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Simulation Study of Direct Torque Controlled BLDC Motor Drive

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ABSTRACT:
In this paper, the direct torque controlled BLDC motor with trapezoidal back emf is simulated and investigated. Both torque and flux are controlled simultaneously. Instead of PI controller, hysteresis controller is used to generate the reference i.e torque and flux. To obtain the optimum current and torque control with low torque pulsation, several methods have been proposed in literature for BLDC motor drives. Out of which, some methods are complicated and they do not consider the stator flux control because of which, the high speed operations are not possible. The method presented in this paper provides advantages of classical DTC such as fast dynamic response. The replacement of PI controller by hysteresis controller avoids trial & error for guess about proportional and integral constants. The BLDC motor drive is tested for different operating conditions in Matlab/ Simulink environment to verify its effectiveness and performance.

KEYWORDS*:* Brushless dc motor, direct torque control, sensorless control, stator flux control

I. INTRODUCTION

Now a days, due to several distinct advantages such as high power density, high efficiency, large torque to inertia ratio and simplicity in their control, the Permanent Magnet Synchronous motor (PMSM) and Brushless DC Motor (BLDC) drives are being used widely. One of the most popular approaches is a generalized harmonic injection [1]. In high speed applications like traction, the primary concern of drives is to obtain a low frequency and ripple free torque and even flux control. For such applications, a great deal of study has been devoted. But these studies have some limitations such as calculation complexity because of Fourier co-efficient, use of PWM techniques for driving the motor, which complicates the real time implementation ; requirement of very fast controllers ; fast torque response cannot be achieved; flux weakening is not possible; two phase conduction instead of three phase conduction etc. These methods avoid the complicated harmonic coefficient calculation based on the

optimisation approach. In the mid of 1980s, the Direct Torque Control (DTC) was first proposed for induction motor drives [2] [3]. After a decade later, in 1990‘s it was analysed for both interior and surface mounted PMSM [4]. Now more recently it is extended to BLDC motor drives [5]-[6]. References [5] and [6] shows the controlling of electromagnetic torque in DTC of BLDC motor under two phase conduction mode. Since due to the sharp changes in flux, whose amplitudes is unpredictable and is dependent on several factors such as load torque, dc-line voltage, winding inductance etc, the flux control is not possibleIn this study, like conventional DTC which was used for sinusoidal AC motors, where both torque and flux control are provided simultaneously, a simple position sensorless direct torque and indirect flux control of BLDC motor is presented [1]. The advantages of this method over classical DTC are fast response compared to vector control, no pulse width modulation (PWM), no proportional integral (PI) controller, no inverse Parks and inverse Clarke transformation (which makes the calculations much simpler) and a position sensor less drive operation. As in [5] and [6], where two phase conduction DTC methods were used for BLDC motors, the proposed DTC technique provides position sensor less operation of the drive and along with that the indirect methods of controlling the flux, by controlling the d-axis stator current, because of which the flux weakening operation is possible. In this study, here we are using the line-to-line Parks transformation for co-ordinate transformation which forms 2 x 2 matrix instead of conventional 2 x 3 matrix. Because of this, instead of 3 line to neutral back emf waveforms, the two line-to-line back emf‘s are obtained and then converted into d-q reference frame. Then they are stored in look-up table for estimation of electromagnetic torque.

II. LINE TO LINE PARK AND CLARK TRANSFORMATION

A balanced 3-phase system when transformed in ‗*dqo*' frame does not have the zero sequence term. For obtaining the balanced system, initially the line-to-line Clarke transformation from the balanced three phase quantities can be derived and then the line-to-line Park transformation forming 2x2 matrix instead of 2x3 matrix can be obtained. With the help of some algebraic simplifications, the original Clarke transformation forming 2x3 matrix excluding zero sequence term can be simplified to a 2x2 matrix as follows.

$$[T_{LL}] = \begin{bmatrix} -\frac{1}{3} & -\frac{1}{3} \\ \frac{\sqrt{3}}{3} & -\frac{\sqrt{3}}{3} \end{bmatrix} \qquad (1)$$

flux amplitude is uncontrollable. Fig shows the block diagram of diagram of direct torque and indirect flux control of BLDC motor drive.

