Review Article

REVIEW OF DIFFERENT CONTROL TOPOLOGIES FOR THE PERMANENT MAGNET BRUSHLESS DC MOTOR DRIVES

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ABSTRACT

Permanent magnet brushless DC (PMBLDC) motors are the latest choice of researchers due to their high efficiency, silent operation, compact size, high reliability and low maintenance requirements. These motors are preferred for numerous applications; however, most of them require Sensor less control of these motors. The operation of PMBLDC motors requires rotor-position sensing for controlling the winding currents. The Sensor less control would need estimation of rotor position from the voltage and current signals, which are easily sensed. This paper presents state of the art PMBLDC motor drives with the Sensor less control of these motors.

KEYWORDS Permanent magnet machines, brushless machines, PMBLDCM and sensorless control, low cost controllers

INTRODUCTION

The use of permanent magnets (PMs) in electrical machines in place of electromagnetic excitation results in many advantages such as no excitation losses, simplified construction, improved efficiency, fast dynamic performance, and high torque or power per unit volume [1].The PM excitation in electrical machines was used for the first time in the early 19th century, but was not adopted due to the poor quality of PM materials. In 1932, the invention of Alnico revived the use of PM excitation systems, however it has been limited to small and fractional horse power dc commutator machines [3].In the 20th century, squirrel cage induction motors have been the most popular electric motors, due to its rugged construction. Advancements in power electronics and digital signal processors have added more features to these motor drives to make them more prevalent in industrial installations. However squirrel cage induction motors suffer from poor power factor and efficiency as compared to synchronous motors. On the other hand, synchronous motors and dc commutator motors have limitations such as speed, noise problems, wear and EMI due to the use of commutator and brushes. These problems have led to the development of permanent magnet brushless or commutator less synchronous motors which have PM excitation on the rotor [1]. Therefore, permanent magnet brushless (PMBL) motors can be considered a kind of three phase synchronous motor, having permanent magnets on the rotor, replacing the mechanical commutator and brush gear. Commutation is accomplished by electronic switches, which supply current to the motor windings in synchronization with the rotor position. The popularity of PMBL motors are increasing day by day due to the availability of high energy density and cost effective rare earth PM materials like Samarium Cobalt (Sm-Co) and Nd-Fe-B which enhance the performance of PMBLDCM drives and reduce the size and losses in these motors. The advancements in geometries and design innovations have made possible the use of PMBL motors in many of domestic, commercial and industrial applications. PMBL machines are best suited for position control and medium sized industrial drives due to their excellent dynamic capability, reduced losses and high torque/weight ratio. PMBL motors find applications in diverse fields such as domestic appliances, automobiles, transportation, aerospace equipment, power tools, toys, vision and sound equipment and healthcare equipment ranging from microwatt to megawatts. Advanced control algorithms and ultra-fast processors have made PMBLDC motors suitable for position control in machine tools, robotics and high precision servos, speed control and torque control in various industrial drives and process control applications. With the advancement in power electronics it is possible to design PMBL generators for power generation onboard ships, aircraft, hybrid electric cars and buses while providing reduced generator weight, size and a high payload capacity for the complete vehicle. In view of these requirements of PMBLDCM drives, an attempt is made in this paper to introduce various aspects of PMBLDCM drives.

STATE OF THE ART

PMBLDC motors are generally powered by a conventional three-phase voltage source inverter (VSI) or current source inverter (CSI) which is controlled using rotor position. The rotor position can be sensed using Hall sensors, resolvers, or optical encoders [1]. These position sensors increase cost, size and complexity of control thereby reducing the reliability and acceptability of these drives. Due to the high cost of the motor and controller, very few commercial applications of PMBLDC motor. Recently some additional applications of PMBLDC motors have been reported in electric vehicles (EVs) and hybrid electric vehicles (HEVs) due to environmental concerns of vehicular emissions. PMBLDC motors have been found more suitable for EVs/HEVs and other low power applications, due to high power density, reduced volume, high torque, high efficiency, easy to control, simple hardware and software and low maintenance [9]. The cost of a PMBLDCM drive has two main components; one is the motor and other is the controller. Extensive research attempts have been made to reduce the cost and to increase the efficiency of these motors [4]. However, the cost of controllers and the power quality aspects of the drives are still under consideration. Due to ease of control in PMBLDC motors, they are preferred for numerous applications in low power and variable speed drives.

