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Postion Sensorless Direct Torque With Indirect Flux Control Of BLDC Motor In Three Phase Conduction Mode

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Abstract*—*In this work, an analysis on position sensorless direct torque control of BLDC Motor with indirect flux control have been studied using two level, six switch Voltage Source Inverter (VSI). By adopting the indirect flux control in direct torque control, the stator flux can be effectively controlled in the constant torque region. This scheme is adapted to three phase conduction mode of VSI. Maximum torque efficiency can be obtained in this method since the torque is estimated in the dq reference frame. In direct torque with indirect flux control of BLDC in three phase conduction mode, the commutation torque ripple can be minimized as well as torque ripple can be effectively reduced. Since the scheme is position sensorless, the electrical rotor position is estimated using stator winding inductance, stationary reference frame currents and flux linkages. The voltage vector selection is set up in the look-up table so that fast torque response is possible. Since the neutral point of the motor is not available, conventional 2×3 matrix is replaced by 2×2 Park's and Clarke's transformations for the balanced systems. The experimental results are validated in MATLAB/SIMULINK.

***Index Terms*—Brushless DC (BLDC) Motor, Constant torque region, Direct Torque Control (DTC), Three phase conduction mode, Voltage Source Inverter (VSI).**

I. Introduction

Electric motors plays an important role in industrial applications[2] thereby enhancing its production quality and service rate. BLDC motors made an impact in industrial applications owing to its advantages such high efficiency, high torque to inertia ratio, absence of brushes, high life span, possibility of operation in different environmental conditions etc. In earlier days the use of BLDC motors is limited due to the cost of its permanent magnets, but with the advent of rare earth metals and its alloys like samarium cobalt made BLDC motor a promising one in wide area applications ranging from servos to traction purposes with reduced cost. BLDC motors mostly employed current and torque control strategies with the assumption that the torque and current developed are in a linear relationship. But this assumption goes to wrong in real cases because of the torque pulsations of the motor. Direct Torque Control (DTC) and Field Oriented Control (FOC) are the two instantaneous electromagnetic torque controls available for AC motor drives. The idea of DTC was originally developed for induction machine drives by Takahashi and Depenbrock in the mid-1980s [1]. According to the conditions of torque error, stator flux error and sector, a switching table is developed and stored so that faster torque response is obtained as compared to conventional PWM methods. Since the beginning the DTC was characterized by simplicity, good performance and robustness. Using DTC it is possible to [3]obtain a good dynamic control of the torque without any mechanical transducers on the machine shaft. The torque pulsation of BLDC motor can be reduced by operating the VSI of the motor in three phase conduction mode.

Procedure for Paper Submission

II. Modeling of BLDC Motor

The BLDC motor produces trapezoidal shape back emf due to its stator winding construction and inorder to produce smooth torque, 120 degree spaced rectangular shaped currents are given to the windings through the voltage source inverter(VSI).For the modeling [5] of BLDC motor, the following assumptions are made.

- The three phase stator windings are Y connected and symmetrical with uniform air gap.
- The magnetic saturation of the motor is neglected.
- The hysteresis loss, eddy current loss, iron loss and cogging torque of the motor are neglected.
- The stator winding resistance and inductance of all three phases are identical.
- The back emfs shape of all the phases are identical and are 120 degree phase shifted from the other phase.
- Power semiconductor devices in the inverter are ideal.
- DC voltage source is infinite and is capable of delivering infinite di/dt.

Dynamic modeling of the BLDC motor is represented by equations given by

$$V_{an} = R_a I_a + \rho\lambda_a + e_{an} \quad (1)$$
$$V_{bn} = R_b I_b + \rho\lambda_b + e_{bn} \quad (2)$$
$$V_{cn} = R_c I_c + \rho\lambda_c + e_{cn} \quad (3)$$

Where V_{an}, V_{bn} and V_{cn} are the stator phase voltages of A, B and C phase respectively. R_a, R_b, R_c are the stator phase resistances. I_a, I_b and I_c are the stator currents. ρ is the differential operator. e_{an}, e_{bn} and e_{cn} are the back emfs voltages.

