Four Quadrant Operation of BLDC Motor with Current Controller

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Abstract- BLDC motors are conquering more popularity in aerospace, automation, computers, military, household appliances and traction applications for the reason that of its high competency and low maintenance cost. This makes the four quadrant operation of BLDC motor very crucial and important. BLDC motor control requires rotor position and speed measurements. In this paper, the modelling of BLDC motor drive system along with its control systems have been presented using MATLAB/SIMULINK. The four quadrant operation of BLDC motor was also presented.

Keywords- BLDC motor, PI controller, Hysteresis controller, Four quadrant operation.

I. INTRODUCTION

Energy saving is the main aim behind all the development and control of motors. Conventional dc motors have good control characteristics but their performances are reduced due to commutation problems. This commutation problems are completely absent in induction motors, butthey have limitations such as stumpy power factor and deviating speed torque features. As a result of focussing on energy saving, the demand for variable speed permanent magnet motor drives has increased. The usage of motor drives in the field of automation also resulted in the increased demand for high efficiency PM motor drives. This give rise to the emergence of BLDC motors. New energy efficient electric drives using PMBLDC motor have been introduced to overcome the above mentioned limitations. The permanent magnet machines have better power factor and very good dynamic characteristics and low inertia. Compared to induction motor and other brushed dc motors, BLDC motors have many advantages such as higher efficiency, long operating life, higher speed ranges, noiseless operation etc. These qualities of permanent magnet BLDC motor results in widespread applications like aerospace, automation, computers robotics, electric vehicles etc.

II. BLDC MOTOR AND CONTROLLER

BLDC motor can be projected as a brushed dc motor twisted inside out, where the permanent magnets are fixed onthe rotor and windings onthe stator. As a result, there are no brushes and commutator in this motor and thus all the drawbacksconnected with the flashing of brushes are eliminated. This motor is denoted to as a dc motor because its coils are driven by dc power source. The dc power is given to the windings on the stator.

III. FOUR QUADRANT OPERATION

For a BLDC motor, four modes of operations namely forward motoring, forward braking, reverse motoring and reverse braking are possible. The operating modes are as shown in fig 2. In the first quadrant, both speed and torque is positive so motor rotates in forward direction. In second quadrant speed remains in positive direction but torque is in reverse direction. Reverse torque is used to brake the motor.

Fig. 1 Block diagram of BLDC motor

Here the controller we used is hysteresis current controller. The required reference current of the controller is obtained from PI speed controller. The PI controller eliminates delay and provides faster control. This method of control scheme is quite pleasing and robust.
Fig. 2. Operating modes

Third quadrant is just opposite of the first quadrant, i.e., both speed and torque is negative so rotating in reverse direction. Exactly opposite of second quadrant is fourth where power is being produced. The supplied voltage is greater than back EMF during the motoring modes and is less than back EMF during generating modes.

Fig. 3 Closed loop drive

IV. MODELING OF BLDC MOTOR

There are two possible methods to model a BLDC motor, one is abc phase variable model and the other is d-q axis model. BLDC motor is a permanent magnet motor with trapezoidal back EMF whereas synchronous motor has sinusoidal back EMF. Since trapezoidal the mutual inductance sandwiched between stator and rotor is non sinusoidal. So transforming to d-q axis does not provide any added benefit, thus abc phase variable model is chosen. Here we assume that all windings have equal stator resistance and self and mutual inductances are constant. The equivalent circuit diagram of the BLDC motor is as shown in the fig.4.

The generated back EMF is trapezoidal in shape due to permanent magnet straddling on the rotor and its expression is as given below:

\[ E_a = K_e \cdot \sin(\theta) \cdot w(t) \]
\[ E_b = K_e \cdot \sin\left(\theta + \frac{2\pi}{3}\right) \cdot w(t) \]
\[ E_c = K_e \cdot \sin\left(\theta + \frac{2\pi}{3}\right) \cdot w(t) \]

Where \( K_e \) is the back EMF constant and \( w \) is the mechanical speed of rotor.

The electromagnetic torque equation is

\[ T_e = \frac{1}{\omega_m} (e_a i_a + e_b i_b + e_c i_c) \]
Where $\omega_m$ is the speed of rotor and $T_e$ is the electromagnetic torque.

The equation of motion is:

$$J \frac{d}{dt} \omega_m + B \omega_m = T_e - T_L$$

Where,

$B$ = damping constant.
$J$ = moment of inertia of the drive.
$T_L$ = load torque.

Fig.5. Simulink model of BLDC Motor.

**A. SPEED CONTROLLER**

The speed controller used to accomplish speed regulation is conventional PI controller. The predetermined speed and restrained speed are the feedback signals to the controller. PI controller compares the motor speed with reference speed and the speed error is processed to control the motor.

Fig.6. Simulink model of PI Controller.

accordingly. It involves two separate modes – proportional mode and integral mode. The reaction to the current error is determined by proportional mode while integral mode determine the reaction based recent error.

The sensitivity of controller and speed overshoot is controlled by varying proportional gain and the increase of integral gain will allow the motor speed to catch up with the reference speed. The proportional and integral gain must be varied within the limits otherwise it cause instability and the controller become insensitive. Too high gains may also result in saturation of the system. The $K_p$ and $K_i$ values of the controller are resolved by trial and error method.

