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Direct Torque with Direct Flux Control of BLDC Motor in Two Phase Conduction Mode

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ABSTRACT: BLDC motors are well known and are widely used in many high performance applications owing to its distinct advantages such as higher efficiency, higher output, increase armature current loading, absence of commutator, long life, less maintenance etc. In this work, an analysis on position sensorless direct torque control of BLDC motor with direct flux control have been studied using two level, six switch Voltage Source Inverter (VSI). This control algorithm is implemented in the constant torque region of BLDC motor drive. Owing to the two phase conduction mode of VSI in direct torque with direct flux control of BLDC motor, the commutation torque ripples are present and also the amplitude of the stator flux cannot be controlled effectively. 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.

KEYWORDS: Direct Torque Control (DTC), Brushless DC Motor (BLDC), Constant Torque Region, Two phase conduction mode, Voltage Source Inverter (VSI)

I.INTRODUCTION

The performance of motor and its control systems enhances the production rate and the quality of the products in the industrial applications[2]. The advancement of control theories, power electronics equipment in combine with electric motors led to a new era in industries. The great example is that Brushless DC Motors (BLDC). BLDC motor is a type of synchronous motor in which it is differentiated from other motors by its trapezoidal shaped back emfs, 120 degree rectangular currents and its electronic commutation. Earlier the use of BLDC motors is limited due to its material cost. But the emergence of magnetic materials like Neodynium, Samarium Cobalt and the alloys of neodymium with its attractive features like high magnetic density per volume and enables the rotor to compress further for same torque made them so popular for BLDC motors with further cost reduction. The BLDC motors have its own advantages compared to other motors and include higher efficiency, higher output, increased armature current loading, absence of commutator, elimination of radio frequency and electromagnetic interference, operation from a low dc voltage is possible, long life, less maintenance, high speed of operation etc. These advantages of BLDC motors leads to wide range applications extending from household appliances to traction purposes and in aerospace applications when space and weight makes a crucial factors.

There are two competing control strategies for AC drives available in industries. They are Field Oriented Control (FOC) and Direct Torque control (DTC). Both techniques works well with the on-off conditions of inverter switches. Among them DTC made an important impact in industrial applications. The name DTC is derived by the fact on the basis of the errors between the reference and the estimated values of torque and flux, it is possible to directly control the inverter states in order to reduce the torque and flux errors within the prefixed band limits.

BLDC motors mostly employed torque and current controlled strategies, assuming that torque produced is directly proportional to the currents developed by the motors. But this assumption goes to wrong in real cases because of the torque pulsations of the motor.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

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DTC it is possible to [3]obtain a good dynamic control of the torque without any mechanical transducers on the machine shaft.

The BLDC motor was always operated in 120 degree / two phase conduction mode. In 120 degree conduction or two phase conduction mode, the two phases are active at any time except during commutation period. The method is simple but having disadvantage of torque pulsation during commutation period.

II. DIRECT TORQUE WITH DIRECT FLUX CONTROL OF BLDC MOTOR

Fig 1. Shows the overall block diagram of direct torque with direct flux control of BLDC motor in two phase conduction mode.The basic idea of direct torque with direct flux control [3] is to control electromagnetic torque and stator flux linkage directly and independently 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.