The developed electromagnetic torque may be expressed as

$$T_e = \frac{e_{an}I_a - e_{bn}I_b - e_{cn}I_c}{\omega_r} \quad (4)$$

The mechanical equation of motion in speed derivative form can be expressed as

$$\rho\omega_r = \left(\frac{P}{2}\right)\frac{(T_e - T_L - B\omega_r)}{J} \quad (5)$$

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Where T_L is the load torque, B is the friction coefficient and J is the moment of inertia.

III. DIRECT TORQUE WITH INDIRECT FLUX CONTROL

The basic idea of direct torque with indirect flux control [7] is to control electromagnetic torque directly and stator flux linkage indirectly through d-axis stator current by the help of voltage vector switching table which depends upon the torque error, stator flux error and the sector. There are eight possible voltage space vectors available for a two-level Voltage Source Inverter (VSI). This voltage vector selection table enables the stator flux linkage vector rotates along the reference frame trajectory and produces desired torque.

The overall block diagram of the position- sensorless direct torque and indirect flux control of BLDC motor drive using three phase conduction mode is shown in fig 1.

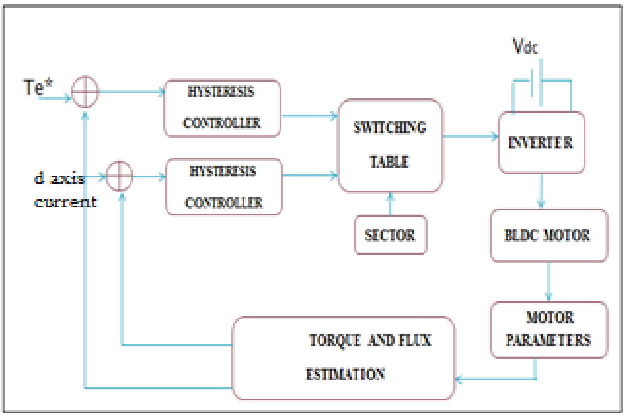

Fig. 1 Direct Torque with Indirect Flux Control of BLDC Motor

The features of direct torque with indirect flux control as compared to direct torque with direct flux control of BLDC motor are the torque estimation is in dq reference frame, the mode of operation of VSI is in three phase conduction mode and the stator flux is controlled indirectly through d-axis stator current of the rotor reference frame.

Since the VSI is operated in three phase conduction mode, the three stator windings are active at any time. Current flow in each winding produces a magnetic field vector, which sums with the fields from the other windings. By controlling currents in the three windings, a magnetic field of arbitrary direction and magnitude can be produced by the stator. Torque is then produced by the interaction between net stator field and the magnetic field of the rotor or in other words if the stator field is orthogonal to the field produced by the rotor, the torque is maximized. The stator field with arbitrary direction and magnitude can be decomposed into components parallel and orthogonal to the rotor field. In this case, the orthogonal(q axis) component produces torque, while the parallel component produces (d axis) useless compression force.So for efficient brushless motor drive, we have to minimize the direct component of the stator field and maximizes the quadrature component.Now we can say that torque produced [8] is proportional to the q-axis component of stator current and rotor magnetic field. This is all about torque. For efficient , constant ,smooth torque, the stator current space vector should ideally be constant in magnitude and should turn with the rotor so as to always be in quadrature direction, irrespective of the rotor angle and direction. This is possible if we see the stator space vector in the dq reference frame of the rotor.So we can say that, for obtaining maximum and smooth torque,Measured components must be mathematically transformed from three phase static reference frame of the stator winding to the two axis rotating dq reference frame of the rotor axis.Make the d axis stator current vector component to be zero (or in other words making the d axis current component to be parallel in with rotor axis) and therefore forces the current space vector to be exclusively in the quadrature direction.Since only the quadrature component produces useful torque, this maximizes the torque efficiency of the system.This is the reason for the estimation of torque in dq reference frame of the rotor axis.

