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Correction of flux error in low speed range of DTC drives of induction machines

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Abstract
The conventional direct torque control (DTC[1]) method suffers a flux drop at low speeds, which is due to the long selection of zero (neutral) voltage vectors in these speed areas. Past studies with the continuous switch of direct and reverse active vectors to achieve proper flux adjustment, this procedure causes high and consecutive overshoots in the hysteresis band that causes a sharp increase in the switching frequency and increase in the torque and current ripple, which means decrease in the drive efficiency. In this article, a modified method for setting the standard DTC current is introduced, which can be achieved by controlling only one band (low or high band) at low speeds. The introduced method by reducing the selection of zero voltage vectors and at the same time minimizing the number of reverse voltage vectors prevents the loss of flux in low speed areas. In addition, it is effective in reducing torque ripple and current in low speed mode and a significant reduction in switching frequency will also be achieved. The effectiveness of the proposed method in the simulation which is done in MATLAB software will be proved.

Keywords: direct control torque, flux adjustment, induction motor

Introduction

Asynchronous (induction) machines have been used since about a hundred years ago due to advantages such as no complicated structure, high power, good reliability, more reasonable price, low volume and weight. Among the advantages of asynchronous motors compared to DC motors are size, weight and less rotor inertia, higher efficiency, better stability, lower cost, less maintenance and easier maintenance than DC motors. The modern method of driving induction motors is called DTC. In this method, by using the feedback signals obtained from the current and voltage of the stator of the induction motor and by modeling the operation of the motor, the torque and linkage flux of the motor are estimated and based on the error of the flux and torque of the motor, appropriate keying commands are applied to the inverter. Therefore, the torque and stator current of the induction motor will be controlled, and the appropriate speed control will be created. Advantages such as convenient implementation, fast dynamic response and lack of dependence on engine parameters have caused this control method to attract a lot of attention in the research community. Although classical DTC still has its own defects such as high torque ripple [2], it requires very fast sampling and flux drop in low speed areas. It is true that these flaws are important and significant. Various methods have been introduced in order to improve the performance of the DTC method in the drive of induction motors. some of this methods are increasing the number of state vectors, using three-level inverters instead of two levels, DTCs based on multi-level inverters [3-10] A common method is integration of SVM[2] with DTC under the title of DTC-SVM. Most of these methods solve the basic defects of the classical DTC method to an acceptable extent, but they greatly increase the computational load of the system and make the structure of the drive complicated, and for its implementation, it is necessary to know the parameters of the motor at any moment. Therefore, introducing a method that can improve the defects of the classic DTC method while being simple and independent from the parameters of the motor is of great importance.

Control of induction machines by DTC method

The general schematic of direct torque control of induction motors is figure1:

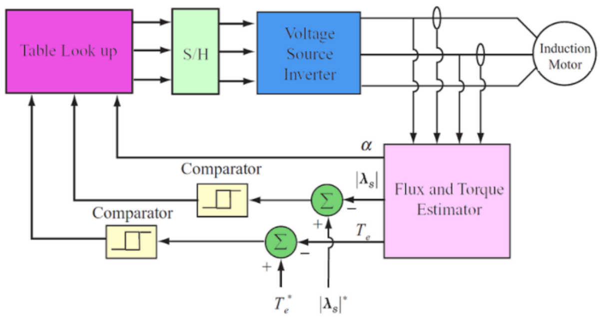

Figure 1 Schematic of direct torque control of induction motors

The hysteresis controller in the direct torque method generates torque and flux error status. Based on these error states and the stator flux angle vector in order to maintain the torque error and the stator flux within the hysteresis band. the required control voltage vector is selected as shown in figure 2,

Table 1. DTC method switch table

stator		1	2	3	4	5	6
Flux	Torque						
$\Delta\psi$=1	ΔT=1	V_2	V_3	V_4	V_5	V_6	V_1
	ΔT=0	V_7	V_0	V_7	V_0	V_7	V_0
	ΔT=-1	V_6	V_1	V_2	V_3	V_4	V_5
$\Delta\psi$=0	ΔT=1	V_3	V_4	V_5	V_6	V_1	V_2
	ΔT=0	V_0	V_7	V_0	V_7	V_0	V_7
	ΔT=-1	V_5	V_6	V_1	V_2	V_3	V_4

[1] direct torque control

[2] spatial vector modulation

The structure of a 2-level voltage source inverter (VSI) used in DTC drives is shown in figure3.

