,5}} + \boldsymbol{v_{sd,6}}), (\boldsymbol{v_{sq,5}} + \boldsymbol{v_{sq,6}})] \quad (1)$$

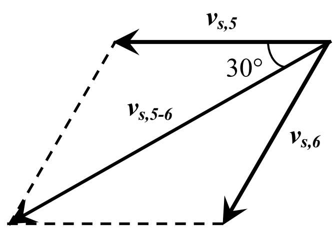


Figure 3. Vector's Parallelogram Law

In Figure 4, the red line indicates the proposed voltage vector whereas the black line represents the conventional voltage vector. In proposed method, $\boldsymbol{v_{s,5\text{-}6}}$ is activated instead of $\boldsymbol{v_{s,6}}$ when the flux is required to be reduced. The proposed voltage vector has a larger tangential to stator flux in which it is believed to improve the torque performance when decreasing the flux. In conventional DTC system, the switching of voltage vector is more regular in the middle of a sector compared to the beginning and end of a sector. Consequently, activating the proposed voltage vector also reduces the switching of voltage vector when it is in the middle of a sector and thus, it increases the torque dynamically.

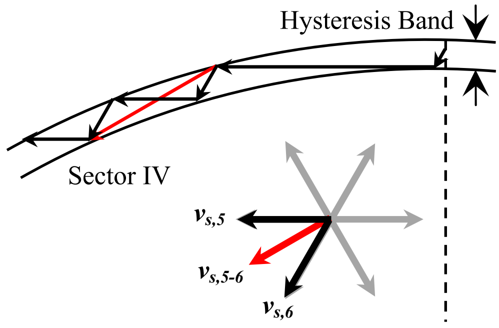


Figure 4 Proposed Voltage Vector

By applying the proposed method, the amplitude of proposed voltage vector is almost twice of the amplitude of conventional method. The increasing amplitude of voltage vector will cause the value of stator flux and output torque to be increased as well. Therefore, the amplitude of proposed voltage vector can be reduced by estimating a ratio between proposed and conventional voltage vector, as follows:

$$Ratio = \frac{V_{s,k-k}}{V_{s,k}} \tag{2}$$

where $V_{s,k\text{-}k}$ is the amplitude of proposed voltage vector and $V_{s,k}$ is the amplitude of conventional voltage vector.

After introducing the estimated ratio, it can be seen that the d-q axis of proposed voltage vector is exchanged with the d-q axis of conventional voltage vector. Therefore, the d-q axis of proposed voltage vector is given in (3) and (4):

$$\boldsymbol{v_{sd,k-k}} = \frac{2}{3} V_{DC}(0.866S_b - 0.866S_c) \tag{3}$$

$$\boldsymbol{v_{sq,k-k}} = \frac{2}{3} V_{DC}(S_a - 0.5S_b - 0.5S_c) \tag{4}$$

The switching state of VSI can be implemented in the look-up table with modified DTC algorithm since d-q axis of proposed voltage vector is exchanged with d-q axis of conventional voltage vector. The proposed look-up table with modified DTC algorithm is shown in Table 1. In order to improve the dynamic of output torque, the modified look-up table with DTC algorithm is implemented only during transient state. Meanwhile, the conventional look-up table is applied during steady-state.

Table 1 Modified Look-Up Table

Stator Flux Error Status, Ψ_s^+	Torque Error Status, T_{stat}	Sector 1	Sector 2	Sector 3	Sector 4	Sector 5	Sector 6
1	1	$v_{s,2}$	$v_{s,3}$	$v_{s,4}$	$v_{s,5}$	$v_{s,6}$	$v_{s,1}$
	0	$v_{s,0}$	$v_{s,7}$	$v_{s,0}$	$v_{s,7}$	$v_{s,0}$	$v_{s,7}$
	-1	$v_{s,5\text{-}6}$ ($v_{s,6}$)	$v_{s,1\text{-}6}$ ($v_{s,5}$)	$v_{s,1\text{-}2}$ ($v_{s,4}$)	$v_{s,2\text{-}3}$ ($v_{s,3}$)	$v_{s,3\text{-}4}$ ($v_{s,2}$)	$v_{s,4\text{-}5}$ ($v_{s,1}$)
0	1	$v_{s,2\text{-}3}$ ($v_{s,3}$)	$v_{s,3\text{-}4}$ ($v_{s,2}$)	$v_{s,4\text{-}5}$ ($v_{s,1}$)	$v_{s,5\text{-}6}$ ($v_{s,6}$)	$v_{s,1\text{-}6}$ ($v_{s,5}$)	$v_{s,1\text{-}2}$ ($v_{s,4}$)
	0	$v_{s,7}$	$v_{s,0}$	$v_{s,7}$	$v_{s,0}$	$v_{s,7}$	$v_{s,0}$
	-1	$v_{s,5}$	$v_{s,6}$	$v_{s,1}$	$v_{s,2}$	$v_{s,3}$	$v_{s,4}$