A. Line to Line Values, Modified Clarke's and Park's Transformation

Since the neutral point of BLDC motor is not available at out in real cases, [4] we can't use phase values for the 3×3 park and Clarke transformation. So the transformation prefers line to line values instead of phase value measurements. Also a balanced system doesn't require a zero sequence term and the equation is given by

$$\begin{bmatrix} X_\alpha \\ X_\beta \end{bmatrix} = \begin{bmatrix} \frac{-1}{3} & \frac{-1}{3} \\ \frac{1}{\sqrt{3}} & -\frac{1}{\sqrt{3}} \end{bmatrix} \begin{bmatrix} X_{ba} \\ X_{ca} \end{bmatrix} \quad (6)$$

Equation 6 is the corresponding line to line Clarke's equation

$$\begin{bmatrix} X_d \\ X_q \end{bmatrix} = \frac{2}{3} \begin{bmatrix} \sin\left(\theta - \frac{\pi}{6}\right) & -\sin\left(\theta - \frac{\pi}{6}\right) \\ -cos\left(\theta - \frac{\pi}{6}\right) & cos\left(\theta - \frac{\pi}{6}\right) \end{bmatrix} \begin{bmatrix} X_{ba} \\ X_{ca} \end{bmatrix} \quad (7)$$

Equation 7 represents the line to line park's transformation.

B. Electromagnetic Torque Estimation in DQ Reference Frame

The electromagnetic torque T_{em} estimation algorithm can be derived for a balanced system in dq reference frame is given by

$$T_{em} = \frac{3P}{4\omega_{re}} \left(e_q(\theta_{re}) i^r{}_{qs} + e_d(\theta_{re}) i^r{}_{ds}\right) \quad (8)$$

Where P is the number of poles, $\omega_{re}$is the electrical rotor speed,$e_q(\theta_{re})$and $e_d(\theta_{re})$, $i^r{}_{qs}$and $i^r{}_{ds}$ are the dq axesback EMFs, currents accordingto the electrical rotor position, respectively.

C. Stator Flux Linkage and Sector Selection

The stator flux linkages in stationary reference frame can be obtained from stationary reference frame stator voltages and given by

$$V_{s\alpha} = Ri_{s\alpha} + \frac{d\varphi_{s\alpha}}{dt} \quad (9)$$

$$V_{s\beta} = Ri_{s\beta} + \frac{d\varphi_{s\beta}}{dt} \quad (10)$$

And therefore

$$\varphi_{s\alpha} = \int (V_{s\alpha} - Ri_{s\alpha}) \quad (11)$$

$$\varphi_{s\beta} = \int (V_{s\beta} - Ri_{s\beta}) \quad (12)$$

Where $V_{s\alpha}$ and $V_{s\beta}$ can be found from a dc-link voltage sensor depending on the sector where stator flux linkage is located. R is the stator resistance.

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The amplitude of stator flux linkage is given by

$$\varphi_s = \sqrt{{\varphi_{s\alpha}}^2 - {\varphi_{s\beta}}^2} \quad (13)$$

If the resistance term in the stator flux estimation algorithm is neglected, the variation of the stator flux linkage (incremental flux expression vector) will only depend on the applied voltage vector.
The sector can be obtained by equation

$$\theta_s = \tan^{-1}\frac{\varphi_{s\beta}}{\varphi_{s\alpha}} \quad (14)$$

Where θ_s the stator flux linkage, $\varphi_{s\alpha}$ and $\varphi_{s\beta}$ are the alpha-beta stator flux linkages.

D. *Switching Table*

The switching table [6] for controlling both the amplitude and rotating direction of the stator flux linkage is given in Table 1.
The voltage vector plane is divided into six sectors so that each voltage vector divides each region into two equal parts. In each sector, four of the six non-zero voltage vectors may be used. All the possibilities can be tabulated into a switching table. The output of the torque hysteresis comparator is denoted as τ. The output of the flux hysteresis comparator as φand the flux linkage sector is denoted as θ. The torque hysteresis comparator is a two valued comparator; τ = -1 means that the actual value of the torque is above the reference and out of the hysteresis limit and τ = 1 means that the actual value is below the reference and out of the hysteresis limit. The flux hysteresis comparator is a two valued comparator as well where φ =1 means that the actual value of the flux linkage is below the reference and out of the hysteresis limit and φ= -1 means that the actual value of the flux linkage is above the reference and out of the hysteresis limit.

