A REVIEW ON CONTROL TECHNIQUES FOR BRUSHLESS DC (BLDC) MOTORS

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Abstract — The development in engineering material technology and tremendous improvement in solid state devices and circuits have resulted in the emerge of new types of electric motors like stepper motors, switched reluctance motors and permanent magnet BLDC motors. Brushless DC (BLDC) Motors have increasing popularity and are the latest choice for motor drive applications due to their reliability, higher values of efficiency, compact size, better dynamic response, silent operation and very low maintenance requirements. These motors are more advantageous over other motors like brushed DC motors and induction motors because of their superior speed-torque characteristics, higher speed and absence of arcing. The BLDC motor also has higher delivered torque to size ratio. The above advantages make it appropriate in applications where space and weight are major factors of consideration. These motors can be controlled in either sensor or sensor-less mode, but to reduce the overall cost and size of motor assembly, sensor-less control techniques are generally employed. This paper gives a brief review on the various control techniques employed for BLDC motors.

Keywords : Brushless DC (BLDC) motor, Hall-effect sensors, Pulse Width Modulation (PWM), Back EMF, Neural Network, Fuzzy Logic.

1. INTRODUCTION

Motors, in general, are machines that convert electrical energy into mechanical energy. Most electric motors operate through the interaction between the motor's magnetic field and winding currents to generate force in the form of rotation. Electric motors can be powered by direct current (DC) sources, such as from batteries, rectifiers, or by alternating current (AC) sources. Electric motors may be classified by considerations such as power source type, internal construction, application and type of motion output. In addition to AC versus DC types, motors may be brushed or brushless, may be of various phase (single-phase, two-phase, or three-phase), and may be either air-cooled or liquid-cooled [1]. Each motor has its own characteristics and specifications which defines the application of that motor. Electrical motor and their drives have become crucial parts of any industrial process. They are needed in many applications such as automotive and textile industry. Because of their effect on product quality, the observation and control of the motors and drives are very necessary.

BLDC Motor is a rotating electric motor consisting of armature winding in the stator and permanent magnets in the rotor. They have three phase armature windings that are wound in star or delta fashion that need a three phase inverter bridge for electric commutation. Majority of BLDC motors are implemented with star connections as the star connection delivers a higher torque. In the delta connection, circulating current occurs in the windings due to the Third Harmonic, causing undesirable losses and reduces the efficiency [2]. The BLDC motor is a kind of three phase synchronous motor that has permanent magnets on its rotor, instead of commutator and brushes. Commutation is achieved with the help of electronic switches that supply electric current to the motor armature windings in synchronization with rotor position. Electronic commutator arrangement located in the stator comprises of power semiconductor devices that act as switching devices. It requires less maintenance as it needs no sliding contact and hence no sparking. The voltage available across the armature tappings can be controlled easily by employing PWM techniques. Reliability depends on the proper design of the devices and protective circuits. Performance can be improved by suitably operating the power devices [3].

Earlier squirrel cage induction motors were popularly used for most of the applications due to their rugged construction. But they exhibit poor power factor and low efficiency when compared to synchronous motors. Meanwhile, the synchronous and DC motors have disadvantages like wear and tear, noise problems and electromagnetic interference due to usage of commutator and brush assembly. This paved way for the development of permanent magnet brushless DC motor or commutatorless synchronous motor [4].

Replacing electromagnetic excitation with permanent magnets in electrical machines has resulted in many positive outcomes such as no excitation losses, elimination of field copper loss, higher power density, improved efficiency, simplified and robust construction of the rotor, fast dynamic performance, lower rotor inertia and high torque per unit volume. The PMBLDC motor is gaining popularity each day due to the presence of high energy density and low cost rare earth permanent magnet materials such as Alnico, Samarium Cobalt, Barium and Strontium Ferrites and Neodymium Iron Boron that improve the performance of PMBLDCM, reducing the size and losses [5]. In permanent magnets, high retentivity and high coercivity are the most desirable features in order to resist demagnetization. Alnico has high service temperature, good thermal stability and high flux density but has low coercive force which may lead to sooner demagnetization. Barium and Strontium Ferrites are easy to produce and is suited for moderately high service temperature. The cobalt Samarium magnet is made of Iron, Nickel, Cobalt and rare earth Samarium. It has high remanence, high energy density and linear demagnetization characteristics. But the material is very expensive because of an inadequate supply of Samarium. The Neodymium Iron Boron magnet has the highest energy density, highest remanence and very good coercivity. But it is sensitive to temperature and care should be taken for working temperatures above 100ºC. It is found that the magnetic performance of Neodymium Iron Boron alloys is about 30% better compared to Cobalt Samarium magnets. Based on mounting of permanent magnets, BLDC motors can be divided into two categories, Surface Mount Permanent Magnet (SMPM) motor (permanent magnets are surface mounted on the rotor) and Inside Permanent Magnet (IPM) motor (permanent magnets are installed inside the rotor) [6].

Permanent magnet brushless DC motors are a good choice for medium sized industrial drives and position control because of their high torque/weight ratio, excellent dynamic capability and reduced losses. These motors are predominantly being used in various applications like aerospace equipments, domestic appliances, toys, power tools, vision and sound equipments, automobiles and healthcare equipments ranging from microwatt to megawatts. Emerging advanced motor control algorithms and ultra-fast microprocessors have made BLDC motors more appropriate for position control in machine tools, robotics and high precision servos, also in speed and torque control of various industrial drives and process control applications [7].

