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A Novel Sensorless control scheme for BLDC motors used in Electric Vehicle

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Abstract. Position and speed control strategies play an important role in electric vehicle domain employing Brush less DC motor (BLDC). Elimination of sensors owing to high complexity also gave rise to many sensorless estimation schemes. Most of the estimation algorithms exploited the motor model and were involved in either position or speed estimation. This paper presents a novel technique for Sensorless control of BLDC used in electric vehicle. In the proposed method, the control signals for the drive system are generated directly from the average terminal voltage of the BLDC motors. The proposed method eliminates the speed sensors required for the control of a BLDC drive, thereby improving the system reliability. The simulation studies of the proposed control technique are performed in Matlab/Simulink environment. Simulation results are compared with the conventional position sensor based control of BLDC drive. Simulation results validate the effectiveness of the proposed control method.

Keywords: sensorless, converter, hall-effect sensor, BLDC, electric vehicle

1 Introduction

In 20th century automakers got a renewed interest in electric cars. Innovations with the brushless DC motor were helping NASA scientists roam the Moon in lunar rovers at that time. The wheels in the moon buggies NASA built each had a BLDC motor in them. Electric cars again piqued interest in, while energy crises in the 1970s and 1980s. The 40% of U.S. consumers expressed interest in owning an electric vehicle, because of the ever-growing cost of gas. It may explain why more than in 2013. With help of the BLDC motor, today's electric cars are:

- High efficient than traditional cars
- Less expensive to drive
- Eco friendly

Most of today's hybrid vehicles use a BLDC motor. Due to the peak point efficiency is higher and rotor cooling is simpler, green car manufacturers often prefer BLDC motors over the alternatives. The motors can even operate at unity power factor, which implies its higher efficiency. The most important components of the BLDC motor drive system of an electric vehicle is the battery which is used as the DC. In addition to supplying energy to the engine, they allow the electrical receivers to function through regenerative braking. So, it is important that the batteries in green cars must be as efficient as possible.

Brush less DC motor (BLDC) requires position sensors to generate control pulses for converter. The rotor position of the BLDC motor is required for starting and the providing proper commutation sequence to turn on the power devices in the inverter bridge which supplies the motor. Fig. 1 shows the inverter topology and equivalent circuit of a BLDC machine. Most commonly used sensor for position sensing is the Hall Effect

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sensor. But they are very sensitive to flux and heat variation if they are used in electric vehicles during harsh driving conditions. Many other sensors for position sensing were available. In the last two decades, many sensorless schemes have been presented in the literature to eliminate the costly and fragile position sensor for BLDC motors with trapezoidal back-EMFs. In the domain of vehicular technology, position sensing occupied considerable research space. Sliding mode control schemes for electric vehicles exhibited better performance than the traditional proportional-integral-differential (PID) control schemes in terms of stability and system performance. The research focus for BLDC motors centred on the commutation sequence, angular position and back EMF estimation. Relevant estimation schemes such as Sliding Mode Observer, Extended Kalman Filter, Model Reference Adaptive System, Adaptive observers and Artificial Neural Networks depended on model based design.

Moreira[9] has implemented a back emf sensing technique based Sensorless control for BLDC drive. This third harmonic back-EMF sensing method provided wider speed range than the terminal voltage-sensing method. [13] and [4] presented Sensorless control based on back EMF integration. The position information is extracted by integrating the back-EMF of the silent phase. This technique has also issues at low speeds because of the error accumulation problem. Rao et. al proposed a scheme for sensorless control of a BLDC motor by direct back EMF detection method[12]. The results confirm the effectiveness of the control scheme over a wide speed range. However, there are issues during low speed operation. Wu et. al[14] proposed a position sensorless control based on coordinate transformation for BLDC motor drives. In this technique, only two line voltages are used to generate the commutation signal for the motor. Halvaei et. al[10] presented a low cost Sensorless scheme for BLDC drive using one-cycle current control strategy. Hysteresis current control has been substituted using a unified controller and Pulse width modulation (PWM) based on one-cycle control strategy. Lad and Chudamani proposed a sensorless scheme based on Commutation instants derived from the Line Voltages and Line Voltage Differences[8]. The requirement of the timer-counter for deciding the commutation instant is eliminated as compared to conventional back-EMF based methods with zero crossing point identification. However, the simulation results are presented only for a particular operating speed and not for wide ranges.