E. *Hysteresis Controllers*

The command stator flux [1]and the commanded torque magnitudes are compared with their respective estimated values. The errors are then processed through the two hysteresis comparators, one for flux and the other for torque which operate independently of each other. The flux and torque are two level comparators.
The flux controller has two levels for the digital output, which have the following logic:

$$d_\varphi = 1 \text{ For } |\varphi| < \varphi^* \text{- } H_\varphi \quad (15)$$

$$d_\varphi = -1 \text{ For } |\varphi| > \varphi^* \text{- } H_\varphi \quad (16)$$

Where $2H_\varphi$ is the total hysteresis-band width of the flux comparator and d_φ is the digital output of the flux comparator.
By applying the appropriate voltage vectors the actual flux vector is constrained within the hysteresis band and it tracks the command flux in a zigzag path without exceeding the total hysteresis-band width.
The torque controller has two levels for the digital output, which have the following logic:

$$d_\tau = 1 \text{ For } |\tau| < \tau^* \text{- } H_\tau \quad (17)$$

$$d_\tau = -1 \text{ For } |\tau| > \tau^* \text{- } H_\tau \quad (18)$$

Where $2H_\tau$ is the total hysteresis-band width of the torque comparator and d_τ is the digital output of the torque comparator.
Knowing the output of these comparators and the sectors of the stator flux vector, the look-up table can be built such that it applies the appropriate voltage vectors via the inverter in a way to force the two variables to predefined trajectories.

Table 1 Switching table for direct torque with indirect flux control in three phase conduction mode

Flux (φ)	Torque (ŧ)	Sector (Θ) Θ(1)	Θ(2)	Θ(3)	Θ(4)	Θ(5)	Θ(6)
φ = 1	ŧ=1	V_2 (110)	V_3 (010)	V_4 (011)	V_5 (001)	V_6 (101)	V_1 (100)
	ŧ=-1	V_6 (101)	V_1 (100)	V_2 (110)	V_3 (010)	V_4 (011)	V_5 (001)
φ = -1	ŧ=1	V_5 (001)	V_6 (101)	V_5 (001)	V_6 (101)	V_1 (100)	V_2 (110)
	ŧ=-1	V_5 (001)	V_6 (101)	V_1 (100)	V_2 (110)	V_5 (001)	V_6 (101)

F. *Electrical Rotor Position*

Since the method is position sensorless [6], the electrical rotor position can be estimated using following equation

$$\theta_{re} = \tan^{-1}\frac{\varphi_{s\beta} - L_s i_{s\beta}}{\varphi_{s\alpha} - L_s i_{s\alpha}} \quad (19)$$

Where θ_{re} is the electrical rotor position,$\varphi_{s\alpha}$ and $\varphi_{s\beta}$is the alpha-beta stator flux linkages,$i_{s\alpha}$ and $i_{s\beta}$ are the alpha-beta stator current and L_s is the stator phase inductance.

IV. SIMULATION RESULTS

The validity of the direct torque controlled with direct and indirect flux control has been checked in MATLAB/SIMULINK model. The specifications used for the modeling of the drive system are shown in table 2.

Table 2 Specification of BLDC motor

Specification	Unit
Rated Power	1.57KW
Rated Torque	5Nm
Rated Current	6.75 A
Rated Speed	3000 rpm
No of poles	8
DC Voltage	310V
Stator winding resistance	3.52 ohm
Stator winding inductance	3.285mH
Moment of Inertia	1.8e-4Kgm^2
Friction Coefficient	0.001Nms

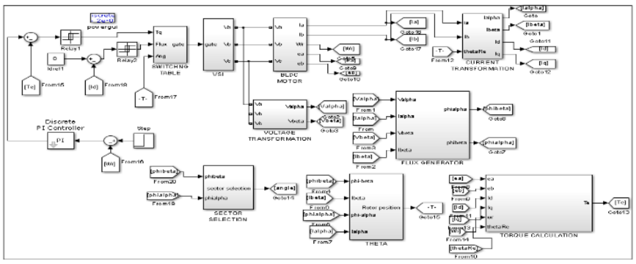

Fig.2. Simulation diagram of direct torque with indirect flux control in three phase conduction mode

