Study on DC-DC Converter fed Sensor-less Motor Drive

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Abstract: Brushless DC motor widely used in different sectors for high efficiency and very low maintenance. The report concerns about the performances of Brushless DC (BLDC) motor with KY and four quadrant converters. Input voltage has been varied for both of them and instantaneously the output voltage is recorded along with the theoretical value. The simulation of the converter circuits have been made using MATLAB/Simulink platform. The parameters of the BLDC motor under argument are stator back electromotive force (emf), electromagnetic torque and motor speed. An attentive determination has been made to represent the motor parameters in a simply comparable manner for both the converters. Lastly, a conclusion has been drawn on the best outcome of the converter among the two to enable the motor to function efficiently and help us get desirable results when the motor is in operation.

1. Introduction
The invention of modern solid state devices like the MOSFET switch provides good switching speed and operates well even at low voltages. These permit us to achieve a faster dynamic response to the quick change in load current or input voltage. In this research work two converter topologies are considered: four quadrant converter and KY converter. These converters generate their own DC output which is fed to a Brushless DC motor via a three-phase inverter [1, 2]. Brushless DC motors find applications in automation like electric vehicles (EV), aerospace, medical industries, and in various applications like actuators, compressors, types of instruments used in health, heating purposes, and ventilation, in motion control systems due to their reliability and good response [3]. The absence of field windings and brushes enables the Brushless DC motor to commutate electronically. This is an important advantage over the traditional Brushed DC motor because electronic commutation cancels the opposing effects of sparking and wear and tear of the brushes to a greater extent [4]. This makes sure low maintenance, high-speed ability, and greater longevity of the motor. Furthermore, the Brushless DC motor is much more efficient compared to a traditional Brushed DC motor whose efficiency is markedly lower. Considering the size of the motor, the torque delivered is quite high and thus, it is practically usable in applications where space and weight are constraints [5]. For this work, a 3-phase synchronous permanent magnet Brushless DC motor having trapezoidal back emf has been considered. A DC input voltage is supplied to the DC-DC converter. The generated DC voltage is converted into a three phase AC voltage by an inverter to run the motor. The motor has Hall effect sensors placed 120° to each other [6], which detects the position of the rotor and produces a feedback signal to be used by the motor controller to ensure the desired functioning of the motor subject to reference parameters. Nowadays sensorless BLDC motors are used more often because of its certain advantages like when the motor is running for a longer time the sensor gets heated up, which in turn creates error results but as in sensorless BLDC motor this error can be avoided [7]. Though ideally, the BLDC motors should have trapezoidal back emf and the electromagnetic torque should be constant but in practical working that is not always
the case [8, 9]. The deviation of the waveform from their ideal nature may lead to the formation of torque ripples. Regardless, the BLDC motor has far greater merits than demerits like high efficiency, reliability, low acoustic noise, good dynamic response, and as there is no brush erosion present therefore it has a longer lifetime [10]. Figure 1 shows the block diagram of the converter output fed BLDC motor. In the next two sections, that is, section 2 and section 3 presents the explanation of KY converter and four quadrant converter respectively. Detailed description of the converters which includes different modes of the converters has been explained in section 4 and section 5. The next section-6 deals with the simulation and the output analysis of both the converters and also the Brushless DC motor with the converters connected to it. Section 7 is about the output results of the Brushless DC motor which has different waveforms of the output parameters of the motor. Finally, this paper concluded in section 8.

![Figure 1. Block Diagram of converter fed BLDC motor](image)

### 2. KY converter

![Figure 2. Circuit diagram of theKY converter](image)

The above figure-2 is a circuit diagram of KY converter which consists of, two MOSFET switches $S_1$ and $S_2$, one diode, one inductor $L$, one output capacitor $C$ and one energy-transferring capacitor $C_b$ which is large enough to keep the voltage across itself constant at a certain value. The input voltage is $V_i$ and the output voltage source across the load is $V_o$. When this converter is operating in continuous conduction mode (CCM) [11], it has a lot of advantages such as non-pulsating current, low output ripple, and good load transient response which can eliminate the problems exhibited by the boost converter thus a KY converter can be used instead of boost converter which will have better output response comparing with the traditional boost converter. Figure 2 shows here the circuit diagram of the KY converter. The below equation is for the voltage gain where D is the duty cycle. $V_o$ and $V_i$ is the input and output voltage of the converter.