As shown in Table 1, the respective proposed voltage vector can be obtained when the voltage vector in bracket is activated. In other words, the voltage vector in bracket indicates the switching state of the respective proposed voltage vector. For example, in sector 1, $\boldsymbol{v_{s,2}}$ is applied to increase the flux and $\boldsymbol{v_{s,2\text{-}3}}$ is activated to decrease the flux. Both of these voltage vectors are capable to increase the output torque. But in order to activate $\boldsymbol{v_{s,2\text{-}3}}$, the switching state of $\boldsymbol{v_{s,3}}$ has to be implemented.

4. RESULTS AND ANALYSIS

The simulation of DTC drive system has been constructed using MATLAB's SIMULINK blocks, as shown in Figure 5. The specifications and parameters of induction machine used in the simulation are given in Table 2. The modified look-up table with DTC algorithm has been attached in parallel to the conventional look-up table with DTC algorithm. The modified look-up table with DTC algorithm has been activated for 5ms only during transient state whereas during steady-state, the conventional look-up table with DTC algorithm has been implemented.

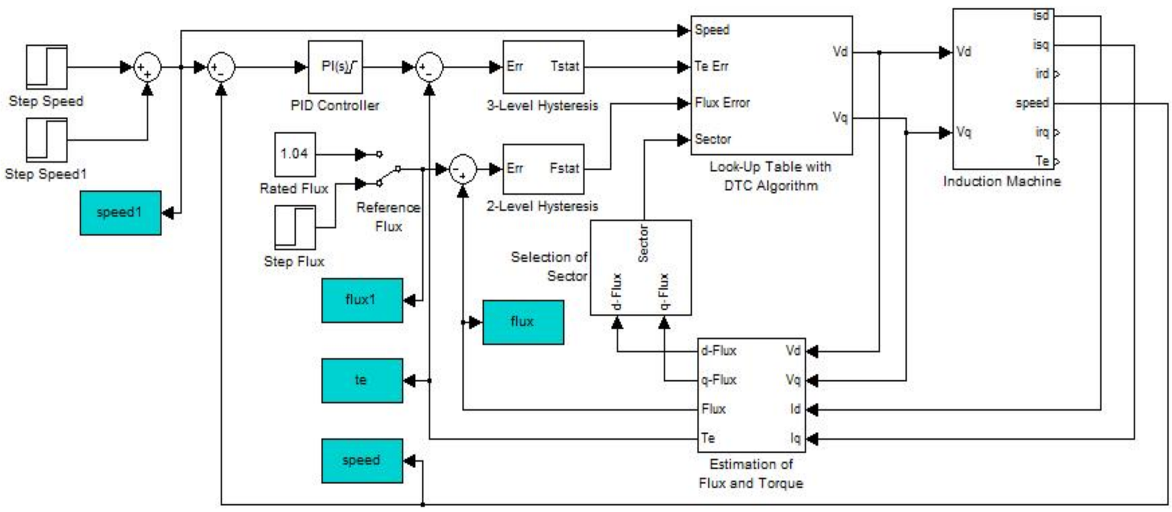


Figure 5. Simulation of DTC Drive System

Table 2 Specifications and Parameters of Induction Motor

Parameters	Values
DC voltage	340V
Stator resistance, R_s	0.25Ω
Rotor resistance, R_r	0.2Ω
Stator inductance, L_s	0.0971H
Rotor inductance, L_r	0.0971H
Mutual inductance, L_m	0.0955H
Frequency,f	50Hz
Inertia motor, J	0.046kgm^2
Pole pairs, p	2
Sampling time	50µs
Rated flux	1.04Wb
Rated torque	150Nm

In order to optimize the efficiency of drive system, the SC method has been implemented in DTC drive system. The SC is activated at t=1s with step flux of 0.043Wb, sample time of 0.1s and at its rated speed. Basically, the rated flux is applied to the system and after the system has reached its steady-state, the corresponding current value is measured. Then, the flux is decreased with step flux and the corresponding current value is measured again. When the new stator current ($I_{s,\ k}$) is smaller than the previous stator current ($I_{s,\ k\text{-}1}$), the flux value is decreased with step flux, and vice-versa. The SC method is continuing until it reaches its optimum flux value. From Figure 6, the optimal flux is obtained after 0.3s with flux value of 0.89Wb.