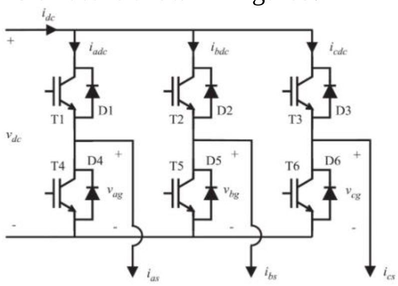

figure3- The structure of a 2-level voltage inverter

The important thing about this 2-level inverter is that two keys that exist in the same leg cannot be activated at the same time because it causes a short circuit of the source. The table 1 shows the different modes for the keys,

Table 1. Different switch states to create different voltage vectors

Voltage Vector	T_1/T_4	T_2/T_5	T_3/T_6
V_0	0	0	0
V_0	1	0	0
V_0	1	1	0
V_0	0	1	0
V_0	0	1	1
V_0	0	0	1
V_0	1	0	1
V_0	1	1	1

The state vector when all switches are inactive (V0) and the state vector when all switches are active (V7) are called zero or neutral voltage vector. The other situation that remains are the active or main vectors whose absolute magnitude is 2/3 of the DC[3] link voltage.

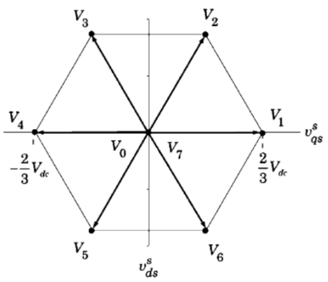

figure4- Different inverter output voltage vectors

According to the 6 active vectors, the voltage vector page is divided into 6 parts, each of which is named with its own vector. figure 5 shows this zoning.

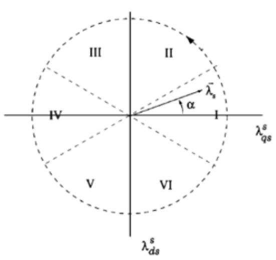

figure5- Zoning of inverter vectors

[3] direct current

Each vector is located exactly in the center of its respective area. Now that we have fully understood the structure of the inverter, we will discuss how to directly control the torque.

The electric torque relationship in terms of rotor and stator variables can be expressed as follows:

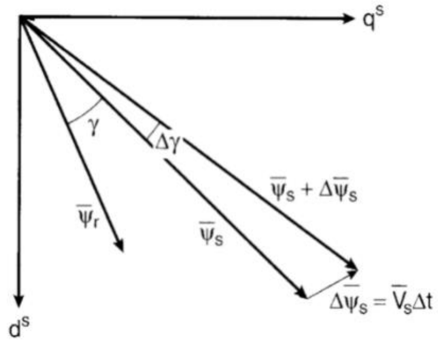

figure6- Display vectors on dq page

$$T_e = \frac{3}{2} p \frac{L_m}{\sigma L_s L_r} |\vec{\psi}_s||\vec{\psi}_r| sin\gamma \quad (1)$$

$$\vec{\psi}_s \left(= \left[\psi_{sd}\ \psi_{sq}\right]^T\right) \quad (2)$$

$$\vec{\psi}_r (= \left[\psi_{rd}\ \psi_{rq}\right]^T) \quad (3)$$

$\vec{\psi}_s$ is stator flux vector and $\vec{\psi}_r$ is rotor flux vector

ω_r is the rotor speed of the electromotor in radians per second. P is the even number of motor poles, and γ is the load angle between the stator and rotor shafts.

$$\sigma = 1 - L_m^2 / L_s L_r \quad (4)$$

$$0 = R_r . \vec{i}_r - j\omega_r . \vec{\psi}_r + \frac{d\vec{\psi}_r}{dt} \quad (5)$$

$$\vec{\psi}_s = L_s . \vec{i}_s + L_m . \vec{i}_r \quad (6)$$

$$\vec{\psi}_r = L_r . \vec{i}_r + L_m . \vec{i}_s \quad (7)$$

8 shows the relationship between stator flux and stator voltage

$$\vec{v}_s = R_s . \vec{i}_s + \frac{d\vec{\psi}_s}{dt} \quad (8)$$

if we ignore the stator ohmic voltage drop

$$\frac{d\vec{\psi}_s}{dt} = \vec{v}_s - R_s . \vec{i}_s \approx \vec{v}_s \quad (9)$$