$$\frac{V_o}{V_i} = 1 + D$$  \hfill (1)
3. Four quadrant converter

The figure-3 shows the circuit diagram of a four quadrant converter, there are four MOSFET switches named as $S_1, S_2, S_3, S_4$ with four body diodes named as $D_1, D_2, D_3, D_4$, a voltage source with input voltage $V_i$, capacitor $C_a$ is connected to the input side and capacitor $C_b$ is connected to the output side, one inductor $L$ is present between the input side and the output side and load is connected on the right hand side. DC-DC converters are capable of operating the motor in the first quadrant. Some converters can operate in two quadrants and some in all four quadrants. The four quadrant converter operates in all quadrants which means, it is capable of transporting energy in both directions and of stepping voltage up [12]. When the voltage source supplies power to the motor, the voltage and current are in the same direction. Now the motor is said to be operating in motoring mode, its operation corresponds to the first quadrant. If there is a possibility of reversing the current direction but the voltage polarity kept same, the motor is said to be operating in the second quadrant. This happens when regenerative braking is applied to the motor [13]. During regeneration operation, power flows in the reverse direction i.e. power will be fed back to the voltage source. If the voltage polarity and load current are reversed simultaneously, the motor will operate in the opposite direction (but the power is consumed by the load). This operation corresponds to the third quadrant and even now it is said to be in motoring mode (in the reverse direction). If the voltage polarity is reversed maintaining the current direction from source to load, the power reversed and the motor operates in the fourth quadrant. The motor is said to be in reverse regeneration operation (i.e. regeneration in the reverse direction).

4. Operation of KY converter

Here the input and output voltage are $V_i$ and $V_o$, respectively. Since the voltage across energy-transferring capacitor $C_b$ follows the input voltage $V_i$ entirely, so we tell that the voltage across $C_b$ is $V_i$. The voltage across C is represented by $V_C$. Moreover, the input current is signified by $i$. The currents flowing through $C_b$, C and L are denoted by $i_b$, $i_c$ and $i_L$, respectively. The basic operating principle of KY converter discussed here which always operates in continuous conduction mode (CCM). The corresponding operating principle rule is that the turn-on type of these two switches ($S_1 & S_2$), where D is the duty cycle ratio of the PWM control signal.
The KY converter has mainly two operating modes. The above figure-4 shows the Mode-1 operation of the KY converter. $S_1$ is turned on and $S_2$ is turned off, the voltage across inductor, $L$ is the input voltage $V_i$ plus the voltage $V_i$ across $C_b$ minus the output voltage $V_o$, thereby causing $L$ to be magnetized [14]. Equation (1) shows the voltage across inductor $L$. Also, the current flowing through $C$ is equal to the current $i$ flowing through $R$ subtracted from the current flowing through $L$. Besides, in this mode, $C_b$ is discharged. Equation (2) shows the current across the output capacitor $C$. In the Mode-2 operation $S_1$ is turned off and $S_2$ is turned on, the voltage across inductor, $L$ is the input voltage $V_i$ minus the output voltage, thereby causing $L$ to be demagnetized. In this mode, $C_b$ is abruptly charged to $V_i$ in a short period of time, which is much less than $T_s$.

$$L \left( \frac{dl}{dt} \right) = 2V_i - V_o$$  \hspace{1cm} (2)$$
$$C \left( \frac{dv_o}{dt} \right) = I - \frac{v_o}{R}$$  \hspace{1cm} (3)

5. **Forward motoring mode or first quadrant operation in boost mode**

The current flows from source to load then it is referred to as positive load current and the current flows from load to source then it is referred to as the negative load current. When the converter operates in the first and third quadrants, the motor receives the power and operates in the motoring mode and the power is transferred from source to load, it is boosted up. When the motor operates in the second and fourth quadrant, the power is fed back to the source and the motor operates in braking mode. The armature current $I_a$ is either positive or negative (flow into or away from armature) and the armature voltage $V_a$ is also either positive or negative [13]. This paper explained the first quadrant operation of four quadrant converter in boost mode.