In all the above mentioned techniques, none of the technique work for the complete speed range of the motor. They are not reliable particularly at low operating speed. In practical applications, the minimum speed of the conventional sensorless drive is around 10% of the rated speed. Also, the position error from a phase delay circuits affects the transient response of the sensorless control scheme[1]. These are some of the drawbacks of sensorless techniques which act as hindrance for the use of sensorless BLDC drive in electric vehicle applications. So to improve the system reliability a cost-effective sensor-less commutation method is needed. But in conventional sensor-less control method motor neutral voltage is needed, the extracted signal is very sensitive to the common mode noise. Moreover it needed the complex phase shift circuit for zero crossing detection.

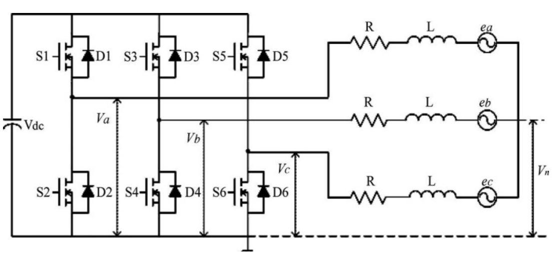

Fig. 1: Inverter topology for BLDC drive

The back-EMF waveform of an ideal BLDC machine with 120° ?at top is shown in Fig. 2.

In order to resolve with the aforementioned problem this simple and efficient method is proposed. In this technique the, control signals are generated directly from the average terminal voltage of the BLDC motors with low cost comparators. The proposed eliminates the need of motor neutral voltage, the phase delay circuit, multistage analog filters, A/D converters when compared with the conventional solutions. It also eliminates the use of a speed sensor, thereby saving additional space for mounting, additional electronics and cost. The paper is organized as follows. Section 2 depicts the mathematical model of the BLDC for the purpose of estimation

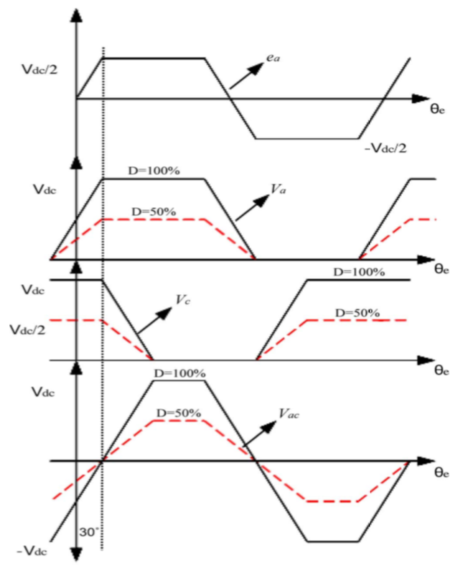

Fig. 2: Back emf, phase voltages and line voltage waveforms

and control. Section 3 discusses the extraction of commutation sequence from the terminal quantities of the motor. Section 4 showcases the offline simulation results followed by analysis and conclusion.

2 Bldc modeling

The BLDC motor can be modeled similar to the three phase synchronous machine. Dynamic characteristics of BLDC motor are different, since the rotor itself mounted with a permanent magnet. Flux linkage from the rotor is dependent upon the permanent magnet. The detail Modeling can be found in several literatures. The voltage equation of a BLDC Motor can be given as [1]

$$V_{abc} = RI_{abc} + Z_p I_{abc} + E_{abc} \tag{1}$$

$$V_a = RI_a + L(di_a)/dt + e_a \tag{2}$$

$$V_b = RI_b + L(di_b)/dt + e_b \tag{3}$$

$$V_c = RI_c + L(di_c)/dt + e_c \tag{4}$$

$$T_e = K_f w_m + j(dw_m)/dt + T_l \tag{5}$$

Where R is the stator resistance assumed as equal for all phases, Z_p is the impedance of the network assumed as equal for all phases, L is the stator inductance per phase assumed as equal for all phases, ia, ib, ic are the stator phase current of the three phases and Va, Vb, Vc are the phase voltages.