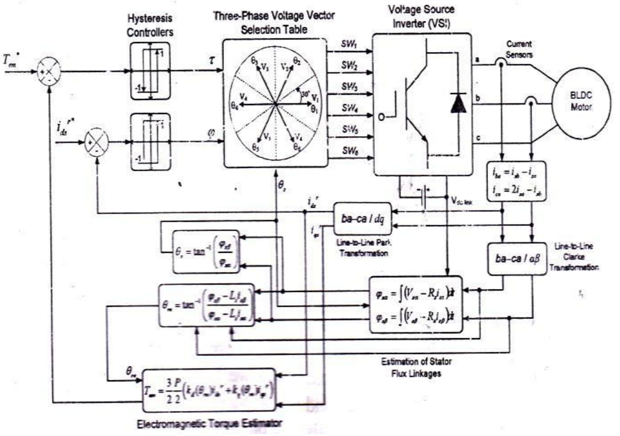


Fig 1 Block diagram of the position sensorless direct torque and indirect flux control of BLDC motor

The inverse of original Clarke Transformation [$T_{\alpha\beta}$] is required for obtaining the line-to-line Park's transformation forming 2x2 matrix. The [$T_{\alpha\beta}$] matrix will not be a square because the zero sequence form has been removed. Now the pseudo inverse can be found as follows:

$$[T_{\alpha\beta}]^{+} = [T_{\alpha\beta}]^{T}\left([T_{\alpha\beta}][T_{\alpha\beta}]^{T}\right)^{-1} \qquad (2)$$

$$[T_{\alpha\beta}]^{+} = [T_{\alpha\beta}]^{T}\left([T_{\alpha\beta}][T_{\alpha\beta}]^{T}\right)^{-1} \qquad (2)$$

where and are the pseudo inverse and transpose of the original Clarke transformation matrix, respectively. Here *abc* to *ba–ca* transformation can be represented as follows

$$[T_{\alpha\beta}]^{+}[T_{\alpha\beta}]\begin{bmatrix} X_a \\ X_b \\ X_c \end{bmatrix} = [T_{\alpha\beta}]^{+}[T_{LL}]\begin{bmatrix} X_{ba} \\ X_{ca} \end{bmatrix} \qquad (3)$$

After (3) is expanded and multiplied by the original 2×3 Park transformation matrix in both sides, algebraic manipulations lead to simplifications using some trigonometric equivalence. Therefore the following 2 × 2 line-to-line Park transformation matrix form is obtained:

$$\begin{bmatrix} X_d \\ X_q \end{bmatrix} = \frac{2}{3}\begin{bmatrix} \sin\left(\theta - \frac{\Pi}{6}\right) & -\sin\left(\theta + \frac{\Pi}{6}\right) \\ -\cos\left(\theta + \frac{\Pi}{6}\right) & \cos\left(\theta + \frac{\Pi}{6}\right) \end{bmatrix}\begin{bmatrix} X_{ba} \\ X_{ca} \end{bmatrix} \qquad (4)$$

Xa and Xca=Xc-Xa, where X may be any variable such as current, voltage etc.

III. SENSORLESS BLDC MOTOR DRIVE WITH DIRECT TORQUE CONTROL

Direct torque and indirect flux control technique is used which is suitable for sensorless and flux weakening operation. This transforms abc frame quantities into dq frame by using Parks transformation. For the estimation of torque, two emf constant are required i.e (and . Parks transformation is given by (4). From the equation we see that the number of input variables are reduced from three to two.This method uses three phase conduction technique. Compared with the two phase conduction technique this DTC method differs by its torque estimation. In two phase conduction mode only electromagnetic torque can be controlled. The amplitude of flux is not controlled due to several factors such as load torque dc link voltage. Also statorIn three phase conduction mode torque and flux are controlled simultaneously. It also controls stator flux indirectly using d axis current. This DTC method controls the voltage vector directly from the look up table. Hysteresis controller are used for varying reference i.e torque and flux. Compared to the conventional PWM control technique this control techniques is simple and gives fast torque response.