CONTROLLERS FOR PMBLDC MOTORS

The control of PMBLDC motors can be accomplished by various control techniques using conventional six pulse inverters which can be classified in two broad categories as voltage source inverter (VSI) and current source inverter (CSI) based topologies. The controllers can further be divided on the basis of solid state switches and control strategies. The PMBLDCM needs rotor-position sensing only at the commutation points, e.g., every 60°electrical in the three-phases; therefore, a comparatively simple controller is required for commutation and current control. The commutation sequence is generated by the controller according to the rotor position which is sensed using Hall sensors, resolvers or optical encoders. These sensors increase the cost and the size of the motor and a special mechanical arrangement is required for mounting the sensors. The system reliability also reduces due to the additional components and wiring. Therefore, the control complexity and high cost of the drive hold back the widespread use of PMBLDC motors. The cost reduction of controllers for PMBLDCM drives can be accomplished by two approaches, namely topological approach and control approach. In the topological approach, the number of switches, sensors and associated circuitry used to compose the power converter is minimized, whereas, new algorithms are designed and implemented in conjunction with the converter to produce the desired characteristics, in the control approach. To begin with the topological approach, topologies with more than one switch per phase, but less than conventional two switches per phase can be considered for low cost applications. However, there are some conventional topologies (i.e. six switch topology) for low cost applications also reported in the literature [6]. As the majority of applications of these motors are at low power levels, therefore, single phase AC mains fed PMBLDCM drives are considered in this paper.

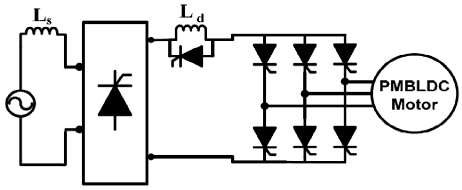

Fig. 1 Load commutated converter topology [6]

A single phase AC mains input based thyristorised load commutated converter topology as shown in Fig. 1, has been reported [6] based on a current source inverter. Four-quadrant operation, current Sensor less control and wide operating speed range are good features of the proposed topology. However, the requirement of a big inductor for high capacity applications has been a major disadvantage of this topology.

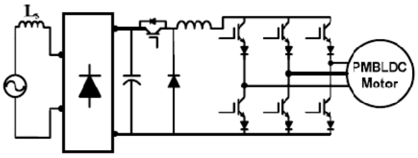

Fig. 2 Buck converter-CSI based topology [8]

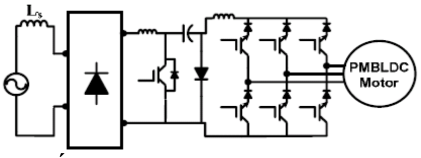

Fig. 3 Ćuk converter-CSI based topology [8]

Some modifications in this thyristorised drive based on the buck and Ćuk topology (schematic shown in Figs. 2 and 3) have been proposed in the literature [8] for reduction of harmonics and cost as well. The topologies with switches less than one per phase reported in the literature [5, 7] are modified from the basic VSI topology [1] (conventional six switch configuration as shown in Fig. 4). One such reported topology is a three phase four switch topology shown in Fig. 5, which has been tested with different schemes like PWM and hysteresis current control methods [5]. It has been modified for power factor correction [5, 7] resulting in a topology with a total of six switches as shown in Fig. 6. This topology has single phase to three phase conversion with sinusoidal input current close to unity power factor. This topology enables regenerative braking due to bidirectional power flow between ac input and PMBLDC motor via the DC link. This topology requires a symmetric PWM scheme for switching control, which can be generated using a digital signal processor (DSP) or a field programmable gate array (FPGA) [21].

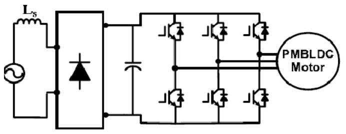

Fig. 4 Conventional VSI based topology [1]

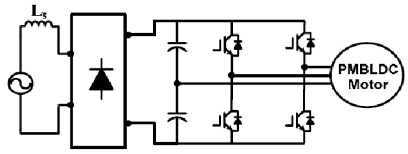

Fig. 5 Three phase four switch topology [4, 5]

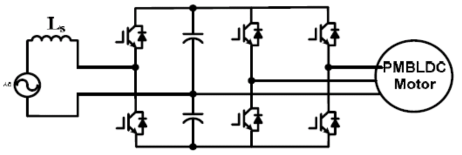

Fig. 6 3-ph. 4 switch topology without input rectifier [5, 7]

Another topology in this category is the C-dump converter topology (shown in Fig.7) which has (n+1) switches for an n-phase machine [12]. For a three phase PMBLDC motor it has four sets of power switches and power diodes (one switch and one diode per set), of which three are connected with phase windings and one remaining set is connected with the capacitor for energy recovery. Since each phase has only one switch, the current in it could only be unidirectional; hence, it is very much similar to the half wave converter driven PMBLDCM in operation [12].