3 Commutation point from average line to line voltage

The conventional back EMF sensing technique has several drawbacks including the need for neutral voltage of the motor and need for circuits to produce phase delays. The noise level of the motor increases while sensing the motor neutral voltage. Hence a low pass filter circuit is required to filter the unwanted noise signals. It is also very difficult to implement the sensorless scheme with a single phase delay circuit for a wide speed rage of motor application. The digital phase delay circuit can be a solution. However, with digital hardware, the over cost of the system increases.

In order to overcome the above mentioned problem, the proposed technique extracts the commutation sequence directly from the terminal quantities of the motor. The additional hardware requited are a comparator and a single stage low pass filter. From the polarity of the armature current the terminal voltage per phase can be divided into three[2], i.e, positive current conduction, negative current conduction and zero current conduction.

The average terminal voltage in terms of duty ratio and input voltage is given by [3]

$$V(a) = DV_{dc} \qquad \theta = 30^\circ \sim 150^\circ \tag{6}$$
$$V(a) = (\theta + 30)/60 * DV_dc \qquad \theta = -30^\circ \sim 30^\circ \tag{7}$$
$$V(a) = DV_{dc} - (\theta - 150)/60 * DV_{dc} \qquad \theta = 150^\circ \sim 330^\circ \tag{8}$$
$$V(a) = 0 \qquad \theta = 210^\circ \sim 330^\circ \tag{9}$$
$$\tag{10}$$

When compared with the back EMF waveform, it is observed that the zero crossing point of the average terminal voltage is leading 30 degree electrical.

From this average line to line voltage is given by [2]:

$$V(a) = DV_{dc} \qquad \theta = 90^\circ \sim 150^\circ \tag{11}$$
$$V(a) = DV_{dc} \qquad \theta = 270^\circ \sim 330^\circ \tag{12}$$
$$V(a) = -DV_{dc} + \frac{((\theta + 30))}{120} * 2DV_{dc} \qquad \theta = -30^\circ \sim 90^\circ \tag{13}$$
$$V(a) = DV_{dc} - \frac{((\theta - 150))}{120} * 2DV_{dc} \qquad \theta = 150^\circ \sim 270^\circ \tag{14}$$

While analyzing the zero crossing points of the average line to line voltage, it is occurring at 30 and 210 degrees, which is in phase with the ideal commutation points. It is easy to find that the output of the average phase to phase voltage has an inherent lagging angle of 30 electric degrees compared with the back EMF, namely the zero crossing points of the phase to 120 phase voltage are in phase with the ideal commutation points.

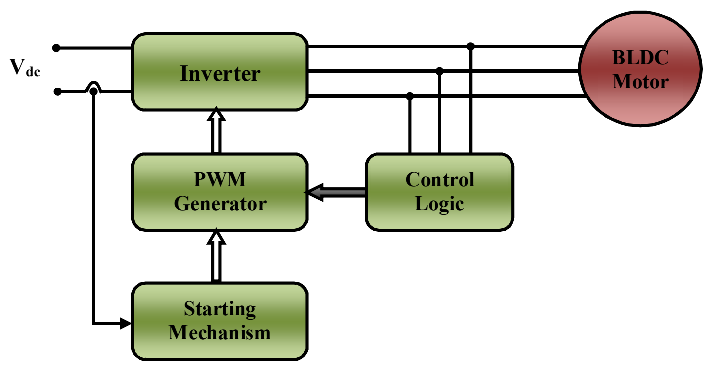

Fig. 3: Block diagram of the proposed sensorless scheme

The control points can be generated directly from the motor terminal voltages without the neutral voltage, according to the properties of the average terminal voltage. The reduction in additional hardware results in reduction of the overall cost of the system.