2. CONSTRUCTIONAL FEATURES OF BLDC MOTOR

Brushless DC Motors also known as electronically commutated motors are synchronous motors powered by DC electricity via an inverter or switching power supply which produce an AC electric current to drive each phase of the motor via a closed loop controller. The controller provides pulses of electric current to the motor armature windings that control speed and torque of the motor. The brushless DC motor is driven by an electronic drive which switches the supply voltage between the stator windings as the rotor turns. The rotor position is monitored by the transducer (optical or magnetic) which supplies information to the electronic controller and based on this position, the stator winding to be energized is determined. This electronic drive consists of transistors (2 for each phase) [8].

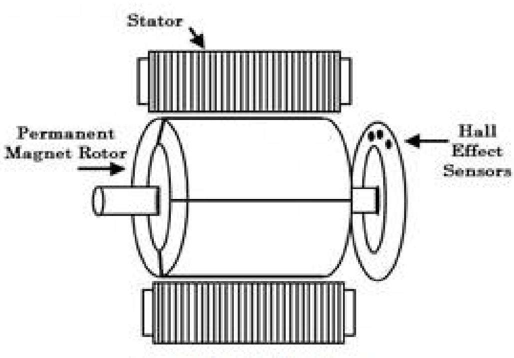

Figure1: BLDC Motor

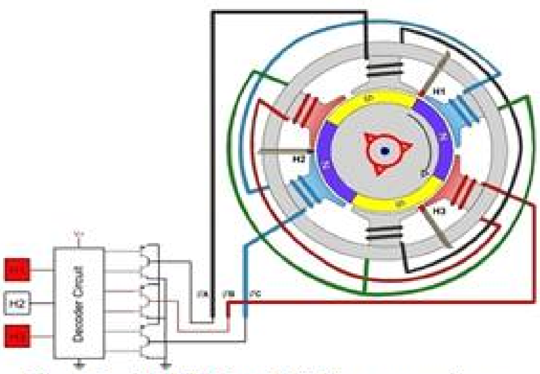

Figure 2: BLDC Motor Winding connections

The brushless permanent magnet DC motors can be constructed in several different physical configurations. The main two types are conventional (in runner) configuration and out runner configuration. In the conventional in runner configuration, the permanent magnets are mounted on the rotor. The stator armature windings surround the core. In the out runner configuration, the radial relationship between the coils and magnets is reversed, i.e. the stator coils form the center (core) of the motor, while the permanent magnets spin on an overhanging rotor, which surrounds the core [9]. The stator of the BLDC motor is made of silicon steel stampings with slots in its interior surface. These slots accommodate either a closed or opened distributed armature winding. Usually it is a closed one. This winding is to be wound for a specified (even) number of poles and the winding is suitably connected to a DC supply through a power electronic switching circuitry (electronic commutator). The rotor is made of forged steel. The rotor accommodates the permanent magnet. The number of poles of the rotor is same as that of the stator. The rotor shaft carries a rotor position sensor. This position sensor provides information about the position of the shaft at any instant to the controller which sends suitable signals to the electronic commutator. For a normal electronic commutator, usually six switching devices are employed hence the winding should have three tappings [10]. The BLDC motor with windings in delta configuration gives low torque at low *rpm*, but can give higher ranges of *rpm*. Star (wye) configuration gives high torque at low *rpm*, but can't be operated in higher *rpm* ranges. Although the efficiency is greatly affected by the motor's construction, the star connection is normally more efficient. Delta connected windings can allow high frequency parasitic electrical currents to circulate entirely within the motor. A star connected winding does not contain a closed loop in which parasitic currents can flow, preventing such losses [11]. Hence, like other machines the BLPMDC motors have stator and rotor. Here the stator carries the armature and rotor the permanent magnet. So, the permanent magnets rotate and the armature remains static. Figure.1 and Figure.2 show the constructional details and winding connections of BLDC motor respectively.

3. PRINCIPLE OF OPERATION OF PMBLDC MOTOR

The brushless permanent magnet DC motor is a synchronous electric motor which is powered by DC supply and it has an electronically controlled commutation system instead of a mechanical commutation system based on brushes. In these motors, the current and torque, voltage and *rpm* are linearly related. When DC supply is given to the motor, the armature winding draws a current. The current distribution within the stator armature windings depends upon the rotor position and the devices turned ON. This current sets up an *mmf* which is perpendicular to the main *mmf* set up by the permanent magnet field. According to Fleming's left hand rule, a force is experienced by the armature conductors. As it is in the stator, a reactive force develops a torque in the rotor. If this developed torque is more than the load torque and frictional torque, the motor starts rotating. It's a self starting motor. As the motor picks up speed, there exists a relative velocity between the stationary armature conductors and the rotating rotor. Therefore, according to Faraday's law of electromagnetic induction, an emf is dynamically induced in the armature conductors. As per Lenz's law, this emf opposes the cause (armature current drawn from the mains). As the supply voltage is maintained constant, the current drawn is reduced. Thus the developed torque reduces. When the developed torque is exactly equal to the opposing load torque, the rotor attains a steady state speed. When the load torque is increased, the speed tends to fall. Therefore it reduces the back emf induced in the armature. Then the current drawn from the mains increases which increases the torque. The motor attains a new equilibrium condition when the developed torque is equal to the new load torque [12].