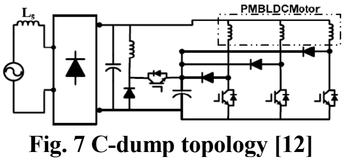

Fig. 7 C-dump topology [12]

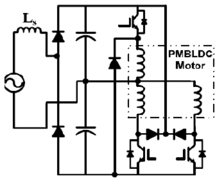

Fig. 8 Split supply converter topology [13]

A half bridge power converter topology known as a split supply converter topology (shown in Fig.8) has also been used for PMBLDCM having one switch per phase and only two diodes for rectification [13]. This topology can be used with bifilar winding after incorporating some modifications; however it reduces motor utilization [4]. A buck converter based two phase PMBLDCM drive with bifilar winding (as shown in Fig. 9) can be used for low voltage applications only. Another topology, which combines the advantages of C-dump converter and split supply converter topologies, has been reported in the literature for the control of PMBLDCM [14]. This topology named the variable DC link converter topology (shown in Fig.10) has variable DC link voltage, four quadrant operation and low voltage rating power switches as major strengths. Some topologies have been reported [5, 7-8, 21] which provide power factor correction (PFC) as well while controlling the operation of PMBLDC motors. A SEPIC converter based unipolar control has been reported [21] as one such topology (shown in Fig.11). These topologies have also been claimed as low cost controllers for PMBLDC motors.

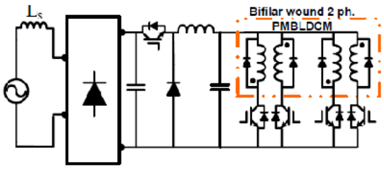

Fig. 9 Buck converter based topology for bifilar wound two Phase PMBLDC Motor [2]

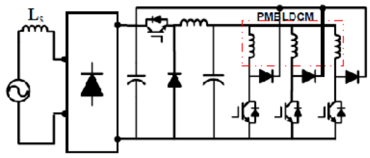

Fig. 10 Variable DC link converter topology [14]

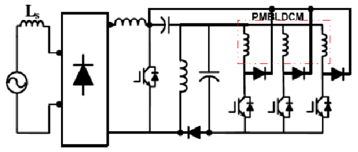

Fig. 11 SEPIC converter based topology [9]

Some of researchers have proposed unipolar excitation for PMBLDC motors, which need less electronic components and use a simple circuit as compared to conventional bipolar excitation of PMBLDC motors [9]. This leads to converter cost minimization and opens up scope for substantial applications where cost matters more than the accuracy of control. For proper operation of a PMBLDC motor, the flow of current in the stator windings must be synchronized to the instantaneous position of the rotor and therefore, the current controller must receive information about the position of the rotor. However, the presence of the position sensor is undesirable in many applications; therefore, position Sensor less schemes may be employed in which rotor position information is deduced from the voltages and currents in the motor windings.

POSITION SENSORLESS CONTROL METHODS

The basic idea of position Sensor less control methods is to eliminate the position sensors (usually three Hall sensors). To accomplish this task, additional circuitry and computational0 efforts are required to estimate the commutation instances of the PMBLDC motor from the voltage and current signals which can easily be sensed. Therefore, Sensor less techniques demand high performance processors with large memory and program codes for computation and estimation, as compared to sensor-based drive systems. PMBLDC motors can be modeled by the same equivalent circuit for each phase winding, where the source voltage ‘v’ supplies current ‘i’ to the phase circuit consisting of series-connected resistance ‘R’, inductance ‘L’, and back EMF ‘e’. The back EMF is a result of the movement of the PM rotor, thereby, dependent on rotor position and proportional to rotor velocity. The machine voltage and current waveforms reflect the rotor-position dependence of the inductance and back EMF. Therefore, the voltage and current waveforms can be analyzed to extract the back EMF or inductance (or a combination of the two), from which the rotor position can be estimated in the position Sensor less schemes. The position Sensor less approach has many advantages, e.g. minimum installation cost, minimum space requirement, no environmental restrictions (e.g. high pressure and temperature environment in HVAC compressors), EMI free position information, reduced controller cost etc. These Sensor less techniques may be broadly categorized0 0as: back electromotive force (BEMF) 0sensing, inductance or flux-linkage variation sensing [1, 5]. Closed-loop observer based methods to address position sensing in PM machines.