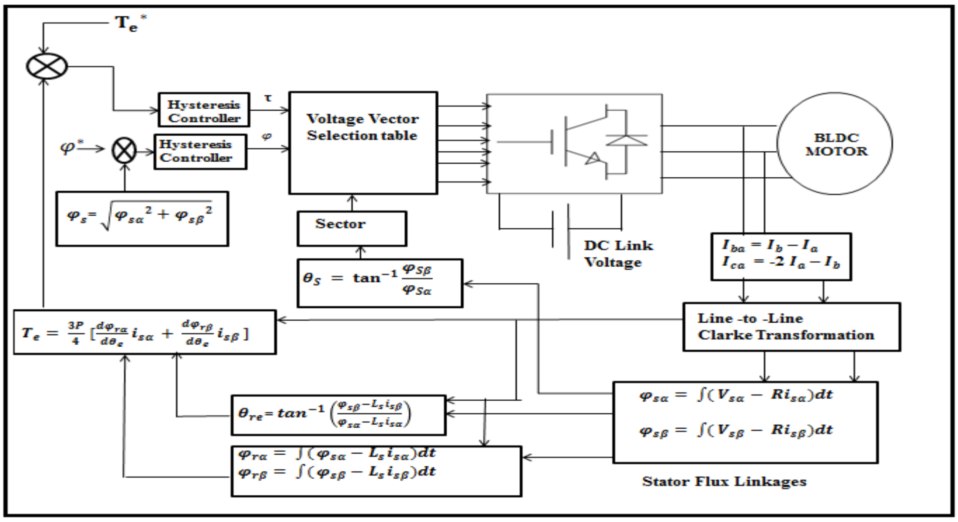

Fig.1 Block diagram of Direct Torque with Direct Flux Control of BLDC Motor

The reason for the stator flux linkage control is explained by the basic torque equation for a Surface Mounted Permanent Magnet Synchronous Motor is given by [1]

$$T_e = \frac{3P}{2L_s}\lambda_s\lambda_r sin\delta \qquad (1)$$

Where P is the no of poles, L_s is the stator phase inductance, λ_s is the stator flux, λ_r is the rotor flux, δ is the torque angle between stator flux and the rotor flux.

Since the rotor is made up of permanent magnet and has constant rotor flux, torque produced is proportional to stator flux. Hence by controlling the amplitude and rotational speed of stator flux, torque is controlled. The stator flux is obtained through the equation given by,

$$\lambda_s = \int(V - R_s I_s)dt \qquad (2)$$

Where V is the dc link voltage R_s is the stator phase resistance and I_s is the stator phase current.

Since the current flowing in the machine is depend upon voltage applied and assumed to be constant, the stator flux depends upon the applied voltage vector. Thereby controlling the voltage vector, stator flux can be controlled and hence the torque can be controlled. This is the reason for the stator flux estimation in direct torque control scheme.

A LINE TO LINE VALUES AND MODIFIED CLARKE'S TRANSFORMATION

Since the neutral point of BLDC motor is not available at out in real cases, 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 [4]

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

Where X represents back emfs, currents, voltages etc.

B. ELECTROMAGNETIC TORQUE EQUATION

The electromagnetic torque equation for a non-salient pole brushless dc motor in the stationary reference frame or in theα-β reference frame is given as [3]

$$T_{em} = \frac{3P}{4}\left[\frac{d\varphi_{r\alpha}}{d\theta_e} i_{s\alpha} + \frac{d\varphi_{r\beta}}{d\theta_e} i_{s\beta}\right] \qquad (4)$$

Where $\frac{d\varphi_{r\alpha}}{d\theta_e} = \frac{e_\alpha}{\omega_e}$ and $\frac{d\varphi_{r\beta}}{d\theta_e} = \frac{e_\beta}{\omega_e}$

Where p is the no of poles,θ_e is the electrical rotor angle,$\varphi_{r\alpha}$, $\varphi_{r\beta}$,$i_{s\alpha}$,$i_{s\beta}$, e_α,e_β are the α-and β- axis rotor flux linkages, stator currents, motor back–emfs 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 [1]

$$\varphi_{s\alpha} = \int (V_{s\alpha} - R i_{s\alpha}) dt \qquad (5)$$

$$\varphi_{s\beta} = \int (V_{s\beta} - R i_{s\beta}) dt \qquad (6)$$

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.
The amplitude of stator flux linkage is given by $\varphi_s = \sqrt{{\varphi_{s\alpha}}^2 + {\varphi_{s\beta}}^2}$(7)

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

$$\theta_s = \tan^{-1}\frac{\varphi_{S\beta}}{\varphi_{S\alpha}} \qquad (8)$$

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

D. SWITCHING TABLE

Table1Switching table

Torque τ	Flux φ	Sector(Θ)					
		1	2	3	4	5	6
1	1	V_1 (100001)	V_2 (001001)	V_3 (011000)	V_4 (010010)	V_5 (000110)	V_6 (100100)
	0	V_2 (001001)	V_3 (011000)	V_4 (010010)	V_5 (000110)	V_6 (100100)	V_1 (100001)
	-1	V_3 (011000)	V_4 (010010)	V_5 (000110)	V_6 (100100)	V_1 (100001)	V_2 (001001)
0	1	V_1 (100001)	V_2 (001001)	V_3 (011000)	V_4 (010010)	V_5 (000110)	V_6 (100100)
	0	V_0 (000000)	V_0 (000000)	V_0 (000000)	V_0 (000000)	V_0 (000000)	V_0 (000000)
	-1	V_3 (011000)	V_4 (010010)	V_5 (000110)	V_6 (100100)	V_1 (100001)	V_2 (001001)