![Figure 5. Four quadrant converter in forward motoring mode](image)

The above figure-5 shows the first quadrant operation of the four quadrant converter in boost mode when MOSFET switch $S_2$ is switching, switch $S_3$ and $S_4$ is kept off and switch $S_1$ is always on. As switch $S_2$ is switching, there are two Modes, Mode-1 switch is ON and Mode-2 switch is OFF. In figure 5, the solid direction arrows shows the power flow when switch $S_2$ is ON and the doted direction arrows shows the power flow when switch $S_2$ is OFF. For the Mode-1, with $S_1, S_2$ is ON, therefore the current moves through the inductor and this two switches, resulting in magnetizing the inductor $L$. During this operation, the energy transferring capacitor $C_b$ is discharged. The capacitor $C_o$ can actually be seen as a low pass-filter on the input signal, which strives to keep the voltage into the converter constant. For the second case, when $S_2$ is OFF, the current is forced to move through the body diode $D_3$ of switch $S_3$, then through the capacitor $C_b$ and the load. The inductor $L$ now gets demagnetized; if we consider zero voltage drop across the diode then the voltage across the inductor will be the equation (4) where $I_L$
denotes the inductor current. The capacitor $C_b$ now gets charged. The output voltage $V_o$ can be found by the equation (5), where $D$ is the duty cycle ratio of the PWM control signal for $S_2$.

$$V_i - V_o = L \frac{dI_L}{dt}$$  \hspace{1cm} (4)

$$V_o = \frac{1}{(1-D)} V_i$$  \hspace{1cm} (5)

6. Simulation and output value analysis

6.1 Simulation of KY converter

In the above figure-6 simulation of KY converter the blocks used are:

Two MOSFET switches are used and there is a PWM generator that provides the gate pulse to both of them. Current measurement block and a voltage measurement block have been used to check the output voltage and current. The table-1 shows the parameter values considered for different blocks of the simulation.

![MATLAB simulation of KY converter](image)

**Table 1. Parameters of KY converter**

| PARAMETERS                        | SPECIFICATIONS |
|-----------------------------------|----------------|
| Inductance (L)                    | 0.018 mH       |
| Resistance (R)                    | 100 Ω          |
| Energy Transforming Capacitance ($C_b$) | 1700 µF       |
| Capacitance (C)                   | 1.64 F         |

From equation (1) calculate the theoretical output voltage, we have considered the value of the duty cycle as 0.5. Table-2 shows the comparison between the theoretical and practical value of the output voltages of KY converter.
The above figure-7 is the simulation of four quadrant converter in first quadrant operation in boost mode. The blocks which are used for the working of the MATLAB simulations are:

Four MOSFET switches are used and there is a PWM generator that provides the gate pulse to one of the switches. The current measurement block and a voltage measurement block have been used to check the output voltage and current. Table-3 shows the parameter specifications of the simulation.

### Table 2. Comparison between the output voltages

| Input voltage, $V_i$ (V) | Theoretical output voltage, $V_o$ (V) | Practical output voltage, $V_o$ (V) |
|--------------------------|-------------------------------------|-------------------------------------|
| 20                       | 30                                  | 30.95                               |
| 24                       | 36                                  | 37.34                               |
| 28                       | 42                                  | 43.86                               |
| 32                       | 48                                  | 49.91                               |
| 36                       | 54                                  | 56.45                               |
| 40                       | 60                                  | 62.94                               |

6.2 Simulation of four quadrant converter

![Figure 7. MATLAB simulation of four quadrant converter](image)

Table 3. Parameters of four quadrant converter

| PARAMETERS | SPECIFICATIONS |
|-----------|----------------|
| $L$       | 400 µH         |
| $R_i$     | 0.01 Ω         |
| $R_o$     | 100 Ω          |
| $C_a$     | 1500 µF        |
| $C_b$     | 0.2 F          |
6.3 Output voltage value comparison of four quadrant converter

The theoretical output voltage can be calculated by:

Equation (5) can be used to calculate the theoretical output voltage value of the forward motoring mode or first quadrant operation in boost mode. To calculate theoretical output voltage the duty cycle considered here is 0.5. Table-4 shows the comparison between the theoretical and practical output voltage for four quadrant converter.