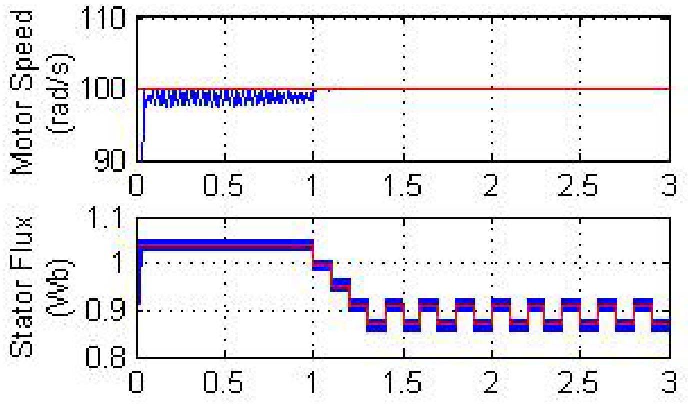


Figure 6. Flux Search Controller

3.1. Voltage Vector

As discussed earlier, the conventional and proposed voltage vector has been proven in Figure 7. The blue line indicates the conventional voltage vector whereas the red line denotes the proposed voltage vector. Based on this figure, the proposed voltage vector has same amplitude as the conventional voltage vector and it is 30° adjacent to the conventional voltage vector.

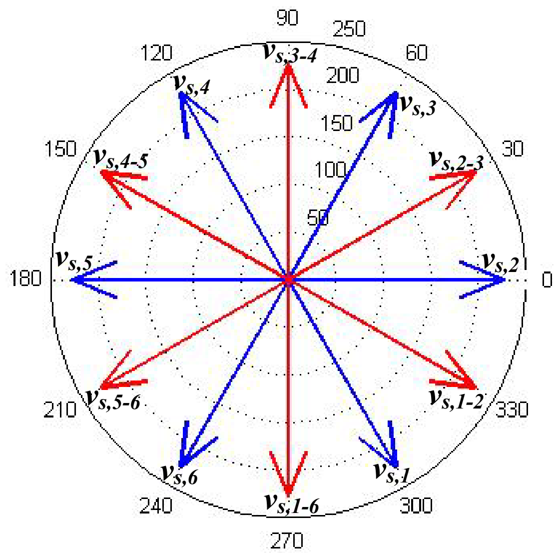
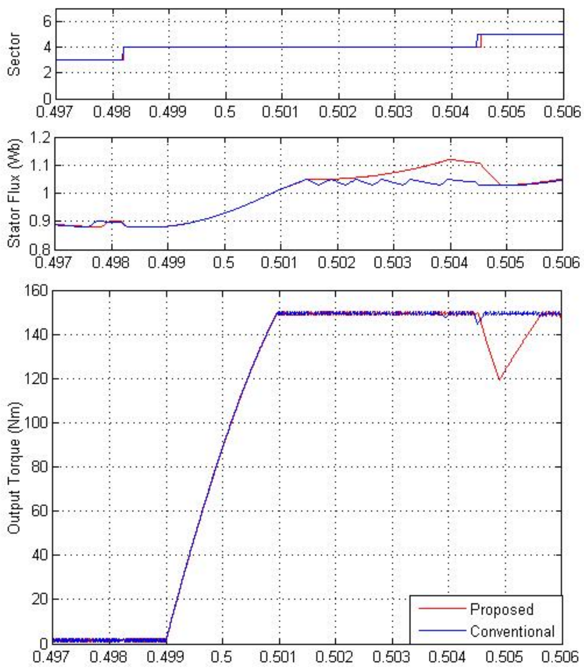