The electronic switching circuit or the drive switches the supply current to the stator so as to maintain a constant angle 0 to 90 degrees between the interacting fields. Hall sensors are mostly mounted on the stator or on the rotor. When the rotor passes through the hall sensor, based on the North or South Pole, it generates a high or low signal [13]. BLDC motors have fixed permanent magnets, which rotate and a fixed armature, eliminating the problems of connecting current to the moving armature. An electronic controller replaces the brush/commutator assembly of the brushed DC motor, which continually switches the phase to the windings to keep the motor turning. The controller performs comparative timed power distribution by using a solid-state circuit instead of the brush/commutator system.

4. BRUSHLESS DC MOTOR CONTROL

Speed control of brushless DC motor is possible in sensor and sensor-less mode. In sensor based technique, Low cost sensors such as hall-effect sensors are being used. Also accelerometers have been used to detect motor position and measure speed. To minimize the total cost of actuating devices, sensor-less control techniques are generally preferred.

The BLDC motor needs information on rotor position for proper commutation of electric current to its stator armature winding, since the commutation sequence is energized only after knowing the rotor position. In the control of brushless DC motors, rotor position detection, PWM generation and three phase inverter play a major role. In these motors, out of the three phases only two phases are energized at a time and the third phase is not energized. Each phase is energized till 120˚ electrical. Speed of the brushless DC motor is directly proportional to the applied electrical voltage. The PWM logic specifies the time intervals, during which the switches should be ON and OFF to average the dc bus voltage applied, thereby controlling the speed [14]. Figure.3 shows the three phase inverter circuit.

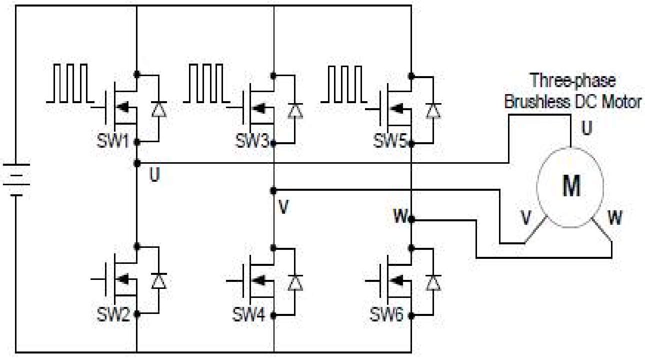

Figure 3: Three-phase inverter circuit powering BLDC motor

The control of permanent magnet brushless DC motors can be achieved by various control techniques using conventional six pulse inverters that are classified into two major categories as Voltage Source Inverter (VSI) and Current Source Inverter (CSI). The controllers are further divided into various types on the basis of solid state switches and control strategies used. The drive electronics switch ON the appropriate windings exactly at the right moment.

The three phase MOSFET bridge acts as an inverter converting the input DC from the battery into AC. This output is controlled by changing the firing angle of the MOSFETs. They consist of 6 MOSFETs that convert the input DC into three phase AC that is to be provided to the BLDC motor [15]. They are well suitable for this operation since they can act as both an inverter and a rectifier. During motoring operation they act as an inverter providing three phase AC supply to the motor. This keeps the motor in running condition. In this operation the firing angle provided to the MOSFETs are well below 90°. This allows them to work as inverter providing the required output. During regenerative braking or braking period, the MOSFET bridge acts as a rectifier. It converts the AC supply given back to the source by the motor into DC supply. This is then used to charge the battery. In this operation the firing angle of the MOSFETs are provided with values higher than 90°. This allows the AC supply to flow through the diodes across the MOSFETs [16].

The purpose of a BLDC motor controller is to provide speed and/or torque control. Usually a controller will provide one of the two, either torque or speed control. Speed control is achieved by monitoring motor speed and adjusting the applied phase voltage to maintain the desired speed [17]. Torque control is achieved by monitoring motor current. The motor current can be controlled to hold a constant value thus providing constant torque using relatively simple techniques [18]. It is possible to incorporate speed and torque control. Speed may be controlled but a hard current limit will also be enforced to stop the motor drawing more than its rated current. Alternatively, current may be controlled with speed limiting to prevent the motor from running faster than its rated speed [19]. Some of the controllers used are Microprocessor, Microcontroller, DSP based controller, FPGA based controller and Neuro Fuzzy controller. These controllers are preferred depending on the application and requirements.

4.1 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 using PWM technique. The required speed is controlled by a speed controller such as a 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 desired speed [20].

4.2 Torque Control

For applications requiring the motor to operate with a specified torque regardless of speed, a current controller can be used, since torque is directly proportional to current. In this, 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 attempts to force the speed above the set value, the motor current will be reversed automatically and the motor enters braking mode, regenerating power to the supply mains. Current controller is implemented as a PI controller. The output from the speed controller will be the input to the current controller, along with the measured DC bus current. The output of the current controller will control the duty cycle of the PWM pulses [21].

To obtain effective torque control, a combination of unipolar and bipolar drives has been tried, which uses the advantage of high starting torque of bipolar drive and greater operating speed of unipolar drive. Also DSP/FPGA based controllers are being used to drive the brushless DC motors with bipolar or unipolar drive and to switch from one and the other at any speed [22].

