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BI - Directional Operation of BLDC Motor for Electric Drives

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Abstract: ***Brushless DC (BLDC) Motors have found various applications in industrial and domestic uses. BLDC motor accomplishes electronic commutation, which enables Bi - directional operation of BLDC motor, which appears in drives like Electric Vehicle, lifts and trolley cars which improves efficiency and increases the running period of drives. The speed control in both directions requires a Bi - directional DC - DC converter in between source and the inverter. Many configurations of Bi - directional converters are available in the literature with different characteristics and applications. In this work, a Bi - directional converter is chosen which have more full conversion ratios, reduced voltage stress and with a low component count. MATLAB modelling and simulation studies validate the proposed strategy. The Bi - directional operation and regeneration of the BLDC motor are possible by controlling the current through Bi - directional converter.***

Keywords: Bidirectional Converters, BLDC Drives, Electric Drives

1. Introduction

The electric drive system is necessary to control speed, position, and torque of electric motors. Brushless DC (BLDC) Motors are gaining importance in drives applications because of their high power - to - weight ratio, high speed, high reliability, low maintenance and an overall reduction soft Electro - Magnetic interference. BLDC Motors are electronically commutated motor powered by a DC supply via an inverter to drive each phase of the motor using a closed - loop controller. The clockwise operation of motor represents motoring while anticlockwise direction stands for regeneration [1].

The speed control in both directions require a bi - directional DC - DC (BDC) converter placed between the source and the

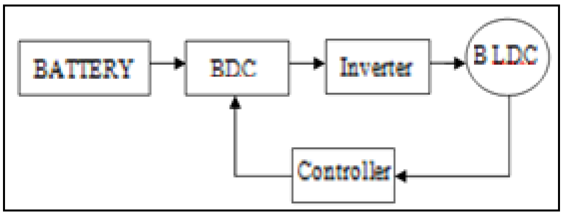

Figure 1: System Description

inverter. BDC allows the battery to absorb power during braking and also release energy during motoring. Different bi - directional converters are available in the literature in various papers [2] – [6]. A bidirectional Cuk converter can be used for dual voltage systems in automobiles [2]. Having an integrated magnetic it has the advantage of zero current ripples. Zero voltage switching employed is useful at all loads. It requires two cascaded power stages which reduce the overall efficiency of the system [2]. A non - isolated bi - directional DC - DC converter having a simple circuit structure and less voltage stress given in [3] has a semiconductor connecting the low voltage and high voltage side grounds. Hence, the potential difference between two ground is a high - frequency PWM pulse. The result is extra maintenance and Electro Magnetic Interference problems. An isolated bidirectional full - bridge DC - DC converter uses a flybacksnubber to recycle the absorbed energy in the capacitor and having less voltage stress. Turns ratio of the transformer in [4] causes high voltage spikes across the semiconductors during switching transitions. Three - level DC - DC topologies with high voltage gain and non - extreme duty cycles presented in [5] suffer from complicated control schemes for balancing the flying capacitor voltage. A new bi - directional transformerless DC - DC converter is used in this paper having less voltage stress, wide conversion ratio and less component count [6]. This converter is useful in Electric vehicle where both motoring and regeneration is required.

2. Speed Control Strategies

Speed control of BLDC motor is essential for making the motor run at desired speed for various applications in electric drives. Suitable controllers ensure speed control. The three main speed control strategies are; Hysteresis band speed control method, Variable DC - link speed control method and Pulse - Width modulation method of speed control. Dual - closed loop speed control is used in BLDC motors where the inner loop adjusts current and outer loop adjusts speed [7]. Speed controller compares actual speed with setpoint speed, and error speed is treated to provide a better signal to the plant.

a) Hysteresis Band Speed Controller

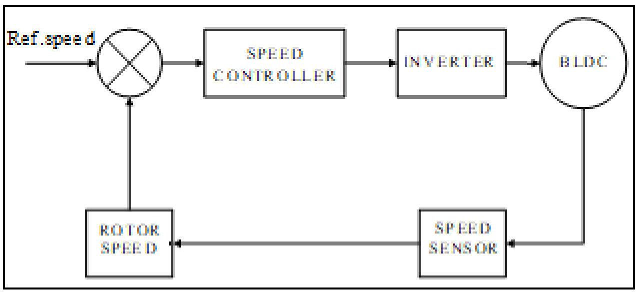

Figure 2: Hysteresis Band Speed Controller

In this simple speed control method, a hysteresis controller is used. In this method, speed is forced to pause within a set - point amount [7]. To control the speed of the motor, as the speed arrives at a certain level over the set - point speed the motor will turn - off by turning off the inverter switches and will turn - on when the speed declines below a certain level below the set - point speed. This method is simple to implement as compared to other methods. Tolerance band is a design parameter of this method, having precise control and produces good quality waveforms [8]. Hard chopping, as well as soft chopping, is possible in this method. The disadvantage of this method is variable switching frequency, causing it challenging to filter acoustic and electromagnetic noises. Used in applications where load and speed do not vary too much.