**Table 4. Comparison between the output voltages**

| Input voltage, $V_i$ (V) | Theoretical output voltage, $V_o$ (V) | Practical output voltage, $V_o$ (V) |
|--------------------------|--------------------------------------|------------------------------------|
| 20                       | 40                                   | 39                                 |
| 24                       | 48                                   | 47.1                               |
| 28                       | 56                                   | 54.8                               |
| 32                       | 64                                   | 62.6                               |
| 36                       | 72                                   | 70.5                               |
| 40                       | 80                                   | 78.2                               |

6.4 Simulation of the Brushless DC motor with converter

The simulation circuit figure-8 depicts the working of the Brushless DC motor (BLDC) with the subsystems of the converter connected to it. In this simulation, the blocks which are used are: A three-phase motor is fed by a six-step voltage inverter. The inverter block used in this simulation is a type of MOSFET Bridge. The gates signals, given to the inverter, are produced by decoding the Hall Effect signals of the motor. The three-phase outputs of the inverter are inserted into the Permanent Magnet Synchronous Machine (PMSM) block's stator windings. The load torque applied to the machine's shaft is first set to 0 and at $t=0.1s$ its steps to its nominal value. The loop synchronizes the gates signals of the inverter with the electromotive forces. This paper compare the performance evaluation of the motor with KY converter and the four quadrant converter. The table-5 shows the comparison between different motor parameters for the respective KY converter and four quadrant converter.
Simulation Results

| Motor Parameters         | KY Converter | Four quadrant converter |
|--------------------------|--------------|-------------------------|
| Input voltage (V)        | 120          | 120                     |
| Output voltage (V)       | 155.2        | 216.5                   |
| Stator current (A)       | -2.8         | -0.052                  |
| Rotor speed (rpm)        | 876.4        | 1243                    |
| Electromagnetic Torque (N.m.) | 3.86     | 3.20                   |
| THD                      | 55.59%       | 60.78%                  |

### Table 5. Comparison of motor parameters for respective converters

7. Simulation Results

![Figure 9. Back emf of motor for both the converters](image1)

![Figure 10. Rotor speed of the motor for both the converters](image2)
Figure 9 shows the back emf waveform for both the converters is trapezoidal in nature. Figure 10 shows the waveform for the rotor speed of the motor, at simulation time equal to 0.1s the speed goes to its nominal value for both the converters. Figure 11 shows that the peak value of electromagnetic torque for the four quadrant converter is around 28.5 N.m. which is greater than the torque of KY converter. Distortion is also relatively less for KY converter than four quadrant converter. Figure 12 and figure 13 shows the total harmonic distortion (THD) graphs for the rotor speed of the BLDC motor by using KY converter and four quadrant converter respectively.

![Figure 11. Electromagnetic Torque of the motor for both the converters](image1.png)

![Figure 12. THD analysis of rotor speed for KY converter](image2.png)
8. Conclusion

It is observed that motor is connected to the four quadrant converter then, the converter gives greater output voltage to the motor, and therefore a greater rotor speed is achieved by the motor, compared to the KY converter. But, other motor parameters are comparatively lower for four quadrant converter and the motor also has greater total harmonic distortion compared to the performance when used with the KY converter. When the KY converter is used with the BLDC motor then it produces greater electromagnetic torque and also has comparatively lower total harmonic distortion. To calculate the output voltages of both the converters, the duty cycle ratio of the PWM generator considered here for both converters is 0.5. Therefore, we can conclude that when the performance of BLDC motor drive is evaluated by using KY converter and four quadrant converter then the KY converter gives better performance.

9. References

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