5. CONTROL OF BLDC MOTORS USING SENSORS

The brushless DC motor needs a rotor position sensor that converts the information about the rotor shaft position into a suitable electric signal. This signal is utilized to turn ON and OFF the various semiconductor devices of the electronic switching circuitry or electronic commutator of BLPM motor [23]. The sensors that are used for detecting rotor position are mostly Hall-Effect position sensors, optical position sensors and Electromagnetic Variable Reluctance (VR) sensors. These are called explicit position sensors [24]. Among these, Hall-Effect sensors are commonly used. They are based on Hall-Effect theory. It states that, if a current carrying conductor is placed in a magnetic field, the field exerts a transverse force on the moving charge carriers which tends to push them to one side of the conductor. The build-up of charge at the sides of the conductors will balance the magnetic influence, producing a measurable voltage between the two sides of the conductor. The Hall sensors require a power supply ranging from 4 V to 24 V. The required current ranges from 5 mA to 15 mA [25].

To rotate the BLDC motor, stator armature windings are energized in sequence. It’s important to know the rotor position to understand which winding has to be energized following the energizing sequence. Rotor position is sensed by Hall-Effect sensors that are embedded into the stator.

Hall-Effect sensor is a device that’s used to measure the magnitude of magnetic field. Its output voltage is directly proportional to the magnetic field strength through it. Hall-Effect sensors are generally used for the purpose of positioning, speed detection, proximity sensing and current sensing applications. They are used in brushless DC motors to detect the position of the permanent magnet. The voltage from the sensor will peak twice for each revolution [26]. A Hall probe contains an indium compound semiconductor crystal such as indium antimonide, mounted on an aluminium backing plate, and encapsulated in the probe head. When the Hall probe is held so that the magnetic field lines are passing at right angles through the sensor of the probe, the meter gives a reading of the value of magnetic flux density. A current is passed through the crystal which, when placed in a magnetic field has a "Hall effect" voltage developed across it. The Hall Effect is seen when a conductor is passed through a uniform magnetic field [27]. In a Hall Effect sensor, a thin strip of metal has a current applied along it. In the presence of a magnetic field, the electrons in the metal strip are deflected towards one edge, producing a voltage gradient across the short side of the strip. When a beam of charged particles passes through a magnetic field, forces act on the particles and the beam is deflected from a straight path. The flow of electrons through a conductor forms a beam of charged carriers. When a conductor is placed in a magnetic field perpendicular to the direction of the electrons, they will be deflected from a straight path. As a consequence, one plane of the conductor will become negatively charged and the opposite side will become positively charged. The voltage between these planes is called the Hall voltage [28]. When the force on the charged particles from the electric field balances the force produced by magnetic field, the separation of them will stop. If the current is not changing, then the Hall voltage is a measure of the magnetic flux density. Basically, there are two kinds of Hall effect sensors. One is linear which means the output of voltage linearly depends on magnetic flux density; the other is called threshold which means there will be a sharp decrease of output voltage at each magnetic flux density [29].

Permanent magnet is fixed at the end of the rotating shaft and the magnetic sensor is placed below. The magnet creates a magnetic field parallel to the sensor surface. This surface corresponds to the sensitive directions of the magnetic sensor. Three-phase brushless DC motors require three signals with a phase shift of 120° electrical for control. Hence for better performance three Hall sensors are used and are placed 120˚ apart on a PCB which is fixed to the enclosure cap on the non-driving end [30]. Whenever North Pole of a magnetic rotor Hall sensor passes near, it produces HIGH Level ('1') of output signal. Rotor position is determined by analyzing the outputs of all three hall sensors. Based on output from all three Hall sensors, the voltages to the three phases of the motor are switched. The relationship between electrical revolution and mechanical revolution depends on pole-pair. As the number of Pole-Pair increases with the motor, more electrical revolutions occur and Hall sensor pattern changes will be faster so commutation change will also be faster [31].

Exciting the appropriate phase coil based on Hall sensor inputs is known as commutation logic. Whenever a new Hall signal change is detected, new drive switching pattern is applied. The commutation logic specifies the coils that need to be energized based on Hall inputs. To obtain Drive Pattern for clock-wise direction and for anti-clock-wise direction, Hall sensor inputs are interchanged [32]. Figure.4 and Table 1 show the power circuit diagram and the commutation logic for clockwise rotation respectively.

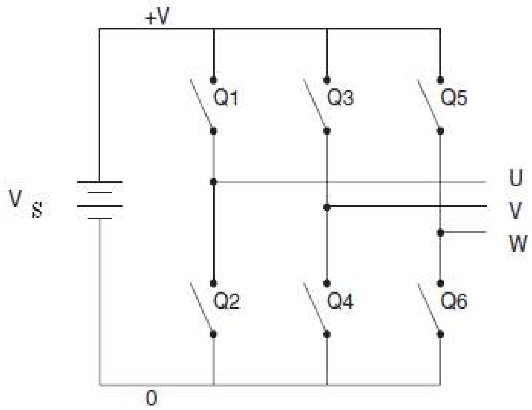

Figure 4: Power Circuit Diagram

Table 1: Commutation Logic for clockwise rotation

HALL SENSOR VALUE (H3 H2 H1)	PHASE	SWITCHES
101	U-V	Q1:Q4
001	U-W	Q1:Q6
011	V-W	Q3:Q6
010	V-U	Q3:Q2
110	W-U	Q5:Q2
100	W-V	Q5:Q4

The advantage of Hall sensor-based commutation is that it has a simple and easily understandable control algorithm. Hall sensor based commutation can also be used to run motors at very low speeds. When a BLDC motor application requires high torque when running at low speed, or when moving from standstill, the Hall sensor commutation technique is an appropriate choice [33].