b) Variable DC Link Voltage Control

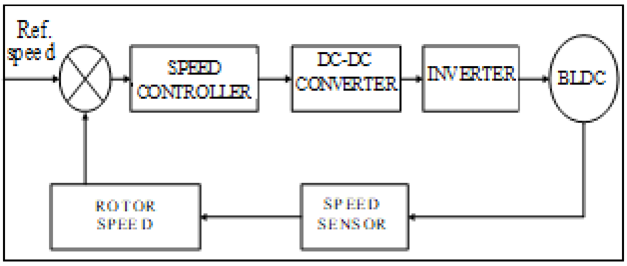

Figure 3: Variable DC link voltage control

For the speed control of the motor, the voltage amplitude of inverter is maintained in this method. The DC - DC converter [7] receives its output from the speed controller, whose performance is dependent on the PWM technique by adjusting the duty cycle. The input of the inverter voltage changes to run the motor at the desired speed. This method is cheaper as compared to other speed control methods. But due to the presence of a DC - DC converter in the control scheme, it suffers from high losses during high current and low voltage conditions [9].

c) Pulse - Width Modulation Method of Speed Control

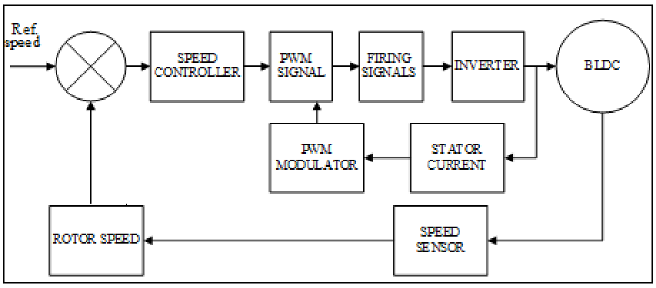

Figure 4: Pulse - width modulation method

In this method, speed control is achieved by controlling the duty cycle of the inverter switches in which motor will turn on and off at a high rate [7]. PWM block in this block diSagram modifies the duty cycle of inverter switches. Speed of the motor directly changes according to the modulation in the duty cycle. The chopping frequency is fixed in this method, making the filtering of acoustic noise and electro - magnetic interference easier. But during high speed, it suffers from torque and current ripple [10]. The various techniques involved in this method are trapezoidal commutation of BLDC motor, Sinusoidal commutation of BLDC motor and Field - Oriented Control of BLDC motor. Based on back - emf of the BLDC motor both trapezoidal and sinusoidal commutations are possible.

d) Trapezoidal Commutation of BLDC Motor

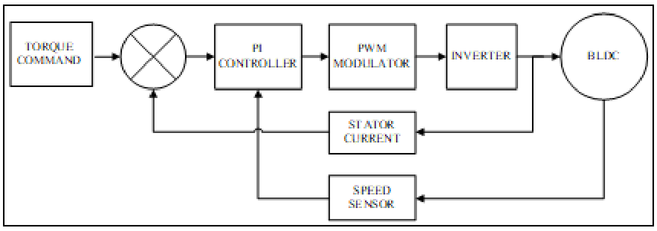

Figure 5: Trapezoidal commutation in BLDC motor

It is the simplest method of control for the BLDC motor. In this method, the two motor terminals control current while the third terminal always electrically disconnected from the source. Hall sensors are embedded to provide rotor position and are given to the controller [11]. As the motor turns, current to the motor terminals is switched every 60 degrees of rotation, and the current waveforms are in staircase form. With rotor rotation, current space vectors are produced with six distinct directions. The open winding detects zero crossing point of back emf, which corresponds to the signal change in the hall sensor. As back - emf is proportional to motor speed, at slower speeds or during start - up motor must be started in open loop until sufficient speed and back - emf are generated. At that particular point, the controller can be switched for commutation. The advantage of trapezoidal commutation over other techniques is their simplicity of control. However, it results in torque ripple at each step of commutation. The applications of this type of control is used where hall–effect sensors are not viable like as in AC, refrigerators etc.

e) Sinusoidal Commutation in BLDC Motor

Even though the back - emf of BLDC motor is trapezoidal, inductive winding in BLDC motor smoothens the waveform to be sinusoidal, and hence sinusoidal commutation is possible in BLDC motor. Each winding of motor has provided with currents that vary sinusoidally as the motor turns. In order to match with the stator winding orientation, the currents are phase - shifted by 120 degrees, and the current space vectors have constant magnitude and are orthogonal to the rotor. For determining actual rotor position, encoders are used instead of hall sensors to provide rotor position.