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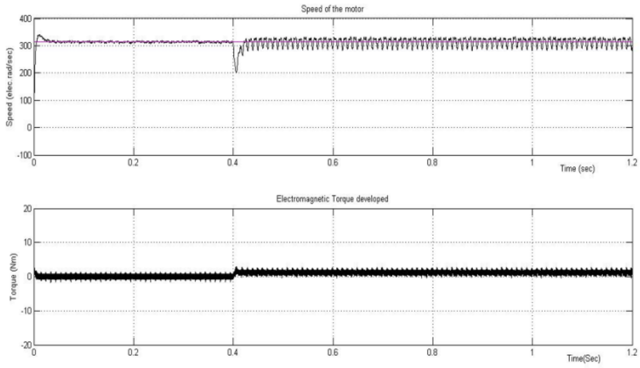

Fig. 3 and 4 Speed and Electromagnetic torque developed in the motor

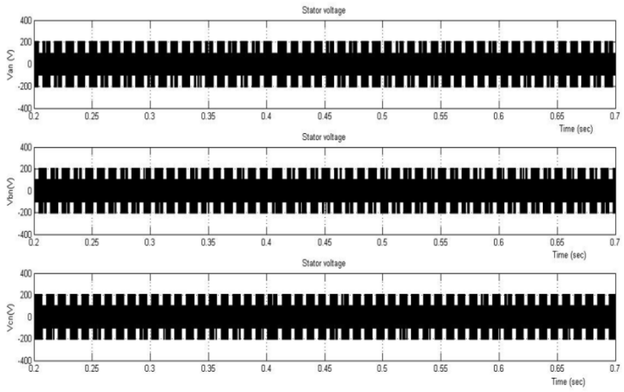

Fig.5 Stator phasor voltages applied to the motor windings

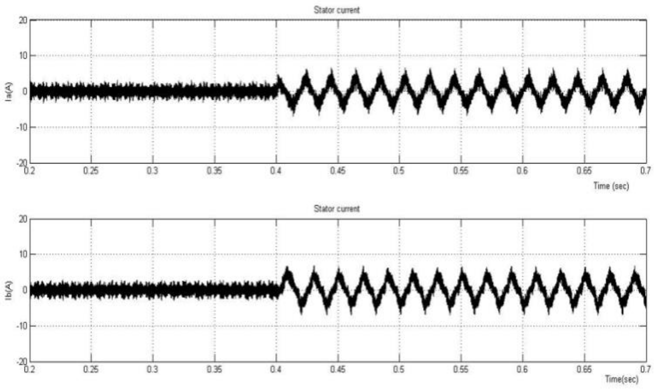

Fig.6 Stator currents of the motor

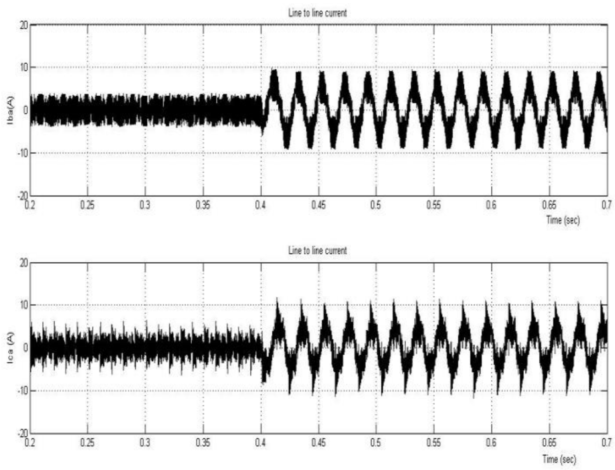