The flux linkages in rotor dq reference frame is given by following equations:

$$\emptyset_{qs}^{r} = L_s i_{ds}^{r} + \emptyset_r' \sum_{n=1}^{\infty}(K_{6n-1} + K_{6n+1}) \sin(6n\theta_r) \quad (5)$$

$$\emptyset_{ds}^{r} = L_s i_{qs}^{r} + \emptyset_r' \sum_{n=1}^{\infty}(K_{6n-1} - K_{6n+1}) \cos(6n\theta_r) + \emptyset_r' \quad (6)$$

Where ϕ_r' =peak value of the rotor magnetic flux linkage

From equation 5 and 6 it can be seen that the stator flux linkage vary by the six times the fundamental frequency

IV. ESTIMATION OF ELECTROMAGNETIC TORQUE

The estimation of torque is the important factor in the direct control torque scheme. First two back emf waveforms are obtained and they are converted into two back emf constants i.e ( ) and ( ). This) represents position of rotor. Then they are stored in look up table for estimation of electromagnetic torque.By equating electrical power absorbed by the motor and mechanical power,the electromagnetic torque is given by

$$T_{es} = \frac{3P}{4}\left(k_q\ (\theta_{re}) i_{qs}^{r} + k_d(\theta_{re})\ i_{ds}^{r}\right) \quad (7)$$

where P is the number of poles, $k_q\ (\theta_{re})$ and $k_d\ (\theta_{re})$ are the back emf constant according to rotor position

V CONTROL OF STATOR FLUX LINKAGE

The stator flux linkage of BLDC motor is given by,

$$\phi_{s\alpha} = V_{s\alpha}t - R_s \int i_{s\alpha} dt + \phi_{s\alpha}(0) \quad (8)$$

$$\phi_{s\beta} = V_{s\beta}t - R_s \int i_{s\alpha} dt + \phi_{s\beta}(0) \quad (9)$$

where $\phi_{s\alpha}(0)$ and $\phi_{s\beta}(0)$ are the initial staor flux linkages

Since BLDC motor does not have sinusoidal back emf ,the stator flux trajectory is not a pure circle So we get dodecagon trajectory of stator flux. Because of decagonal shape it is very difficult to control the amplitude of stator flux. Therefore its amplitude is indirectly controlled by d axis current

Stator flux linkage amplitude is given by

$$\sqrt{(\ {\phi_{qs}^{r}}^{2} + \phi_{qs}^{r}\ )}$$

flux amplitude can be changed by varying d axis current. Here torque is assume as a constant which is proportional to therefore called as indirect flux control.In the constant torque

region is controlled as zero and the flux weakening

operation it is decreased to a certain amount

VI. ESTIMATION OF ROTOR POSITION

Electrical rotor position is required for the estimation of torque and is given by,

$$tan^{-1} = \left(\frac{\phi_{s\beta}}{\phi_{s\alpha}}\right) \quad (10)$$

VII. SIMULATION STUDIES

The scheme shown in Fig. 1 is simulated in Matlab/Simulink. The sampling time is selected as 15μs. The magnitudes of torque and flux hysteresis band are fixed at 0.001 Nm and 0.001Wb.

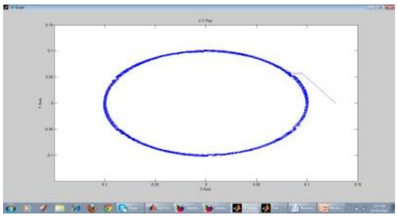
The input currents are transformed into

frame by using Clark‘s transformation and in d-q frame by Park‘ transformation.

using s This components are

essential for calculating stator flux linkage given by (8) and

(9).For the estimation of torque, two emf constants are required ( ) and ( ) which is obtained byPark‘s transformation. So the estimated torque is calculated by using equation (7). This estimated torque is essential for calculating the position of rotor. Now this estimated torque and d axis current which is obtained from (7) and (4) is given to the hysteresis controller. This hysteresis controller is used for varying torque and flux. Their output is given to the three phase voltage vector selection table. The vector should be selected according to requirement and pulses should be given to voltage source inverter. Fig 2 shows the indirectly controlled stator flux linkage trajectory when the value of i_{ds} is changed 0 to -5 A. Simulation Results



fig;-simulated indirectly stator flux linkage trajectory

Fig 2. Simulated indirectly controlled stator flux linkage trajectory when
changed from 0 A to -5 A.

It is very difficult to control the amplitude of stator flux due to its decagonal shape. Therefore instead of its amplitude is indirectly controlled by d axis current. In the constant torque region when is controlled as zero and the flux weakening operation it is decreased to a certain amount.