The drawbacks are that, its implementation requires both separate Hall sensors inside the motor housing and additional hardware for sensor interface. These Hall-Effect sensors increase the cost and size of the motor and require a special mechanical arrangement for mounting the sensors. They are also temperature sensitive. So operation range is limited. System reliability also reduces due to the requirement of additional components and wiring. Hence, the control complexity and high cost hold back the widespread use of PMBLDC motors with sensors [34].

On the other hand optical position sensors are also sometimes used. It makes use of six photo transistors. This device is turned ON, when light rays fall on the device and otherwise the device would be in OFF state. The photo transistors are fixed at the end shield cover of the motor such that they are mutually displaced by 60º. These transistors are illuminated (excited) by a suitable light source. The shaft carries a circular disc which rotates along with the shaft. The disc prevents the light rays from falling on the photo transistors. Suitable slots are punched in the disc such that at any position only two photo transistors are excited. These devices which are turned into ON state turns the two main switching devices of electronic commutation circuitry into ON state. As the shaft rotates, the devices of electronic commutator which are turned into ON state are successively changed. The switches will be turned ON depending on the rotor position. The sequence of switching for clockwise rotation based on circuitry in Fig.2 will be Q1 & Q4, Q1 & Q6, Q3 & Q6, Q3 & Q2, Q5 & Q2, and Q5 & Q4 repeatedly. For counter clockwise direction of rotation, the switching sequence will be Q5 & Q4, Q5 & Q2, Q3 & Q2, Q3 & Q6, Q1 & Q6 and Q1 & Q4 repeatedly [35].

Reduction of sensors in low-cost, low-power brushless DC motor drive is required since it affects the cost of the entire system. Sensors being costly also require a special mounting assembly and their performance is affected by temperature and Electro Magnetic Interference generated by the stator current. So, sensorless control of brushless DC motor is used to eliminate Hall-effect position sensors.

6. SENSOR-LESS CONTROL OF BLDC MOTORS

Recent trend is to minimize size and cost of the overall system, overcoming some disadvantages of using sensor based techniques. The drawbacks with position sensors are: First, the position sensor may increase the volume of the BLDC motor. Second, the position sensor between the motor and control system increase the wiring making the system vulnerable to outside interference effects. Third, the sensor’s sensitivity becomes low when the working conditions are poor such as high temperature, high pressure and high relative humidity. Finally, installation precision of the position sensor has special requirements and inaccurate commutation caused by the errors of machinery installations directly influence the operational performance of the BLDC motor [36]. Therefore the implementation of low cost, reduced parts brushless DC motor with high system reliability is taken by sensor-less techniques.

Sensor-less control techniques use implicit rotor position detection by using the motor voltages or currents that include Back-EMF method, magnetic flux linkage method and inductive method. Out of which Back-EMF method is commonly preferred. When a BLDC motor rotates, each winding generates a voltage known as back Electromotive force or back EMF, as the current passing through the phases generate flux and this voltage opposes the main supply voltage given to the windings according to Lenz’s law. The polarity of induced back EMF is opposite in direction to the supplied voltage. The back EMF depends on angular velocity of the rotor, magnetic field generated by rotor magnets and number of turns in the stator windings [37]. Based on this, new sensor-less techniques are emerging. The Back-EMF method includes detecting the zero-crossing point of the Back-EMF, detecting terminal voltage, Back-EMF integration, Direct Back-EMF sensing, direct phase current sensing and freewheeling diode conduction techniques [38].

In BLDC motors the phase windings are distributed in sinusoidal fashion or in trapezoidal fashion. The back-EMF shape can also be either sinusoidal or trapezoidal. In trapezoidal commutation only two phases will be conducting at any given point of time while in sinusoidal commutation all the three phases will be conducting at any given point of time. Sinusoidal voltage provides a smooth motor rotation and fewer ripples. On the other hand, trapezoidal commutation is the simplest way to control the BLDC motor and easy to implement [39].

The advantage of sensorless commutation is that the hardware design becomes simpler and no sensors/associated interface circuitry are required. The disadvantage is that it requires a relatively complex control algorithm and when the magnitude of back-EMF induced is low, it does not support low motor speeds [40].

Nowadays new sensor-less techniques are available which are independent of speed of the motor. These new sensor-less techniques used for rotor position detection are based on flux function, intelligent estimation method and inductance based method [41].

Recently, sensorless control of brushless DC motor is done by finding out the virtual hall signal by determining the zero-crossing point in the line voltage. Flip-flop has been employed to generate the virtual hall signal corresponding to the zero crossing points which represent the position of the rotor and starts the commutation [42]. This design of the sensorless control of brushless DC motor is very quintessential in its design and features. It has employed the technique of line voltage measurement of the motor and generated the virtual hall signals for the commutation of the motor. The input AC supply has been given to the Power Factor Correction (PFC) converter and its output is fed up to the inverter and supplied to the BLDC motor. Here, the line voltage differences have been used to generate the virtual hall signal. This quintessential method for generating the commutation pulses of required duration has been developed by the use of JK flip-flop through the detection of zero crossing point. The peak input current is rich in harmonics and has a high Total Harmonic Distortion (THD) content and poor input power factor. By IEC-61000-3-2 standard this high amount of THD content is not acceptable [43]. To improve the power quality at input mains a DCDC boost PFC converter is employed. The aim is to reduce the THD to less than 5% and improve the input power factor to almost unity [44].