Figure 7. Voltage Vector

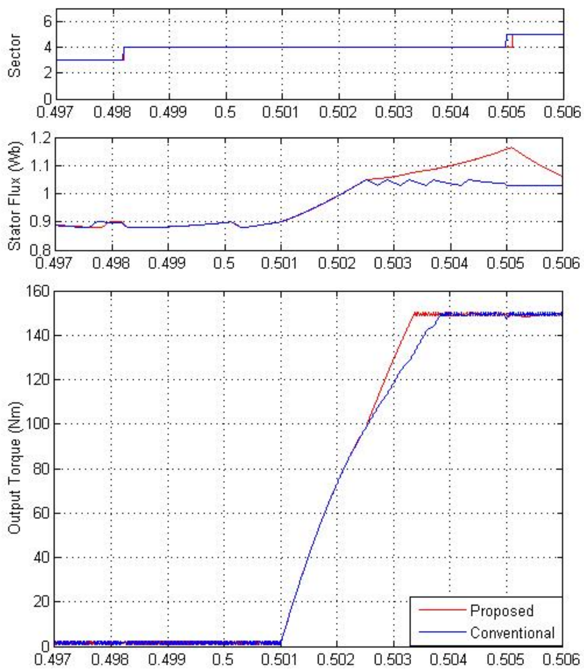
3.2. Torque Performance

In order to examine the effectiveness of proposed voltage vector towards the dynamic torque at light load, a step flux and torque is applied from 0.89Wb to 1.04Wb and from 0Nm to 150Nm respectively at beginning, middle and end of a sector, as shown in Figure 8. In Figure 8 (a) and (b), the stator flux of proposed method is increased beyond rated flux for a short duration because d-axis stator flux is slightly decreased and q-axis stator flux is slightly increased compared to conventional method. However, the output torque is not affected by the slightly increased of stator flux. Meanwhile, in Figure 8 (a), the output torque is decreased to 120Nm at t=0.505s because the flux is decreased to its rated value.

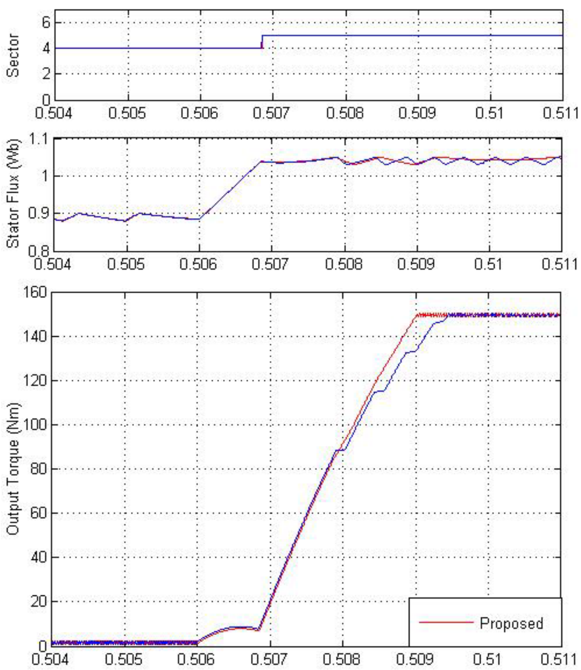
At beginning of a sector, the conventional and proposed method achieved the rated torque in 2ms. But when a step torque is applied at the middle of a sector, the conventional method requires 2.8ms to achieve its rated torque whereas the proposed method needs 2.4ms to attain its rated torque. The proposed method has improved the performance of torque response by 0.4ms compared to conventional method. Meanwhile, at the end of a sector, the conventional and proposed method requires 3.5ms and 3.0ms to reach their rated torque, respectively. By implementing the proposed method, the torque response can be improved by 0.5ms.



(a)



(b)



(c)

Figure 8 Torque Performance on (a) Beginning, (b) Middle, and (c) End, of a Sector

From Figure 8 (a), the applied voltage vector is activated for a longer period since the voltage vector is tangential with respect to stator flux. As mentioned earlier, only the voltage vector that is used to decrease the stator flux is modified; hence, the conventional and proposed method applied the same voltage vector to increase flux in which it caused the conventional and proposed method to reach rated torque at the same time. Based on Figure 8 (b) and (c), it can be seen that the torque performance is improved when the voltage vector is activated for a longer period, in which it can be controlled by generating a larger tangential to the stator flux. Besides that, voltage vector that has larger tangential respective to stator flux is able to reduce the switching of voltage vector. Consequently, it is necessary to modify the angle of voltage vector so that a dynamic torque can be produced during transient state.

5. CONCLUSION

During steady-state, the flux has to be set to an optimum value in order to optimize the efficiency of DTC drive system. However, the dynamic of output torque would be degraded when a torque is suddenly needed and it is not suitable to be implemented in EV applications. Therefore, an adjustment to the look-up table as well as DTC algorithm has been constructed by modifying the angle of voltage vector so that a larger tangential with respect to the flux is yielded. Based on the results, it can be concluded that the proposed voltage vector improves the performance of torque response during transient state. Therefore, this method is believed to optimize the efficiency of DTC drive system and at the same time, the dynamic of torque response is improved.

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