Brushless DC motor drives used in Electrical Vehicles

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Abstract—This paper describes a simple circuit controller of Brushless Direct Current (BLDC) motor for electric vehicle implementation. This control based on the function relationship between the Hall sensor logics and currents that should be supplied on each phase of the motor. The function then simplified using Karnaugh-Map method and implemented using digital circuit. Pulse Width Modulation (PWM) added to produce six triggers that used to regulate the inverter current. Proportional Integral (PI) control based on Ziegler–Nichols also added to PWM circuit to improve motor speed performance. The controller are successfully applied using Matlab-Simulink and simulation results show that the controller have simpler circuit and have better speed performance than conventional controller.

Keywords—Brushless Direct Current, Electric Vehicle, Digital Circuit, Proportional Integral, Pulse Width Modulation, Karnaugh-Map, Ziegler–Nichols

1. INTRODUCTION

Brushless DC electric motor (BLDC motors, BL motors) also known as electronically commutated motors (ECMs, EC motors) are synchronous motors that are powered by a DC electric source via an integrated inverter/switching power supply, which produces an AC electric signal to drive the motor. In this context, AC, alternating current, does not imply a sinusoidal waveform, but rather a bi-directional current with no restriction on waveform. Additional sensors and electronics control the inverter output amplitude and waveform (and therefore percent of DC bus usage/efficiency) and frequency (i.e., rotor speed). The rotor part of a brushless motor is often a permanent magnet synchronous motor, but can also be a switched reluctance motor, or induction motor. Brushless motors may be described as stepper motors; however, the term “stepper motor” tends to be used for motors that are designed specifically to be operated in a mode where they are frequently stopped with the rotor in a defined angular position. This page describes more general brushless motor principles, though there is overlap. Two key performance parameters of brushless DC motors are the motor constants Kv and Km.

2. LITERATURE REVIEW AND SYSTEM MODEL

The use of Brushless DC (BLDC) motors is continuously increasing. The reason is obvious: BLDC motors have a good weight/size to power ratio and excellent acceleration performance, require little or no maintenance and generate less acoustic and electrical noise than universal (brushed) DC motors.

In a Universal DC motor, brushes control the commutation by physically connecting the coils at the correct moment. In BLDC motors the commutation is controlled by electronics. The electronics can either have position sensor inputs that provide information about when to commutate or use the Back Electromotive Force generated in the coils. Position sensors are most often used in applications where the starting torque varies greatly or where a high initial torque is required. Position sensors are also often used in applications where the motor is used for positioning. Sensor-less BLDC control is often used when the initial torque does not vary much and where position control is not in focus, e.g. in fans. This application note describes the control of a BLDC motor with Hall Effect position sensors (referred to simply as Hall sensors). The implementation includes both direction and open loop speed control.

Brushless DC motors, rather surprisingly, is a kind of permanent magnet synchronous motor. Permanent magnet synchronous motors are classified on the basis of the wave shape of their induce emf, i.e., sinusoidal and trapezoidal. The sinusoidal type is known as permanent magnet synchronous motor; the trapezoidal type goes under the name of PM Brushless dc (BLDC) machine. Permanent magnet (PM) DC brushed and brushless motors incorporate a combination of PM and electromagnetic fields to produce torque (or force) resulting in motion. This is done in the DC motor by a PM stator and a wound armature or rotor. Current in the DC motor is automatically switched to different windings by means of a commutator and brushes to create continuous motion. In a brushless motor, the rotor incorporates the magnets, and the stator contains the windings. As the name suggests brushes are absent and hence in this case, commutation is implemented electronically with a drive amplifier that uses semiconductor switches to change current in the
windings based on rotor position feedback. In this respect, the BLDC motor is equivalent to a reversed DC commutator motor, in which the magnet rotates while the conductors remain stationary. Therefore, BLDC motors often incorporate either internal or external position sensors to sense the actual rotor.

BLDC motors have many advantages over brushed DC motors and induction motors. A few of these are:

- Better speed versus torque characteristics
- Faster dynamic response
- High efficiency
- Long operating life
- Noiseless operation
- Higher speed ranges

In addition, the ratio of torque delivered to the size of the motor is higher, making it useful in applications where space and weight are critical factors.

BLDC motors come in single-phase, 2-phase and 3-phase configurations. Corresponding to its type, the stator has the same number of windings. Out of these, 3-phase motors are the most popular and widely used. Here we focus on 3-phase motors.