Conventional scheme of brushless DC motor drive uses an uncontrolled rectifier to feed the motor, which draws harmonic rich electric current from the supply mains. Such peaky current has high total harmonic distortion which results in poor power factor (PF) at the AC mains. Power factor correction (PFC) converters are being used to achieve unity power factor at the AC mains and acceptable power quality (PQ) indices within IEC 61000-3-2 limits [45].

Single-stage PFC converters are commonly used due to lesser component count and thus have lower losses. Operating mode of the power factor correction converter depends on the desired power rating, cost of the overall system and permitted stress on the switch of the PFC converter [46]. There are totally three modes of operation. The operation of power factor correction converter in continuous inductor conduction mode (CICM) has low current stress on the switch, but requires the sensing of supply voltage, DC bus voltage and supply current for its operation. While, the power factor correction converter operating in discontinuous inductor conduction mode (DICM) gives an inherent power factor correction at the supply AC mains without any sensing requirement. But current stress is higher in DICM operation and so it is used only in low power applications [47].

Boost-PFC converter is one of the most widely used configurations for feeding the brushless DC motor drive. This configuration maintains a constant DC bus voltage at the Voltage Source Inverter (VSI) and uses a Pulse Width Modulation (PWM) based switching of the VSI for speed control of the BLDC motor. This facilitates the working of VSI in fundamental frequency switching by electronically commutating the BLDC motor; which reduces VSI's switching losses [48]. A canonical switching cell (CSC) is being used for feeding the BLDC motor due to its ability as an excellent power factor corrector, light load regulation capability and comparatively lower number of components compared to other PFC converters [49].

Calculation of phase Back-EMF by terminal voltage sensing is used to extract the rotor position information. A phase delay of 30º electrical is obtained due to phase Back-EMF sensing that has to be compensated by using analog filters. This method utilizes Back-EMF sensing without creating a virtual neutral, instead the negative DC link voltage of the VSI is used for creating the reference voltage [50]. The switching losses of the voltage source inverter depend on switching frequency that can be reduced by electronically commutating the brushless DC motor.

Techniques based on hysteresis comparator for providing dual operation of phase lead and avoiding false detection of virtual Hall signals are also being used. In such cases a separate Zero Crossing Detection (ZCD) unit is being used. The sensorless unit has a voltage sensing circuitry, hysteresis comparator, phase-lead compensator, negative clipper and an isolation circuitry. The terminal voltage of the brushless DC motor is sensed with the help of a resistive potentiometer and stepped down for it to be compatible with the analog IC's. This output is then given to a phase lead compensator, which is specially designed to compensate the phase delay in the virtual Hall signal estimation caused due to the sensing circuitry and the hysteresis comparator. The output of this phase lead compensator is directed to a hysteresis comparator for obtaining the zero crossing point of the line voltage that is obtained after phase-lead compensation. The band of the hysteresis comparator is chosen in such a way that minimum phase shift is obtained with the permitted band to avoid unwanted switching states. The output of the hysteresis comparator is given to the negative clipper that clips the negative half cycle of the obtained ZCD signals. This makes the ZCD signal compatible to be given to an opto-isolator that provides optical isolation between the power signal conditioning circuitry and the Digital Signal Processor (DSP) [51].

A novel concept of Sensorless Direct Speed Control (SDSC) in brushless DC (BLDC) motor drives does not require proportional plus integral (PI) regulators. Thus, feedback mechanism is minimized [52]. Speed regulation is achieved by controlling rotational speed of stator flux linkage. The PI regulator is replaced with a simple comparator. The BLDC motor is excited based on a look-up table. This is applicable to both two-phase and three-phase conduction modes of the BLDC motors. By assuming the amplitude of stator flux linkage to be fixed, the rotational speed of stator flux linkage affects the electromagnetic torque. An increase in the rotational speed of stator flux linkage leads to a raise in the electromagnetic torque. On the other hand, by reduction of the rotational speed of stator flux linkage, the electromagnetic torque decreases. Thus, motor speed can be regulated by controlling the stator flux rotation speed [53].

One another well-known method is to use filters to extract rotor position information. Rotor position information is derived by filtering only one motor-terminal voltage. In the BLDC mode, only two of the three-phase stator windings that present the peak back EMF are excited by properly switching the active switches of the inverter to produce a current with a quasi-rectangular shape [54]. There are six combinations of the stator excitation over a fundamental cycle with each combination lasting for a phase period of $\pi/3$. Only two of the three state windings are excited at a time and the third phase is open during the transition periods between the positive and negative flat segments of the back EMF. This provides a window to sense the back EMF and this window rotates among the three phases as the stator current commutates from one phase to another [55].

In many industrial applications, the sensorless method based on BEMF zero-crossing detection is an appropriate choice, since it is applicable to both trapezoidal or sinusoidal motor, even if it allows only six-step commutation; It does not require precise knowledge of motor parameters; It is simple to implement, especially with modern microcontrollers and dedicated motor control features [56]. A more efficient solution is implemented if the digital controller is able to sample and digitize BEMF measurements synchronously with PWM modulation (i.e. during PWM off periods) and implement more robust zero-crossing detection algorithms [57]. For these reasons, the digital control system is realized based on a Microchip dsPIC30F6015 Digital Signal Controller (DSC), that supports motor control with PWM generators for three-phase inverters and a 16- channel high-speed ADC. The power converter developed has the standard circuit topology, of a three phase inverter. The preferable technology for the implementation of inverter switches is MOSFET, because of its lower voltage drop compared to IGBT. Phase voltages (including wye mid-point) are fed back to the DSC by means of a voltage divider, made with a resistor network, and voltage follower amplifier [58].