The switching table for controlling both the amplitude and rotating direction of the stator flux linkage is given in the table 1. The output of the torque hysteresis comparator is denoted as τ, the output of the flux hysteresis comparator as ϕ and the flux linkage sector is denoted as Θ. The torque hysteresis comparator is a two valued comparator; τ= 1 means we have to increase the torque and τ =0 means we have to decrease the torque. The flux hysteresis comparator is a three valued comparator as well where ϕ =1 means that the actual value of the flux linkage is smaller than the commanded value and ϕ =-1 means that the actual value of the flux linkage is greater than the flux linkage and ϕ =0 means actual flux linkage is same as the commanded flux linkage.

E.ESTIMATION OF ROTOR POSITION

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

$$\theta_{re} = \tan^{-1}\left(\frac{\varphi_{s\beta} - L_s i_{s\beta}}{\varphi_{s\alpha} - L_s i_{s\alpha}}\right) \qquad (9)$$

Where θ_{re} is the electrical rotor position,$\varphi_{s\alpha}$ and $\varphi_{s\beta}$ are 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.

III. SIMULATION RESULTS

The validity of the direct torque controlled with direct 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 Speed	3000 rpm
No of poles	8
DC Voltage	310V
Stator winding resistance	3.52 ohm
Stator winding inductance	3.285mH