Fig.7 Line- to- line stator currents

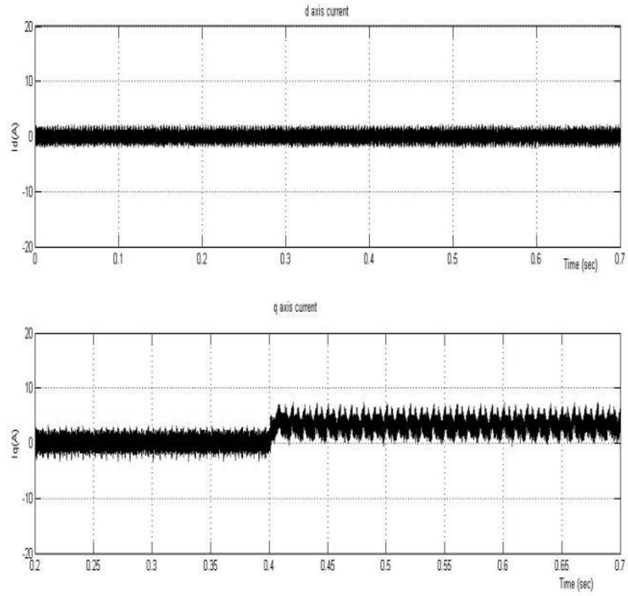

Fig.8d-axis and q-axis currents of the motor

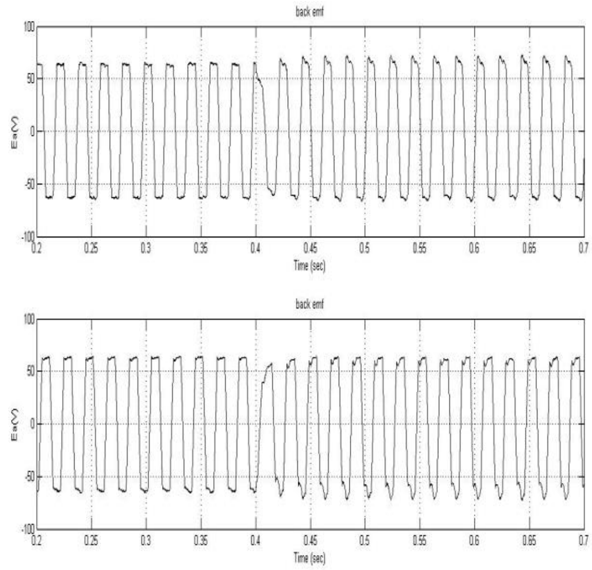

Fig.9 Back emfs of the machine

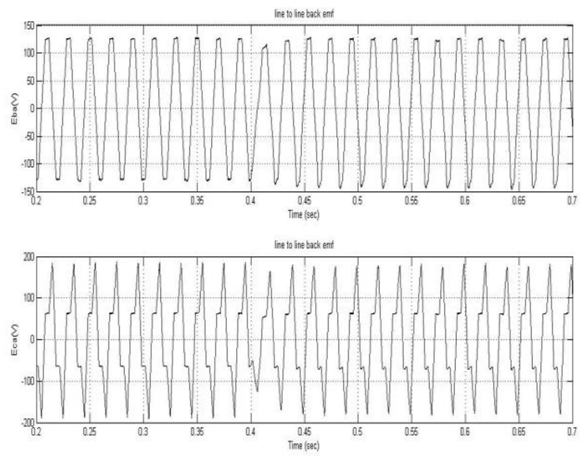

Fig.10 Line to line back emfs

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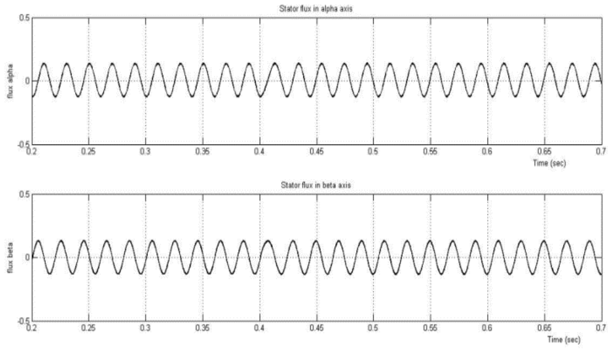