Fig. 3 shows the block diagram for proposed system. It consists of a starting mechanism, PWM generator, control logic, converter and the BLDC motor. For starting procedure BLDC motor run as a synchronous motor and necessary control signals are driven by PWM generator. Ones motor is running and produces enough back emf we will switched over to BLDC motor with the proposed control logic. PWM generator will generate control signal according to control logic and is fed to the switches.

Fig. 4 shows the flow chart of the control logic. Always line voltages are read and NOT is also computed. The signals are ANDed in such a way that $Va(\overrightarrow{Vb})$, $Vb(\overrightarrow{Vc})$, $Vc(\overrightarrow{Va})$, $Vb(\overrightarrow{Va})$, $Vc(\overrightarrow{Vb})$, $Va(\overrightarrow{Vc})$.

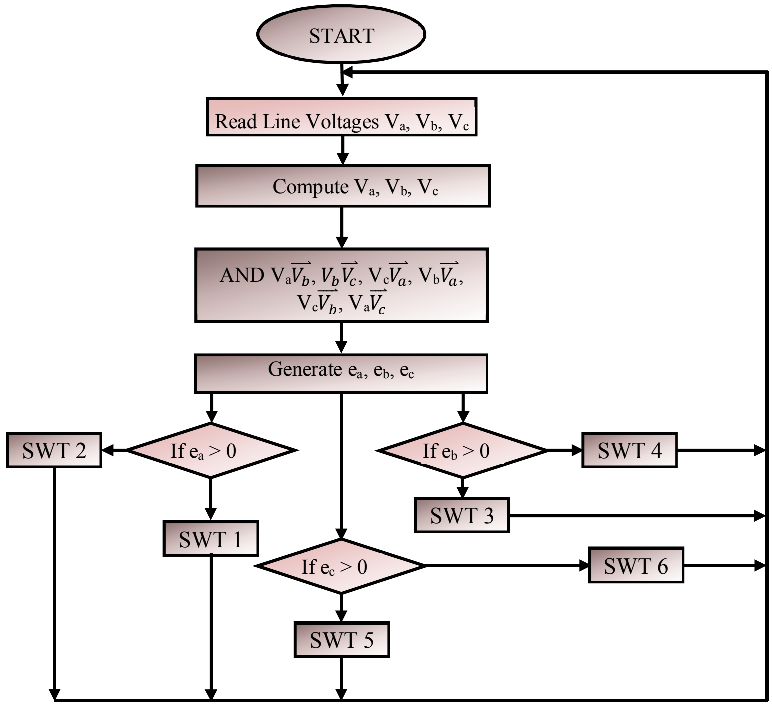

Fig. 4: Flow chart for the control logic

Corresponding emf is generated with the ANDed signal such that,

$$e_a = Va(\overrightarrow{Vb}) + Vb(\overrightarrow{Va}) \tag{15}$$

$$e_b = Vb(\overrightarrow{Vc}) + Vc(\overrightarrow{Vb}) \tag{16}$$

$$e_c = Vc(\overrightarrow{Va}) + Va(\overrightarrow{Vc}) \tag{17}$$

With respect to the emf signal switches are turned on and off. If ea is greater than zero switch1 is triggered otherwise switch2, If not checking whether eb is greater than zero, if it is switch3 is triggered otherwise switch4 is triggered, else checking for ec, if it is switch5 else switch6. This process will be continued. Tables 1 and 2 are the pickup table for above logic. Table 1 implies emf signal generation from line voltages and Table 2 implies generation of triggering pulse from emf signal.