**B. CURRENT CONTROLLER**

Hysteresis current controller is used to limits the phase currents within the hysteresis band. It generates the switching signals to the inverter. This method is a direct current feedback control, in which the actual current is continuously tracks the command current within hysteresis band. When current exceeds upper limit, the upper switch is turned off and lower switch is turned on. Similarly when current exceed lower limit, upper switch is turned on and lower switch is turned off. The limits of hysteresis band is normally selected by considering 10 to 15 percentage of the actual motor current. Thus the lower limit is taken as 10 % of actual motor current and upper limit is 15% of the motor current.

Fig.7. Modelling block of Hysteresis controller

The switching pattern is as given below:

If $i^err > UL, S1$ is on and $S4$ is off.
If $i^err < LL, S1$ is off and $S4$ is on.
If $i^err > UL, S3$ is on and $S6$ is off.
If $i^err < LL, S3$ is off and $S6$ is on.
If $i^err > UL, S5$ is on and $S2$ is off.
If $i^err < LL, S5$ is off and $S2$ is on.

Where $i^err_k = i^ref_k - i^meas_k$ and UL, LL are the higher and lower bounds of hysteresis band.

**C. VOLTAGE SOURCE INVERTER**

The input voltage to be fed to three phase BLDC motor is supplied by voltage source inverter. The inverter is implemented by the following equations:
[S1* Sau + S4*Sal] |E| = Van.
[S3* Sbu + S6* Sbl]|E| = Vbn.
[S5* Scu + S2* Scl]|E| = Vcn.
Where Van, Vbn and Vcn are line neutral voltages.

|E| = Vd /2, Vd is the dc link voltage.

Sau& Sal are the upper & lower pulses of phase A.
Sbu&Sbl are the upper &lower pulses of phase B.
Scu&Scl are the upper & lower pulses of phase C.

**TABLE 1**

<table>
<thead>
<tr>
<th>MOTOR PARAMETERS</th>
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<tbody>
<tr>
<td>No. of poles</td>
</tr>
<tr>
<td>No. of phases</td>
</tr>
<tr>
<td>Rated speed</td>
</tr>
<tr>
<td>Rated voltage</td>
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<tr>
<td>Rated current</td>
</tr>
<tr>
<td>Resistance/phase</td>
</tr>
<tr>
<td>Rated power</td>
</tr>
<tr>
<td>Self &amp; Mutual inductance</td>
</tr>
<tr>
<td>Back EMF constant</td>
</tr>
<tr>
<td>Torque constant</td>
</tr>
<tr>
<td>Moment of inertia</td>
</tr>
<tr>
<td>Maximum torque</td>
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**V. DRIVE SYSTEM**

The voltage required to drive the BLDC motor is fed by three phase inverter. The gating pulses of the inverter are injected by a hysteresis current controller. This controller produce the required pulses by comparing the actual motor currents with reference current. The reference current is generated by speed controller.Here the speed controller is conventional PI controller which compares the actual motor speed with a designed reference speed to give an error signal.

**VI. SIMULATION RESULTS**

The simulation results of the BLDC motor with speed and current controller is as shown below.

The output speed waveform of the motor is as shown above. The reference speed is taken as 1000 RPM. From the figure it is clear that the actual motor speed catches up with the reference speed.

The electromagnetic torque of the motor is as shown in fig.11. In the beginning the torque is high when the speed is increasing to its steady value. Once
speed attain its stable value, torque will also settle to its steady value.

Fig.12 Back EMF waveform of BLDC motor

The above figure shows the trapezoidal back EMF waveform of BLDC motor and it has 120 degree mode of operation. The phase currents of the motor is as shown in fig.13. At the outset the phase current is high, later it is reduced to reference value when speed reaches steady value. Here the reference current is 12 A. The actual motor current in the simulation result is nearly 12 A.

Fig.13 Output waveforms of Phase current

Fig.14 Rotor position of BLDC motor

The phase voltage of three phase inverter is as shown in fig.15. This voltage is used to fed the BLDC motor. In this modelling the inverter is operated according to the sector. So the selection of sector is very important.

Fig.15 Phase voltage of inverter

The simulation results of four quadrant operation of three phase BLDC motor is given below. The transition of quadrant from one to another is easily visible from the following graphs. The output speed and torque of four quadrant BLDC motor is as shown below. The reference speed is set as 1000 rpm and load torque is given as 3 Nm.

Fig.16 Output speed waveform of four quadrant operation of BLDC motor.

Fig.17 Output torque waveform of four quadrant operation of BLDC motor.

Fig.18 Generated back EMF waveform of four quadrant operation of BLDC motor.
VII. CONCLUSION

The simulation model of BLDC motor drive system with PI control and hysteresis current control based on MATLAB/Simulink is presented. The modelling of BLDC motor is also presented, which is very useful in studying the drive system. Closed loop simulation is carried out and the simulation results are presented. The speed oscillations are reduced by closed loop system. The four quadrant operation of BLDC motor is also presented with the required waveforms.

REFERENCES