Therefore, in a very small time slice, flux changes are equal to voltage

$$\Delta\psi_s = V_s \Delta t \quad (10)$$

Also, if we want to write the rotor flux in terms of the stator flux

$$\frac{d\psi_r}{dt} + \left(\frac{L_m}{\sigma L_s L_r} - \frac{R_r}{L_r} - j\omega_{sl}\right)\psi_r = R_r \frac{L_m}{\sigma L_s L_r}\psi_s \quad (10)$$

In 10, R_s and R_r are stator resistance and rotor resistance respectively, and L_s, L_r, L_m are stator inductance, rotor inductance and mutual inductance respectively. 11 is the stator voltage vector, which is obtained based on the selection of switching mode (Sa, Sb and Sc) from the relevant table [11].

$$\vec{v}_s(= [v_{sd}\, v_{sq}]^T) \quad (11)$$

12 is the stator current and 13 is the rotor current.

$$\vec{\imath}_s(= [i_{sd}\, i_{sq}]^T \quad (12)$$

$$\vec{\imath}_r(= [i_{rd}\, i_{rq}]^T) \quad (13)$$

The meaning of the above equations is that the rotor flux depends on the stator flux with a first-order delay, which means that when the stator flux changes, the rotor flux can be considered constant and ignore its changes.

To put it more clearly, by selecting and applying the appropriate voltage vector, the stator flux can be changed and the angle between the rotor flux and the stator flux and as a result the motor torque can be controlled.

The crucial point here is choosing the right voltage vector for the control process. Assuming that the flux is in the first region we have:

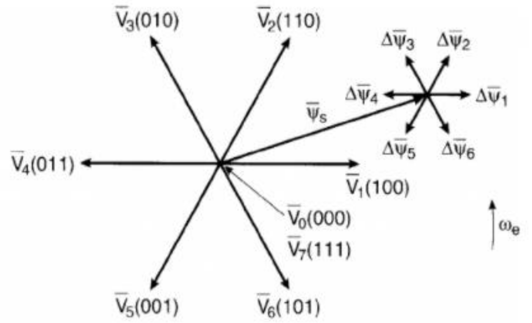

figure7- An example of how to choose the right voltage vector

It is clear in the figure 7 that by applying each of the 6 vectors shown, different torque and flux changes take place. For example, if the voltage vector V3 is applied, the torque will increase and the current will decrease.

As a general rule, it can be said that if the stator flux vector is in the m region, the application of the Vm+2, Vm-2, Vm+3 vectors will decrease the flux, and the application of the Vm-1, Vm, Vm+1 voltage vectors will increase the flux. be made Applying vectors Vm-1, Vm-2 causes a decrease in torque, and applying vectors Vm+1, Vm+2 causes an increase in torque. Vm, Vm+3 vectors can decrease or increase the torque depending on the location of the joint. In table1, it is shown in summary that the selection and application of each of the voltage vectors has the following effect:

Table 1. The effect of choosing different shear and torque voltage vectors

Vector	V_{n-2}	V_{n-1}	V_n	V_{n+1}	V_{n+2}
1	decrease	increase	increase	increase	decrease
2	decrease	decrease	It depends	increase	increase

Hysteresis comparator is used in this control system. A two-level comparator is used for flux, and a three-level comparator is used for torque control (due to increased efficiency and reduced torque ripple). As explained below:

$$\Delta\psi_s = \begin{cases} 1 & if\left|\psi_s\right| \le \left|\psi_s^*\right| - |Hysteresis\ Band| \\ 0 & if\left|\psi_s\right| \ge \left|\psi_s^*\right| + |Hysteresis\ Band| \end{cases} \quad (14)$$

$$\Delta T_e = \begin{cases} 1 & if T_e \le T_e^* - |Hysteresis\ Band| \\ 0 & if T_e = T_e^* \\ -1 & if T_e \ge T_e^* + |Hysteresis\ Band| \end{cases} \quad (15)$$

Calculation of reference flux and torque

The reference current is usually set up to the nominal speed equal to the motor's nominal current (fixed value). After the nominal speed, we must weaken the stator current by $1/_{\omega_m}$ so that the motor voltage does not exceed the nominal value. The size of the stator flux is approximately obtained from the following relationship. Vph is the voltage of the stator phase and f is the nominal frequency.

$$\left|\vec{\psi}_1^S\right| = \frac{L_1}{\sqrt{R_1^2 + (2\pi.f.L_1)^2}}.\sqrt{2}\,V_{ph} \quad (16)$$

The reference torque is generated by the speed control loop. In this way, the speed of the motor is compared with the reference speed, and the appropriate reference torque is generated by a PI controller, in order to zero the error.