Table 1: Control Logic for Line Voltage to Control emf

ha	hb	Hc	emf_a	emf_b	emf_c
0	0	0	0	0	0
0	0	1	0	-1	1
0	1	0	-1	1	0
0	1	1	-1	0	1
1	0	0	+1	0	-1
1	0	1	1	-1	0
1	1	0	0	1	-1
1	1	1	0	0	0

Table 2: Control Signals from emf signal

emf_a	emf_b	emf_c	SWT1	SWT2	SWT3	SWT4	SWT5	SWT6
0	0	0	0	0	0	0	0	0
0	-1	1	0	0	0	1	1	0
-1	1	0	0	1	1	0	0	0
-1	0	1	0	1	0	0	1	0
+1	0	-1	1	0	0	0	0	1
1	-1	0	1	0	0	1	0	0
0	1	-1	0	0	1	0	0	1
0	0	0	0	0	0	0	0	0

4 Simulation results and discussion

Simulation is done on a 1HP BLDC motor model in MATLAB. The sampling time is 50 μ sec. In order to compare the results of proposed sensorless scheme, BLDC with hall-effect sensor is also done and the results are observed[5–7, 11].

Fig. 5 shows the simulation results for hall-effect sensored BLDC model. Here a load is applied at the instant of 6 sec. Current, back emf, speed and torque characteristics are shown below.

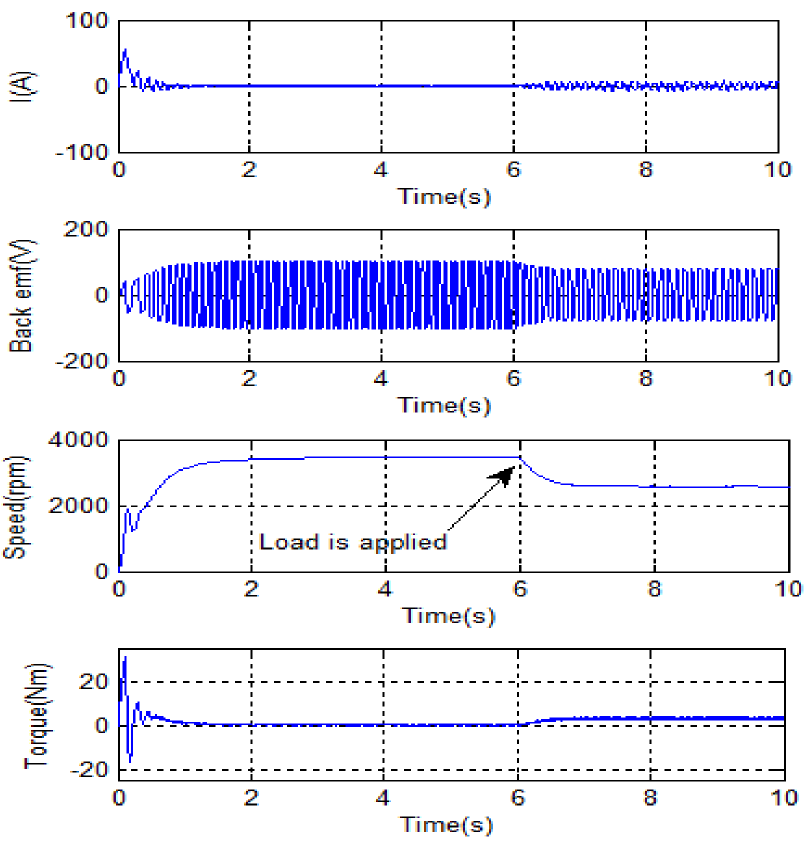

Fig. 5: Simulation results for sensored system

Fig. 6 shows the performance of the proposed sensorless scheme when the motor is started at load as synchronous motor and switched in to BLDC motor at 3.0115 sec. The switching time is selected in such a way that, at the time of switching the motor current is zero. This is done by finding the zero crossing point of the stator current after enough back emf is generated. Switching the motor at zero cross of current greatly reduces the speed oscillation at the time of switching. Fig. 7 shows proposed sensorless performance at loaded condition. A load of 3N is applied at the 6 sec. Current, back emf, speed and torque characteristics of the system in no-load and loaded conditions are also shown. The motor was able to run successfully at no load and loaded condition with the proposed sensorless control scheme.