7. AI BASED SPEED CONTROL OF BLDC MOTOR

PI/PID controllers are widely used for variable speed operations due to simplicity and ease of design. But it has some disadvantages as its performance depends on proportional and integral gains. So as operating conditions like load, motor's parameters change and some disturbances occur re-tuning of gain parameters is necessary [59]. Hence various Artificial Intelligence based speed control techniques have been experimented on BLDC motors using Neural Network and Fuzzy controllers to overcome the drawbacks of PI controllers. In Fuzzy Logic Control, approximate knowledge of the entire system is required, knowledge representation and inference is simple and the implementation is fairly easy. In Neural Network based control, any kind of non-linear mapping between inputs and outputs is possible. Also adaptive training is possible for various operating conditions. Though a Fuzzy controller is a good nonlinear controller, it cannot adapt its structure to the situation demands. On the other hand, Neural Networks become adaptive to such situations by adjusting their weights accordingly. Neural network based controllers improve speed response and reduce torque ripples. Neural Networks are more efficient and less sensitive to parametric variations than conventional controllers [60].

Regenerative Braking in Electric Vehicle (EV) Driven by Brushless DC Motor can be implemented using Fuzzy Logic. The system developed is completely non linear fuzzy logic with PID applied. The implemented Fuzzy Logic Controller (FLC) revolves synchronously along d-q reference frame as it can be easily used in BLDC motor and multilevel H – Bridge inverter. Two different fuzzy logic controllers are designed and implemented for two different axes. To control the BLDC motor, position of the rotor is very essential; on the basis of rotor position commutation of the BLDC is determined [61]. To know the position of the rotor in BLDC motor, Hall Effect sensors are employed. Here motor acts as generator, so they redirect the current in the supply to the battery by using the same drive circuit by using suitable strategy for switching. PWM method is used here in combination with independent switching to implement better control of braking. When the speed of EV is low, the emf generated during this period cannot reach the battery. So it is achieved by turning off all MOSFET of upper arms for given H bridge inverter and by controlling lower arms by using PWM. The fully controllable hybrid brake system uses fuzzy and PID. Mainly FLC is made up of five different blocks; namely fuzzification, defuzzication, data base, rule base and interference engine to obtain proper membership function. By using this system equal distribution of the braking force along with regenerative braking can be accomplished [62].

8. REGENERATIVE BRAKING OF BLDC MOTOR

In certain applications, such as in regenerative braking with traction motors, electric motors can be used in reverse as generators to recover energy that might otherwise be lost as heat and friction. Regenerative braking, in general, is an energy recovery mechanism which slows a vehicle or object by converting its kinetic energy into a form which can be either used immediately or stored until needed. Regenerative braking is a form of braking in electric vehicles in which the loss of kinetic energy from braking is stored and then fed back later to provide power to the electric motor [63]. In Brushless DC Motors the energy produced during braking is significant enough to store and utilize it for future purposes.

In a traditional braking system, brake pads produce friction with the brake rotors to slow or stop the vehicle. Additional friction is produced between the slowed wheels and the surface of the road. This friction is what turns the kinetic energy into heat. With regenerative brakes, on the other hand, the system that drives the vehicle does the majority of the braking. When the driver steps on the brake pedal of an electric or hybrid vehicle, these types of brakes put the vehicle's electric motor into reverse mode, causing it to run backwards, thus slowing the wheels. While running backwards, the motor also acts as an electric generator, producing electricity that's then fed into the vehicle's batteries. In fact, they're most effective in stop-and-go driving situations. In a regenerative braking system, the trick to getting the motor to run backwards is to use the vehicle's momentum as the mechanical energy that puts the motor into reverse [64].

Once the motor has been reversed, the electricity generated by the motor is fed back into the batteries, where it can be used to accelerate the vehicle again after it stops. Sophisticated electronic circuitry is necessary to decide when the motor should reverse, while specialized electric circuits route the electricity generated by the motor into the vehicle's batteries. In some cases, the energy produced by these types of brakes is stored in a series of capacitors for later use [65]. The circuitry finds the position of the rotor during the braking period. The higher the braking force, the different is the switching within the circuit. The position sensing is very much necessary in storing back the energy during braking. When the braking force is too high, harmonics and ripple currents may be formed. This will adversely affect the functioning of the circuit and the battery coupled with the motor. The capacitor filters out the ripples to a certain extent during storing of energy [66]. The controller decides the switching within the circuit. It receives information from the sensors placed on the rotor of the Brushless DC Motor. Depending on the rotor positioning, the controller turns on the switches within the circuit. The circuit for storing energy during braking and for supplying energy to the motor from the battery is the same. The switching signal provided by the controller decides whether the motor is undergoing regenerative braking or acceleration. The circuit may be a Bi-Directional DC/DC Converter or a simple 3-Phase Line Commutated Inverter [67].