Fig.11 Stator flux in alpha-beta axis

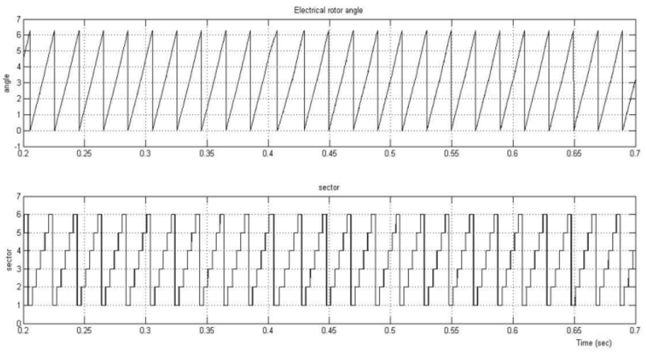

Fig. 12 and 13 Sector and Rotor angle

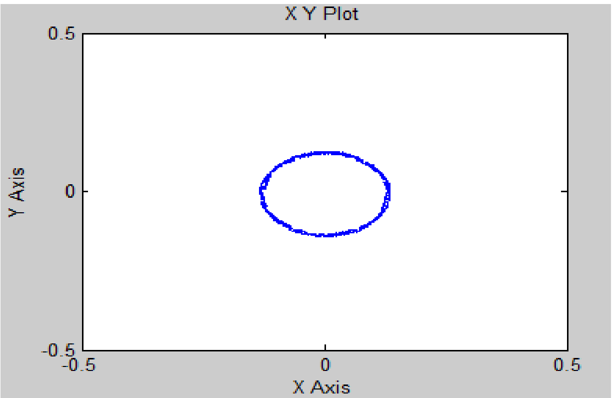

Fig.14Stator flux in XY graph

The machine is unloaded upto 0.4sec and after that a load of 2.5Nm is applied. Fig.2 shows the entire Matlab simulation of direct torque with indirect flux control of BLDC motor in three- phase conduction mode.

Fig.3 and 4 shows the speed and electromagnetic torque developed of the machine. The rated speed of the motor is 3000 rpm. So the rated speed, 314.136 rad/sec is given as the reference speed of the motor. For a time of upto 0.4sec, machine is unloaded, so that torque developed is approximately zero. When the machine is loaded, corresponding electromagnetic torque is developed. From the simulation results it can be observe that the torque ripples is about 1.5%. When the machine is loaded the speed of the machine goes dip, but due to the closed loop operation, within no time, machine is come into the rated speed.

Fig .5 represents the stator phase voltages applied to the motor. The inverter voltage is 310V dc. The simulation result shows that peak-to-peak voltage of about 400V is obtained in three windings.

Fig.6 shows the two phase currents developed inside the winding. Applying balanced condition equation, two line-to-line currents are obtained and are shown in Fig.7. The d-q axis currents are shown in Fig 8.During unloading condition, machine develops zero current and during loading condition of 2.5 Nm loads, a peak-to-peak current of about 10A is obtained. Based upon theory, we are making d-axis component in parallel to the rotor flux or in other words d-axis current is zero and then only q-axis current component produces useful torque. So for a load torque of 2.5 Nm, it develops a current according to the loaded condition.

The back emf of the machine obtained for two phases is shown in Fig.9. The line-to-line back emf waveforms obtained are shown in Fig.10. Owing to the construction of stator winding, the back emfs obtained are in trapezoidal shape. A peak-to-peak back emf of about 132Vis obtained for loaded condition and peak to peak of 144V is obtained at no load condition. Due to the load transition from 0Nm to 2.5Nm at 0.4sec, there is a slip in back emf occurs. After that corresponding to the loading condition, back emf develops. Fig.11 shows the stator flux waveforms in alpha and beta axis. Since they are in alpha –beta axis, they are orthogonal to each other. Fig.12 and 13 shows the sector and electrical rotor angle of the motor respectively. Fig.14 shows the stator flux in XY plot. The XY plot implies that we can control the stator flux indirectly without any commutation issue.

V. CONCLUSION

The thesis work has successfully demonstrated the direct torque control of BLDC motor with indirect flux control. The utility has been validated by MATLAB/SIMULINK. Since the method is position sensorless, the electrical rotor position is obtained using winding inductance, stationary reference frame currents and stator flux linkages. The amount of torque ripples in direct torque with direct flux control is about 1.5%. It has been shown that direct torque control technique is capable of instantaneous torque control and thereby enhancing the performance of entire system. The voltage vector selection is set up in the look-up table so that fast torque response is possible. Since the neutral point of the motor is not available, conventional 2×3 matrix is replaced by 2×2 Park's and Clarke's transformations are used by assuming balanced systems.

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