**Stator**

The stator of a BLDC motor consists of stacked steel laminations with windings placed in the slots that are axially cut along the inner periphery (as shown in Figure). Traditionally, the stator resembles that of an induction motor; however, the windings are distributed in a different manner. Most BLDC motors have three stator windings connected in star fashion. Each of these windings are constructed with numerous interconnected coils, with one or more coils are placed in the stator slots. Each of these windings are distributed over the stator periphery to form an even numbers of poles. As their names indicate, the trapezoidal motor gives a back trapezoidal EMF as shown in Figure 2.1.

In addition to the back EMF, the phase current also has trapezoidal and sinusoidal variations in the respective types of motor. This makes the torque output by a sinusoidal motor smoother than that of a trapezoidal motor. However, this comes with an extra cost, as the sinusoidal motors take extra winding interconnections because of the coils distribution on the stator periphery, thereby increasing the copper intake by the stator windings. Depending upon the power supply capability, the motor with the correct voltage rating of the stator can be chosen. Forty-eight volts, or less voltage rated motors are used in automotive, robotics, small arm movements and so on. Motors with 100 volts, or higher ratings, are used in appliances, automation and in industrial applications.

**Rotor**

The rotor is made of permanent magnet and can vary from two to eight pole pairs with alternate North (N) and South (S) poles. Based on the required magnetic field density in the rotor, the proper magnetic material is chosen to make the rotor. Ferrite magnets were traditionally used to make the permanent magnet pole pieces. For new design rare earth alloy magnets are almost universal. The ferrite magnets are less expensive but they have the disadvantage of low flux density for a given volume. In contrast, the alloy material has high magnetic density per volume and enables using a smaller rotor and stator for the same torque. Accordingly, these alloy magnets improve the size-to-weight ratio and give higher torque for the same size motor using ferrite magnets. Neodymium (Nd), Samarium Cobalt (SmCo) and the alloy of Neodymium, Ferrite and Boron (NdFeB) are some examples of rare earth alloy magnets. Figure 35.3 shows cross sections of different arrangements of magnets in a rotor. S S N N S S S N N N N N N N N.

**Hall Sensors**

Unlike a brushed DC motor, the commutation of a BLDC motor is controlled electronically. To rotate the BLDC motor, the stator windings should be energized in a sequence. It is important to know the rotor position in order to understand which winding will be energized following the energizing sequence. Rotor position is sensed using Hall effect sensors embedded into the stator. Most BLDC motors have three Hall sensors embedded into the stator on the non-driving end of the motor. Whenever the rotor magnetic poles pass near the Hall sensors, they give a high or low signal, indicating the N or S pole is passing near the sensors. Based on the combination of these three Hall sensor signals, the exact sequence of commutation can be determined.
Principle of operation and dynamic model of a BLDC Motor

The coupled circuit equations of the stator windings in terms of motor electrical constants are

The machine is represented in the figure 35.4 by a three-phase equivalent circuit, where each phase consists of stator resistance $R_s$, equivalent self inductance $L_s$, and a trapezoidal CEMF wave in series. Figure 5 shows the phase diagram of $V_{an}$, $V_{bn}$, $V_{cn}$. The spatial orientations of the stator MMF vector, under different switching phases of the inverter are shown below in figure 6. Therefore under a cyclic switching scheme one has a rotating stator MMF vector. If the switching can be synchronized with the rotor position, then an approximately fixed angle between the stator flux and the rotor flux can be maintained, while both rotate around the rotor axis. This is similar to the case of the DC motor, where the commutator brush arrangement maintains a fixed spatial direction of the armature flux aligned with the field flux, which is also fixed in space by construction. This is precisely what the inverter switching sequence shown in Fig.5 achieves. The switching instants of the individual transistor switches, $Q_1–Q_6$ with respect to the trapezoidal emf wave is shown in the figure. Note that the emf wave is synchronized with the rotor. So switching the stator phases synchronously with the emf wave make the stator and rotor mmfs rotate in synchronism. Thus, the inverter acts like an electronic commutator that receives switching logical pulses from the rotor position sensor. This is why a BLDC drive is also commonly known as an electronically commutated motor (ECM).