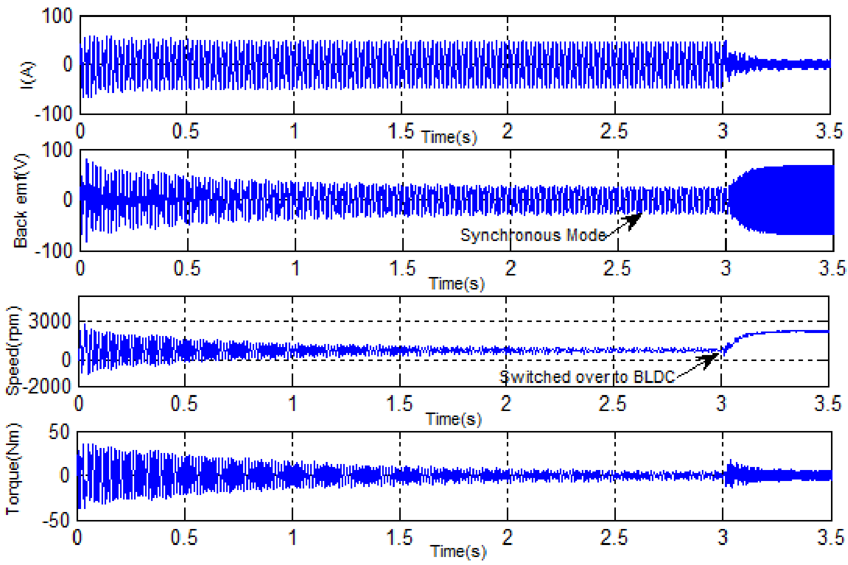

Fig. 6: Simulation for sensorless at no-load condition

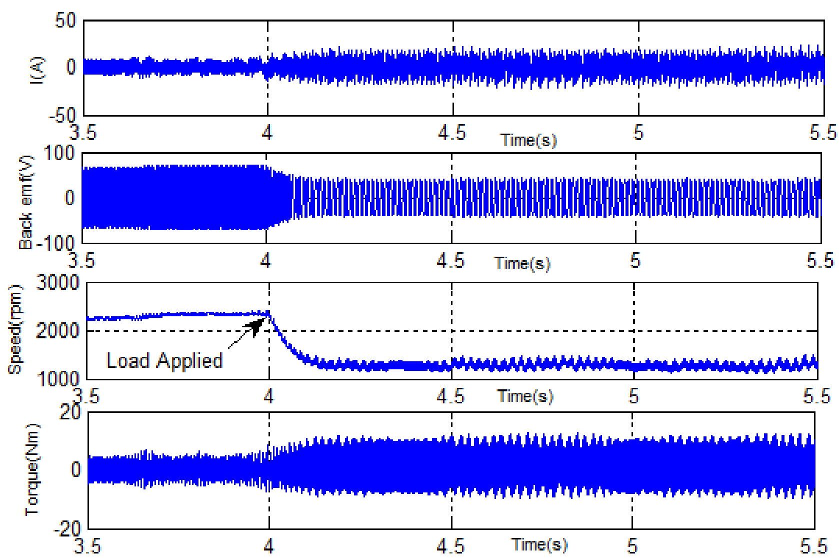

Fig. 7: Simulation results of the proposed sensorless system at loaded condition

5 Conclusion

This paper presented a reliable, compact, and efficient sensorless control scheme for BLDC motor used in electric vehicle. The adopted converter is a simple bidirectional inverter. In contrast to bidirectional converters, additional power switches and inductors are also eliminated in this method. The generated control signals from average line to line voltage do not require complex calculation and obtained by simple comparators and low pass filters. The elimination of speed sensor and the reduction in number of switches reduced the complexity and cost and compared with the conventional method, the proposed new sensorless control technique is more robust in terms of system performance, state estimation and control. Theoretical analysis and simulation results show that the proposed scheme has got satisfactory performance.

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