Introduction of the suggested method of flux adjustment

In the traditional DTC method, a nominal and fixed hysteresis band is always used during the operation, therefore the flux range is strongly affected at low speeds. If we always use a small hysteresis band, the torque ripple will be extremely high and the switching frequency will also increase significantly, which will reduce the efficiency of the driver. To solve this problem, a method has recently been introduced in a study [29] in which variable torque hysteresis band is used. This method makes it possible to avoid the selection of unnecessary small hysteresis band and as a result reverse voltage vectors at medium and high speeds. Of course, the drawback of this method is that at a certain speed The critical speed (high and low band) are switched at the same time, which causes us to have a lot of overshoot in the torque due to the continuous switching of the active voltage vectors instead of the zero voltage vectors. Again, in this method, the torque ripple of the switching frequency is relatively high. In this paper, a small hysteresis band has been introduced, which is used at medium to high speed from the nominal hysteresis band, and at a certain speed, only one of the upper or lower bands is switched to the small hysteresis band. This method is focused on reducing the duration of the negative slope of the torque, which has caused the length of time to select zero voltage vectors to be reduced, and so on. Now the selection of reverse voltage vectors should also be minimized.

In this method, due to maintaining the nominal hysteresis band at medium and high speeds, torque overshoots have been reduced well.

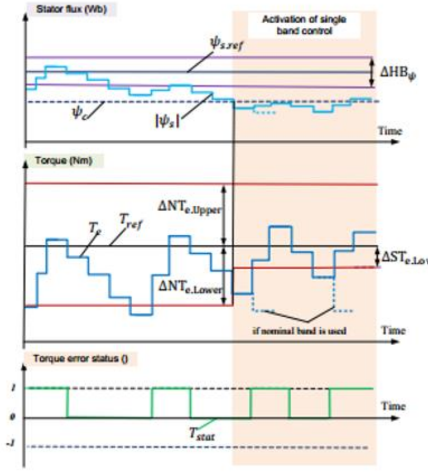

figure8- Schematic of the stator, torque and torque error status by using only one band hysteresis control of the forward degree.

As it is clear in the figure 8, first, a critical flux point (ψ_c)must be selected to determine the range of flux loss at low speeds. The speed corresponding to the critical flux point is also indicated by $\omega_r^{\psi_c}$.

Nominal and small hysteresis bands are switched according to the following conditions:

$$HTB = \begin{cases} \Delta NT_{e.Upper} \text{ and } \Delta NT_{e.lower} & \omega_r > \omega_r^{\psi_c} \\ \Delta NT_{e.Upper} \text{ and } \Delta ST_{e.lower} & 0 \le \omega_r < \omega_r^{\psi_c} \end{cases} \quad (17)$$

$$HTB = \begin{cases} \Delta ST_{e.Upper} \text{ and } \Delta NT_{e.lower} & -\omega_r^{\psi_c} \le \omega_r < 0 \\ \Delta NT_{e.Upper} \text{ and } \Delta NT_{e.lower} & \omega_r < -\omega_r^{\psi_c} \end{cases}$$

It is clear that in relationship A, for speeds higher than the critical speed, both the upper and lower bands are nominal, but in the speed range between zero and the critical speed, the nominal upper band and the small lower band are selected. Relationship B also states this condition for the opposite direction.

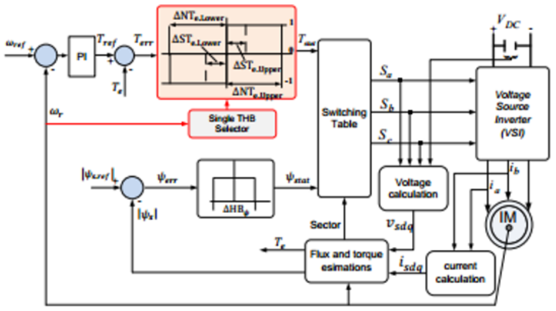

figure9-Control diagram of DTC induction motor based on bandhysteresis with introduced control strategy

In this section, first, 3 different types of DTC method are simulated in MATLAB software, then to prove the superiority of the proposed method of this study, the simulation results are compared.