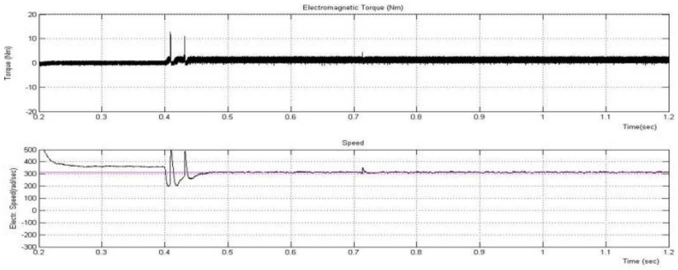

Fig 2 and 3 Electromagnetic torque developed and Speed of the motor

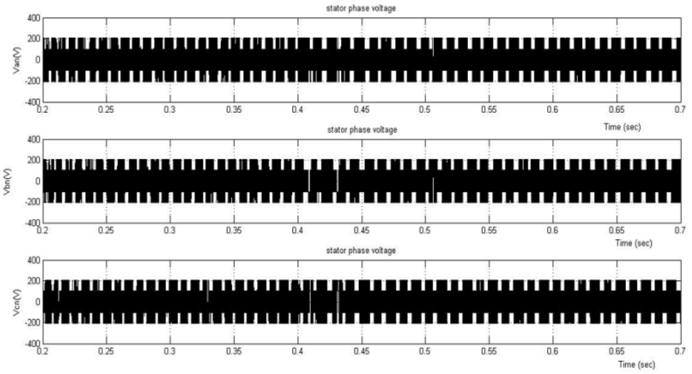

Fig 4 Stator phasor voltages applied to the motor winding

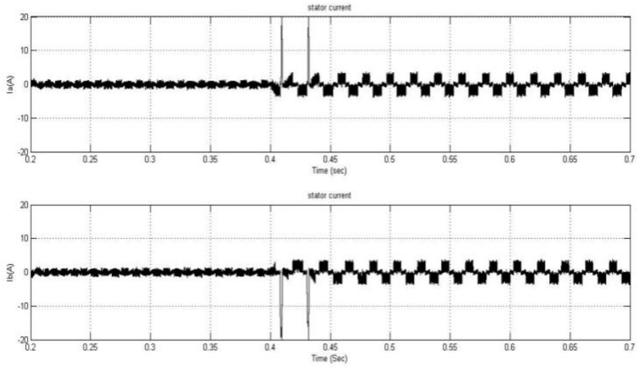

Fig 5 Stator currents of the motor

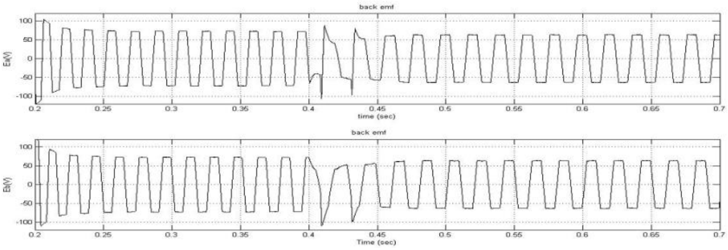

Fig.6 Back emfs of the machine

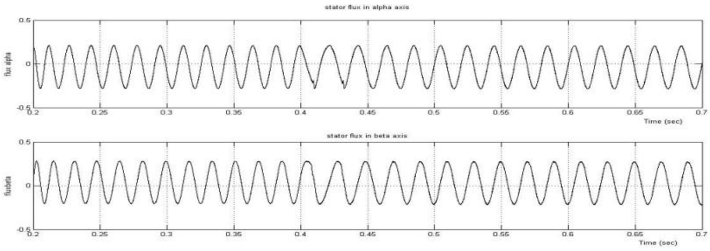

Fig .7 Stator flux in alpha-beta axis

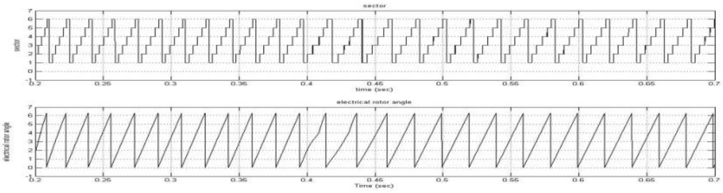

Fig 8 and 9 Sector and Rotor angle

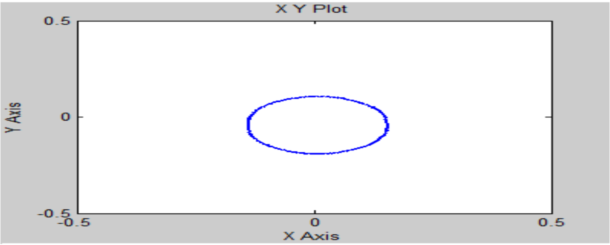

Fig 10 Stator flux in XY graph at no load

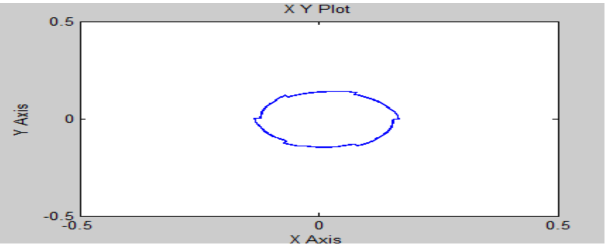

Fig 11 Stator flux in XY graph at load

The machine is unloaded upto 0.4sec and after that a load of 2.5Nm is applied. Fig 2 and 3 shows the electromagnetic torque developed and speed 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 2.8%. 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 4 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 5 shows the two phase currents developed inside the winding.. During unloading condition, machine develops zero current and during loading condition of 2.5 Nm loads, a peak-to-peak current of about 6A is obtained. Since the mode of operation of VSI is in two phase conduction mode, the shape of the current is obtained as in rectangular shape.

The back emf of the machine obtained for two phases is shown in Fig 6. 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 150V 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 7 shows the stator flux waveforms in alpha and beta axis. Since they are in alpha –beta axis, they are orthogonal to each other. Fig 8 and 9 shows the sector and electrical rotor angle of the motor respectively. Fig.10 and Fig.11 shows the stator flux in XY plot at no load and loaded condition respectively. The XY plot implies that during every 60 degree, commutation occurs, so that controlling of stator flux is difficult in direct torque with direct flux control of BLDC motor.

IV CONCLUSION

The thesis work has successfully demonstrated the direct torque control of BLDC motor with direct and 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 2.8%. 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. The simulated works showed that there are torque pulsations during commutation period. The idea of DTC in two phase conduction mode can be extended to three phase conduction mode so that commutation torque ripple can be eliminated.

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