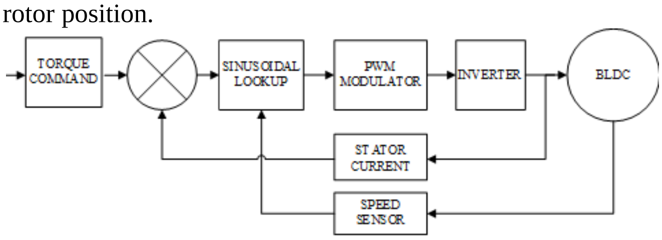

Figure 6: Sinusoidal commutation in BLDC motor

The waveforms are 120^0 phase shifted and these signals are multiplied by torque command. The output of this torque command modulates the voltage amplitude, which is directly proportional to the desired torque. These commands are fed to the controller, which controls the current flow through the windings. According to Kirchhoff's law, the current through the third winding is the negative sum of the current through the other two windings, which cannot be controlled directly. This method eliminates torque ripple as torque is independent of the shaft angle [11]. But it is inefficient at high speeds. As motor speed increases the frequency of sinusoidal signals also increases, resulting in difficulty for the controller to track high - frequency signals. As speed and back emf are directly proportional, it is difficult for the motor to overcome an increase in amplitude and frequency. These conditions cause disturbances in the current loop and hence suffers current phase lags and errors.

f) Field - Oriented Control

Also known as vector control, used in drives to control the speed of the motor by controlling the current. Torque and flux are controlled independently by this method. Here stator currents are measured and are adjusted to make the angle between the rotor and stator flux 900 for achieving maximum torque. The significant feature is that FOC operates on the resultant vector of the three - phase currents without controlling each phase independently as in the above commutation methods [11]. FOC can be direct field - oriented control and indirect field - oriented control. Direct field - oriented control (DFOC) algorithms provide more precision for torque control but require sensors for the speed control by providing the data for the FOC algorithms. Indirect field - oriented control (IFOC) method estimates the phase angle of the rotor magnetic field flux, eliminating the need for additional sensors but adds complexity and computation time of the control system.

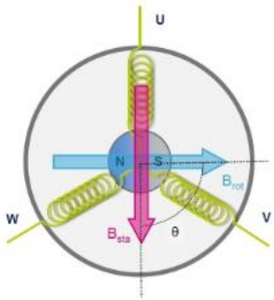

Figure 7: Field - oriented control in BLDC motor

FOC provides better efficiency at higher speeds as compared to sinusoidal control. Provides optimized efficiency during transient operation and have better dynamic load changes by maintaining the stator and rotor fluxes. The downside of FOC is that they use complex algorithms and requires high cost for electro - mechanical sensors. They are used in full range speed applications like washing machines, fans, compressors etc. This paper presents a control strategy in BLDC motor for Electric Vehicle applications using DC link voltage control for achieving less voltage stress on semiconductor switches. Section II explains the speed control strategies of BLDC motor followed by converter selection in section III. Section IV contains the simulation results and discussions/ conclusion is given in section V.

3. Selection of Converter

The choice of converter is important in designing the control system because of the factors like voltage stress, voltage gain, inrush currents, electro - magnetic interferences, voltage conversion ratios, torque and current ripples. Many of these features are complementary in nature. Hence we have selected a converter with simple circuit structure, wide conversion ratios, low component count and less voltage stress [6]. The bi - directional converer consists of three switches, 4 capacitors &2 inductors. G_1, G_2 and G_3 are the triggering signals of Q_1, Q_2 and Q_3. G_2 and G_3 are identical and are complementary to G_1. d_1, d_2 and d_3 are the duty cycle of Q_1, Q_2 and Q_3 respectively.

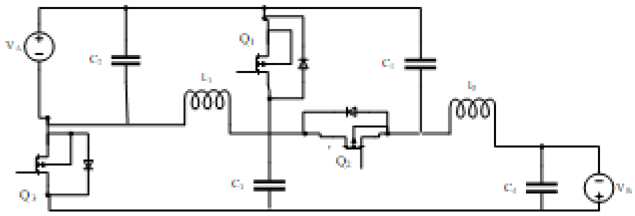

Figure 8: Bi - directional converter

Switching of bi - directional converter is explained in [6].

4. Simulation and Results

The simulation of BLDC motor with bi - directional DC - DC converter is performed using MATLAB/ SIMULINK® model. Input voltage is chosen as 12 V. The components selected for converter simulation are given in Table 1.