The specifications of the 3-phase induction motor as well as the DTC parameters used in these simulations are listed in the table1

Table 1. induction motor and DTC Parameters

Induction Motor Values			
Rated power	3.7 kW	Stator resistance	0.934 ohm
Rated current	8.28 A	Rotor resistance	1.225 ohm
Rated speed	1750 r/min	Stator inductance	146.213 Mh
Rated torque	20.36Nm	Rotor inductance	146.213 Mh
Rated flux	0.6Wb	Mutual inductance	139.516 mH
Pole pairs		2	
DTC Parameters			
DC Link Voltage		300 V	
Torque hysteresis band(nominal)		2.5 Nm	
Torque hysteresis band(small)		0.01 Nm	
Flux hysteresis band		0.0015 Wb	

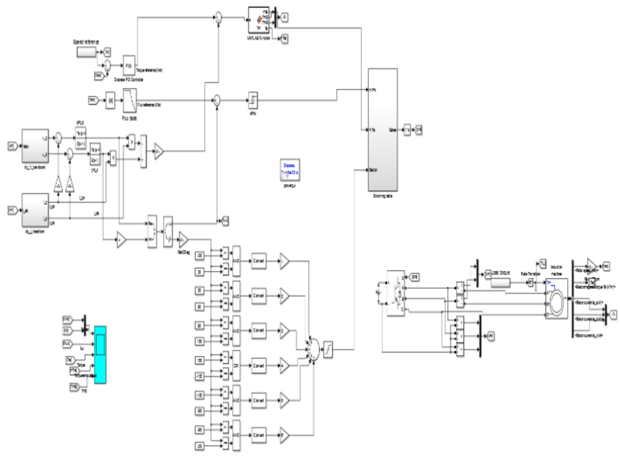

figure10- Block diagram of the simulated system

In this paper, the bandwidth of the torque hysteresis in the normal state (nominal THB) is 2.5 Nm, which is about 10-15% of the nominal torque. Also, the hysteresis bandwidth of the small THB is 0.01 Nm, which is about 0.5% of the nominal torque. The number should be chosen small enough so that the duration of the negative slope of the torque does not increase, which leads to a long selection of zero voltage vectors.

In the following figures, the simulation results for speed, stator current, torque, torque error mode and upper and lower hysteresis bands for all 3 original DTC methods, DTC-HB1 (in this method both upper and lower bands are controlled simultaneously) and DTC-HB2 (our proposed method that controls only one of the bands) be) is shown. The sampling rate in all 3 simulations is selected as 50 microseconds and the critical speed is experimentally considered to be 70 revolutions per minute.

* The important point is that the simulation was done under light load conditions, because in these conditions, the duration of the negative slope of the torque is longer, and these results make our simulation more robust.

First mode: speed change with the original DTC method[1]

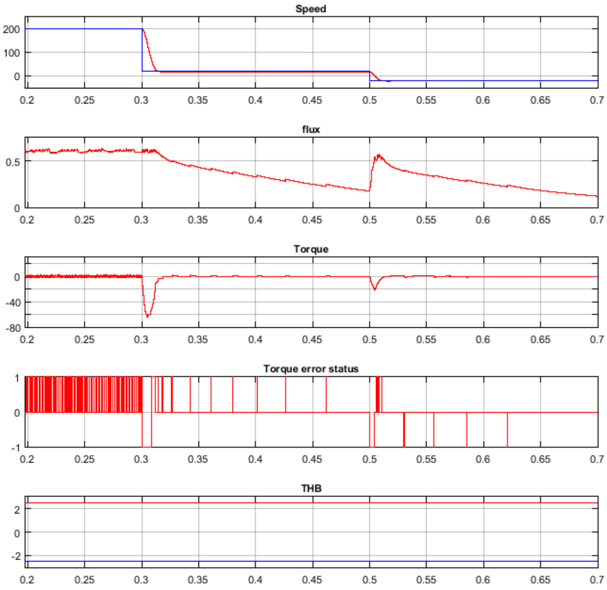

figure11- Block diagram of the simulated system

In figure11, which is related to the conventional DTC, it is clear that at 200RPM the flow is stable and there are no problems. However, at 20RPM and -20RPM, which is less than the critical speed, the problem of current drop is clearly evident. This current drop also causes the speed and torque to fluctuate. Also, in this form, zero voltage vectors are injected for a long time. It is also clear that it originates from the long duration of the negative slope of the torque.