Braking of BLDC Motor using Fuzzy Control for Electric Vehicles is achieved using the motor’s own power converter switches and winding inductance. The charging current of regenerated power has to be controlled to prevent the battery from any possible damage. For regeneration a current developing path is provided by a proper control of inverter as a boosting operation. For higher vehicle speeds and lower State of Charge (SoC) values, the battery pack must be protected properly from harmful excessive charging currents. The BLDC motor current control is done by using PI/PID controller and braking force distribution is controlled by fuzzy logic [68]. The battery pack is paralleled to the super capacitor through a diode which remains reverse biased until the super capacitor voltage is higher than the battery pack voltage. There are two modes of operation, normal mode and regenerative braking with battery and super capacitor. In normal mode, the battery solely supplies the motor. During braking, the motor works as a generator and thus the regenerated energy is boosted, the diode gets forward biased and energy is stored in the super capacitor. The super capacitor used is of high voltage compared to the battery, so energy stored is stepped down using the buck converter and then used to charge the battery [69]. A specific switching pattern is applied alone to the lower switches S2, S4 and S6 of the inverter. The switches are then controlled via a high-frequency PWM signal. When the upper switches are turned off, the diodes transfer current to the battery side. For easily regulating the regenerative voltage, single-switch modulation mode is adopted, where the active switch in the lower side is modulated in turn. Specifically, turns only one of the lower switches to be the PWM, and keeps the other five switches OFF. For a whole electrical cycle of the regenerative charging process, each switch is modulated within 120 electrical degrees [70]. Therefore, the vehicle’s kinetic energy is converted into electrical energy, which avoids the wastage of energy, lengthens the life of batteries, and increases the driving range. In Regenerative Braking mode the dc-link voltage will be boosted with the help of appropriate switching signal pulses to the lower switches of the inverter. Instead of using an extra DC-DC converter, here boosting is accomplished by using the motor’s own winding inductance and bidirectional switches of the inverter. It reduces the components required and also the overall cost [71].

An analysis of braking Characteristics, state that regenerative braking of BLDC motor can be achieved by applying different stator voltage. This new method does not required complex converter with complex switching technique and ultra-capacitor but only a low cost rotary mechanical switch and a multi cell battery system from where rotary mechanical switch will select different voltage based on brake pedal position [72]. BLDC motor generates 3 phase back E.M.F, so a rectifier connected at stator terminal will rectify the back E.M.F which is necessary to transfer energy from motor to the battery cell. Moveable flywheel allows changing the loading condition and Rotary Mechanical Switch (RMS) will allow selecting different stator voltage from Multi cell Battery system. Lower stator voltage will create higher braking current and higher braking current will create higher braking torque. On the other hand higher braking torque will create higher deceleration and required lower braking time to stop the vehicle. So during regenerative braking lower braking time can be achieved by applying lower stator voltage. This method could enhance mileage around 28.842%. Since this control strategy utilizes the variation in stator voltage to bring about regenerative braking, this heavily reduces the cost as it does not involve any other extra circuitry. This proves that regenerative braking based on Stator voltage control is more effective and efficient than Ultra-capacitor and boost converter based braking system [73].

A new electric braking system with energy regeneration for a BLDC motor driven electric vehicle uses an alternative method with the single stage converter which drives the BLDC motor and the switching is decided based on the hall sensor placed on the braking pedal. In this single stage converter, different types of braking methods based on different switching topology namely single switch, two switch and three switch are implemented. Based on the results, it is concluded that single switch and three switch are capable of producing required braking torque and better energy recovery in mid to high-speed range. Moreover, two switch is recommended for low speed or emergency braking case since it produces high braking torque. In single switch braking method, only one switch out of switches S2, S4, S6 is operated in pulse width modulation (PWM) switching mode at each commutation state. In two switch method, two switches out of switches S1-S6 are operated. In three switch method, three switches S2, S4, S6 are operated. The switching sequence of plugging is similar to that of two switch method, where a continuous signal is applied instead of PWM pulses. As single switch and three switch has less deceleration and more energy recovery, it is adapted for normal braking event or deceleration purpose [74].

9. CONCLUSION

BLDC motors have been gaining attention from various industrial and household appliance manufactures because of its high efficiency, long life, low inertia and friction, faster acceleration, high power density, silent operation, low radio frequency interference and noise, low maintenance cost, small size and reliability. With rapid development in power electronics, semi-conductor and manufacturing technology for high performance magnetic materials, the BLDC motors have been used for energy saving applications such as air-conditioners, refrigerators, kitchen appliances and electric vehicles.

BLDC motors are controlled conventionally using Hall sensors, Shaft encoders, accelerometers and electromagnetic variable reluctance sensors. Hall sensors are commonly used while back-EMF sensing techniques are used for sensor-less speed control. Drawbacks of BLDC motor control using Hall sensors are increased cost and size. The cost of a permanent magnet brushless DC motor drive generally depends on the motor and the controller. Extensive research has been done to minimize the cost and to increase the efficiency of these motors. But still cost of the controllers and power quality aspects of the drives are under consideration. Due to ease of control, they are being preferred for various applications in low power and variable speed drives despite the cost.

An exhaustive review of the permanent magnet brushless DC motor has been presented, to provide a clear idea on the various possible control techniques. These motors are suitable for numerous applications. Based on the requirements for a particular application, decision on the choice of the motor control scheme (i.e. Sensorless or with sensors) and controller topology has to be made keeping in mind the accuracy, cost, complexity and reliability of the system.

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