3. Speed Torque characteristics

3.1. Speed Torque characteristics of Brushless DC motor

Since 1980’s new prototype concept of permanent magnet brushless motors has been built. The Permanent magnet brushless motors are categorized into two kinds depending upon the back EMF waveform, Brushless AC (BLAC) and Brushless DC (BLDC) motors [2]. BLDC motors have trapezoidal back EMF and quasi-rectangular current waveform. BLDC motors are quickly becoming famous in industries like Appliances, HVAC industry, medical, electric traction, automotive, aircrafts, military equipment, hard disk drive, industrial automation equipment and instrumentation because of their high efficiency, high power factor, silent operation, compact, reliability and low maintenance. In the event of replacing the function of alternators and brushes, the BLDC motor requires an inverter and a position sensor that exposes rotor position for appropriate alternation of current. The rotation of the BLDC motor is built on the feedback of rotor position that is gained from the hall sensors. BLDC motor generally utilizes three hall sensors for deciding the commutation sequence.

Fig 3.1.: Proteus simulated speed torque characteristics of BLDC motor

In BLDC motor the power losses are in the stator where heat can be easily shifted through the frame or cooling systems are utilized in massive machines.

Fig 3.2.Speed response during stalling of BLDC motor

BLDC motors have many benefits over DC motors and induction motors. Some of the benefits are better speed versus torque characteristics, high dynamic response, high efficiency, long operating life, noiseless operation, higher speed ranges. Till now, over 80% of the controllers are PI (Proportional and integral) controllers because they are facile and easy to comprehend. The speed controllers are the conventional PI controllers and current controllers are the P controllers to achieve high performance drive. Fuzzy logic can be considered as a mathematical theory combining multi-valued logic, probability theory, and artificial intelligence to simulate the
human approach in the solution of various problems by using an approximate reasoning to relate different data sets and to make decisions. It has been reported that fuzzy controllers are more robust to plant parameter changes than classical PI or controllers and have better noise rejection capabilities.

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Here, hardware implementation of the BLDC motor is done by using ARM controller. We propose the Speed Torque characteristics of the BLDC motor drive rotating not only in forward but also in reverse direction. We used dynamometer with hysteresis brake to load the motor. The torque and speed of the BLDC motor is measured in dynamometer and basing on the readings Speed Torque characteristics ware drawn. The paper is organized as follows: Section II explains about construction and operating principle of BLDC motor, Section III elaborates the modelling of BLDC motor, Section IV presents the hardware implementation of BLDC motor. The hardware results are presented in detail in Section V and Section VI concludes the concept.

3.2 Modelling of BLDC Motor

The flux distribution in BLDC motor is trapezoidal and hence the d–q rotor reference frames model is not suitable. It is shrewd to derive a model of the PMBLDC motor in phase variables when if is given the non-sinusoidal flux distribution. The derivation of this model is depends on the postulations that the induced currents in the rotor due to stator harmonic fields, iron and stray losses are neglected. The motor is taken to have three phases even though for any number of phases the derivation procedure is true to life. Modelling of the BLDC motor is done applying classical modelling equations and therefore the motor model is highly adaptable. These equations are illustrated depending upon the dynamic equivalent circuit of BLDC motor. The assumptions made for modelling and simulation purpose are the common star connection of stator windings, three phase balanced system and uniform air gap. The mutual inductance between the stator phase windings are uncountable when compared to the self-inductance and so neglected in designing the model.
However, in the brushless DC motor, polarity reversal is performed by power transistors switching in synchronization with the rotor position. Therefore, BLDC motors often incorporate either internal or external position sensors to sense the actual rotor position, or the position can be detected without sensors.

Digital Control of a BLDC Motor

The BLDC motor is driven by rectangular voltage strokes coupled with the given rotor position; The generated stator flux interacts with the rotor flux, which is generated by a rotor magnet, defines the torque and thus the speed of the motor. The voltage strokes must be properly applied to the two phases of the 3-phase winding system so that the angle between the stator flux and the rotor flux is kept close to 90° for the maximum generated torque. This means the motor requires electronic control for proper operation. A standard 3-phase power stage is used for the common 3-phase BLDC motor, as illustrated in the power stage utilizes six power transistors with switching in either the independent mode or complementary mode. In both mode, the 3-phase power stage energizes two motor phases concurrently. The third phase is unpowered; see Figure. Thus, six possible voltage vectors are applied to the BLDC motor using a PWM technique; see Figure and Figure. There are two basic types of power transistor switching, independent switching and complementary switching, which are discussed in the following sections.