The second mode: speed change with the DTC-HB1 method [26]

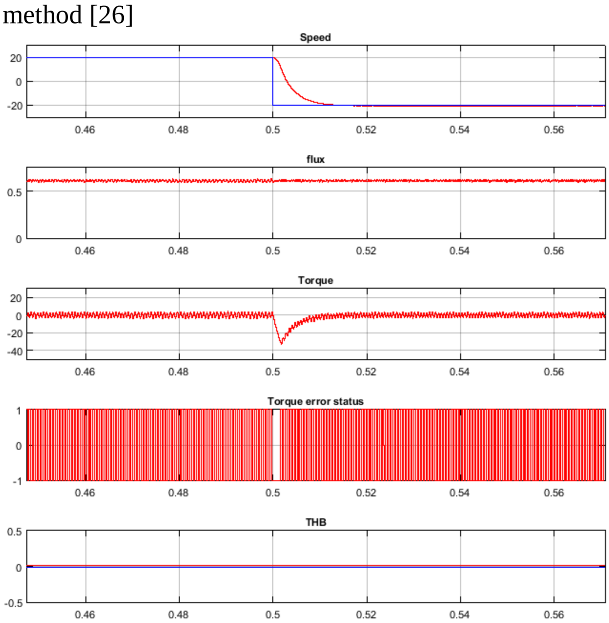

figure12- Simulation results for the DTC-HB1 method of induction motors at 20 and -20 RPM under light load

In Figure 12, DTC-HB1 performance is shown at 20RPM and -20RPM speeds, which are lower than the critical speeds. In this case, the high and low bands are controlled at the same time, the flux is well stabilized and the flux loss defect in the first figure has been resolved, but the switching frequency has increased greatly and the torque ripple has also increased.

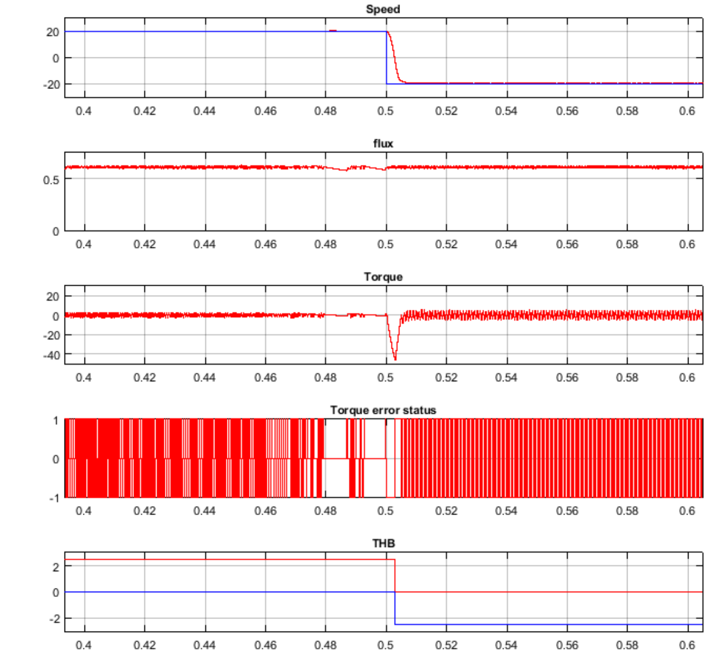

figure13- Simulation results for DTC-HB2 method of induction motors at RPM speeds of 20 and -20 under light load

Figure 13 also shows the performance of DTC-HB2 at 20RPM and -20RPM speeds, which are lower than the critical speeds.

omenclatures

$\Delta\psi$ flux error
V_n voltage vector
T_e electromagnetic torque
p even number of motor poles
$\vec{\psi}_s$ stator flux vector
$\vec{\psi}_r$ rotor flux vector
γ load angle between the stator and rotor shafts
R_r rotor resistance
R_s stator resistance
L_s stator inductance
L_r rotor inductance
L_m mutual inductance

Conclusions

In the proposed method of this study, according to the direction of rotation of the motor at speeds lower than the critical speed, only one of the upper or lower bands is controlled, which causes the torque ripple to decrease significantly while we have a stable flux, as well as the switching frequency. It can be clearly seen that not only the selection of zero voltage vectors has been minimized, but also the unnecessary switch of reverse voltage vectors has been avoided. This means increasing the efficiency and quality of the system while maintaining the simplicity of the structure.

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