The q and d axis currents are shown in Fig. 3 under 0.5 N-m load torque. At 0.65 sec torque reference is increased and change in the q axis current is noted in Fig. 4. d axis current oscillates around the desired reference value which means the stator flux amplitude equals the magnet flux.

Fig3- q axis stator current

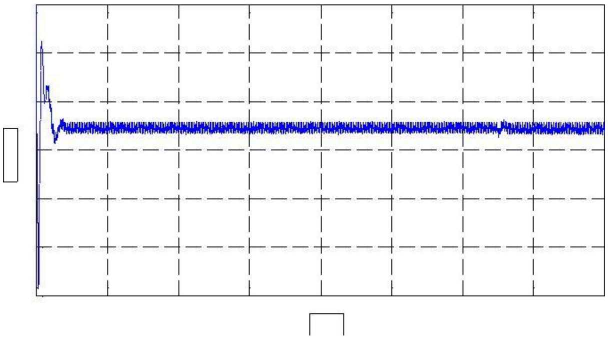


Fig4- d axis stator current

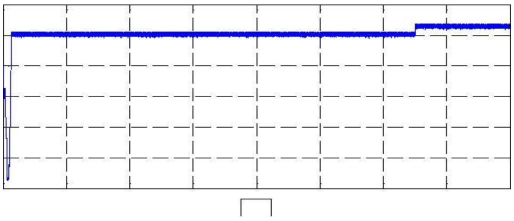
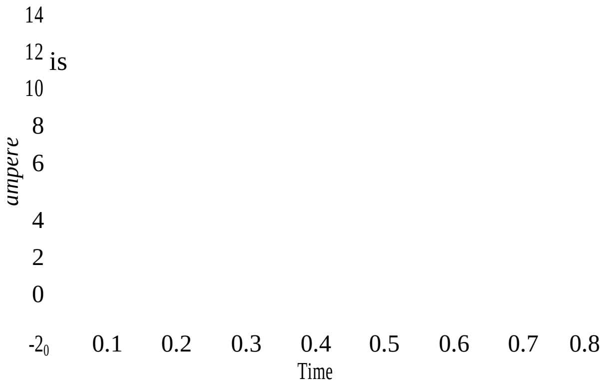
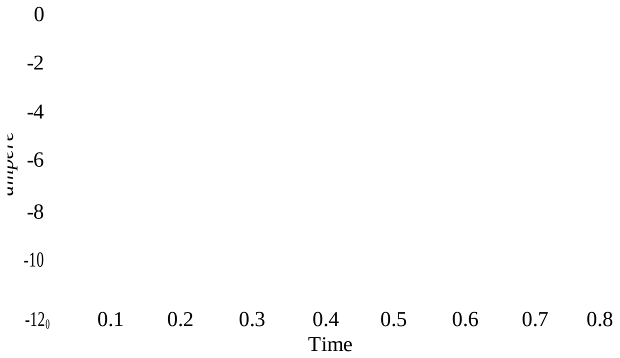


Fig 5-Estimated electromechanical torque





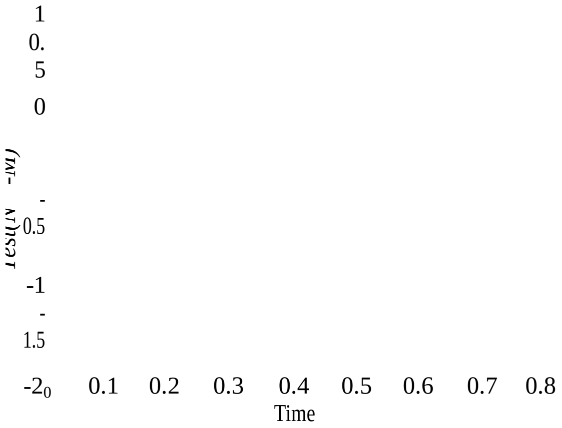


Fig 5 shows the estimated electrical torque .It is shown that the fast torque reponse is obtained and the estimated torque tracks the reference torque closely.

VIII. CONCLUSION

Simulation study of direct torque and indirect flux control of BLDC motor are presented in this paper. Here both torque and flux are controlled. This method provides advantages of classical DTC such as fast response and no PWM strategies PI controller are required. The performance is tested in Matlab/Simulink software. The results prove the effectiveness of the drive.

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