Table 1: Simulation Parameters for BDC

Sl. No	Parameters and Components	Values
1	Input Voltage	12 V
2	Inductors L_1, L_2	68 mH
3	Capacitors C_2, C_3	100 µF
4	Capacitor C_1, C_4	220 µF
5	Switching frequency f_s	100kHz

Table 3 and 4 shows the voltage gain and voltage stress of the power switches for forward (boost) and reverse (buck) operation of bi - directional converter. With different duty cycles.

Table 2: Forward operation

D1	D2/D3	V_{out}	V_{gain}	V_{stress}
0.60	0.40	35.475	33.82	133.0
0.50	0.50	23.815	50.38	87.69
0.45	0.55	19.52	61.46	71.40
0.40	0.60	15.92	75.35	57.89
0.39	0.61	15.28	78.40	55.3
0.37	0.63	14.0425	85.44	50.90
0.34	0.66	12.32	97.36	44.55

The voltage stress increases with voltage gain, but the values are still acceptable for higher gains. In the backward direction, owing to the buck operation, voltage stress is comparatively less.

Table 3: Reverse operation

D1	D2/D3	V_{out}	V_{gain}	V_{stress}
0.50	0.50	5.987	50	22.05
0.45	0.55	7.272	61.11	26.60
0.39	0.61	9.357	78.20	33.99
0.36	0.64	10.632	88.88	38.54
0.35	0.65	11.105	92.80	40.17
0.34	0.66	11.605	97.05	41.95

5. BLDC Motor Control

The control strategy aims at controlling the speed of BLDC motor used as drive for electric vehicle applications. DC link voltage between the converter and the inverter acts as the input to the motor, suitably modulated and supplied to the windings. The simulation studies are carried out using MATLAB/SIMULINK® blocks. The block schematic used in the studies is shown in figure 8.

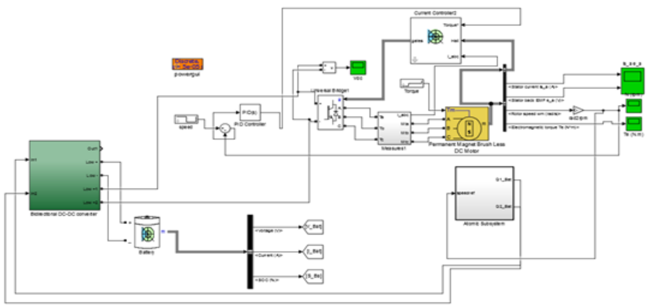

Figure 9: Simulink Model of the proposed BLDC controller

The simulation parameters used in the modelling of BLDC closed loop control is given in Table 4.

Table 1: Simulation Parameters for BLDC

Sl. No	Parameters and components	Values
1	Rated Voltage	48V
2	No. of poles	6
3	Resistance per phase	2.8750Ω
4	Inductance per phase	8.5 mH
5	Moment of inertia	.8e - 3 kgm^2
6	Torque constant	1.4Nm/A
7	Output Power	200 W

The converter raises the level of the battery voltage for the DC link. Inverter switches are fired with the knowledge of the rotor position according to the reference speed. Regeneration corresponds to feeding back the power back to the supply under favourable switching condiotions. The rotor speed response of BLDC motor with a bi - directional converter is shown in figure 10.

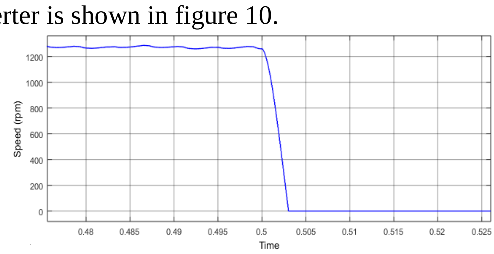

Figure 10: Speed - Timewaveform during regenerative braking of BLDC motor

In order to validate the proposed technology the bi - directional converter is fed to BLDC motor through a three phase inverter. The motor runs at its rated speed and is regenerated at every 0.5 s.

6. Conclusion

Bi - directional control of electric drives and harvesting regenerative power has attracted lot of research. In this paper, BLDC motor is selected as the drive. Speed control in bi - directional operation of BLDC motor requires a bi - directional DC - DC converter. The control strategy relies on DC link voltage control using a bidirectional DC - DC converter. The converter characteristics shows excellent voltage gain in both directions and admissible voltage stress on the switches. The number of components in this topology are also less compared with standard configurations. During braking modes of operation, the kinetic energy is converted to electric energy and fed back to the source with the help of a bi - directional converter. Proper switching of inverter and converter can ensure high efficiency to the proposed system. Simulation studies shows the effectiveness of the proposed strategy. Further, the studies would aim at designing a fuzzy controller to approximate and generate control signals.

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