Independent Switching of Power Transistors

During independent switching, only two transistors are switched on when current is conducted from the power supply to the phase of the BLDC motor. In one phase, the top transistor is switched on; in the second phase, the bottom transistor is switched on and the third phase is not powered. During freewheeling, all transistors are switched off see Figure.

Complementary Switching of Power Transistors

During complementary switching, two transistors are switched on when the phase of the BLDC motor is connected to the power supply. One primary difference occurs during freewheeling. During independent switching, all transistors are switched off. The current continues to flow in the same direction through freewheeling diodes until it falls to zero. In complementary switching, the complementary transistors are switched on during freewheeling, so the current may be able to flow in the opposite direction. Figure depicts complementary switching.

Commutation

Commutation provides the creation of a rotation field. As previously explained, it is necessary to keep the angle between stator and rotor flux close to 90° for a BLDC motor to operate properly. Six-step control creates a total of six possible stator flux vectors. The stator flux vector must be changed at a certain rotor position. The rotor position is usually sensed by Hall sensors. The Hall sensors generate three signals that also comprise six states. Each of Hall sensors’ states corresponds to a certain stator flux vector. All Hall sensor states with corresponding stator flux vectors are illustrated in Figure. The same information is detailed and Table. The following two figures depict the commutation process. The actual rotor position in Figure corresponds to the Hall sensors’ state ABC; see Figure. The actual voltage pattern can be derived from Table. Phase A is connected to the positive DC Bus voltage by the transistor Q1; Phase C is connected to the ground by transistor Q6; Phase B is unpowered. As soon as the rotor reaches a certain position (see Figure), the Hall sensors’ state changes its value from ABC to ABC. A new voltage pattern is selected from Reference Table and applied to the BLDC motor. As shown, when using a six-step control technique, it’s impossible to keep the angle between the rotor flux and the stator flux precisely at 90°. The actual angle varies from 60° to 120°. Commutation is repeated every 60° electrical. The commutation event is critical for its angular (time) accuracy. Any deviation causes torque ripples, leading to a variation in speed.

Speed Control

Commutation ensures proper rotor rotation of the BLDC motor, while the motor speed depends only on the amplitude of the applied voltage. The amplitude of the applied voltage is adjusted by using the PWM technique. The required speed is controlled by a speed controller. The speed controller is implemented as a conventional PI controller. The difference between the actual and required speed is input to the PI controller and, based on this difference, the PI controller controls the duty cycle of PWM pulses, which corresponds to the voltage amplitude required to keep the required speed.

Torque Control

For applications requiring the motor to operate with a specified torque regardless of speed (e.g., in-line tensioning), a current controller can be used, since torque is directly proportional to current. In this mode, the speed will be held at the value set by the speed reference signal for all loads up to the point where the full armature current is needed. If the load torque increases further, the speed will drop because the current-loop will not allow more...
armature current to flow. Conversely, if the load attempted to force the speed above the set value, the motor current will be reversed automatically, so that the motor acts as a brake and regenerates power to the mains. The current controller is implemented as a conventional Proportional-Integral (PI) controller. The output from the speed controller will be input into the current controller, along with measured DCBus current. The output of the current controller will control the duty cycle of the PWM pulses. The combination of both speed and torque controllers is shown in Figure.

Targeting 56800/E Digital Signal Controllers
Freescale’s 56800/E Controllers are well suited for BLDC motor control applications. They combine on a single chip the DSP’s calculation capability with the MCU’s controller features. These devices offer many peripherals dedicated to motor control, such as Pulse Width Modulation (PWM) modules, Analog-to-Digital Converter (ADC), Timers, communication peripherals (SCI, SPI, etc.), on-board Flash and RAM. Implementation of the BLDC application with Hall Sensors will vary slightly from one 56800/E device to another, and it will also depend on type of motor hardware used. See application-specific targeting manuals for more information.

4. CONCLUSIONS

The BLDC motor drive model has been developed both in simulation and hardware realizations for low-power applications. This investigates the motor drive performance for 120-degree commutation switching technique by On-Off control algorithm for variable torque - constant speed applications. The controlling method is a sensed type in which low cost PIC18F4331 microcontroller acts as the main controlling unit. The introduction of Proteus VSM shows its capability and usefulness in designing virtual model, selection of appropriate ICs and other equipments and the troubleshooting before hardware circuit construction, thus requiring a shorter product development time. Experimental verification has also been carried out. Besides, the cost effectiveness of this low cost controller must possess good commercial appeal for low power application.

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