A. Back EMF Sensing

In PM brushless DC machines, the magnitude of the back EMF is a function of the instantaneous rotor position and has trapezoidal variation with 120º flat span. However, in practice, it is difficult to measure the back EMF, because of the rapidly changing currents in machine windings and induced voltages due to phase switching. The back EMF is not sufficient enough at starting until the rotor attains some speed. Therefore, it is a usual practice to make the initial acceleration under open-loop control using a ramped frequency signal so that the back-EMF is measurable for the controller to lock in. One of the popular starting methods is “align and go” [5-8] in which the rotor is aligned to the specified position by energizing any two phases of the stator and then the rotor is accelerated to the desired speed according to the given commutation sequences [22,23]. The “align and go” method suffers demagnetization of permanent magnets due to large instantaneous peak currents at starting. The zero-crossing points of the back EMF in each phase may be an attractive feature to use for sensing, because these points are independent of speed and occur at rotor positions where the phase winding is not excited. However, these points do not correspond to the commutation instants. Therefore, the signals must be phase shifted by 90° electrical before they can be used for commutation. The detection of the third harmonic component in back EMF, direct current control algorithm and phase locked loops have been proposed to overcome the phase-shifting problem. However, the direct current control algorithm suffers filtering problem of sensed voltage signals which limits the operation range above 200 rpm. The third-harmonic approach assumes equal inductance in all three phases, which is only valid for surface-mounted magnet motors; however, in the case of rotors with saliency, errors in position estimation arise due to rapidly changing phase currents. To measure the back EMF across the terminals of a star-connected machine, it is necessary to have the machine's star neutral terminal. The back EMF method has been applied in special-purpose low-cost applications for fans and pumps while ignoring these problems [10].

B. Inductance Variation Sensing

The fundamental concept behind the inductance variation is the rate of current change in the motor which depends on the inductance of the winding. The inductance variation can be sensed after injection of a current pulse in the armature windings [5-8, 11]. This scheme is particularly useful at zero speed when there is no back EMF. This method is suitable for the IPM (Interior Permanent Magnet) BLDC motor with high performance material such as the NdFeB magnet. In order to get various inductance profiles, a large current pulse is required. Thus, these methods are not suitable for a SPM-type BLDC motor with ferrite magnets. Therefore, the application of inductance variation sensing methods may be useful to address the problem of starting, including identification of the rotor position before full excitation of the machine. Initial rotor position identification is particularly important in applications such as traction, where any reverse motion is not acceptable. Some authors [5-8] have also reported the detection of initial rotor position of a salient pole PM motor by high-frequency injection methods using voltage pulses. Despite implementation difficulties, several methods of position sensing from inductance variation have been applied for Sensor less operation. Low frequency excitation pulse results in large current amplitudes which facilitate easy detection, but can cause audible noise from the motor. Whereas high frequency avoids audible noise, but reduces current amplitudes. Therefore, choice of an appropriate modulation frequency and modification in the machine rotor can further improve rotor position sensing using this method.

C. Flux Linkage Variation Sensing

Flux- linkage variation sensing, which is based on the phase voltage equation of the motor. Since the phase flux linkages are a function of current and rotor position, therefore, phase flux linkage can be estimated continuously by integrating the voltage after subtracting the resistive voltage drop from the phase voltage. The open-loop integration is prone to errors caused by drift, which can be reduced if the pure integrator is replaced by a low pass filter or an alternative integrator structure. In most electrical machines, it is not practical to measure the phase voltages directly, because of isolation related issues; therefore, applied phase voltage is estimated from DC supply voltage of the solid-state converter [5].

POWER QUALITY CONSIDERATION

In recent years, the power quality considerations for various drives have been reported reasonably due to increased use of electronic equipment and AC motor drives in all walks of society i.e. household, commercial and industrial applications. A diode rectifier with a smoothing dc capacitor behaves as a harmonic voltage source, however, thyristor converters are a common and typical source of harmonic currents [21]. Therefore, any of these kinds of drives which behave as a nonlinear load are not a good option for power utilities. In view of these problems, some suitable measures are required for the compensation of these current harmonics. One very popular method is the use of filters i.e. passive or active wave shaping (series or parallel). The current source nonlinear loads and voltage source nonlinear loads have dual relations to each other in circuits and properties and can be used with parallel and series filters, respectively, for harmonic compensation [22].

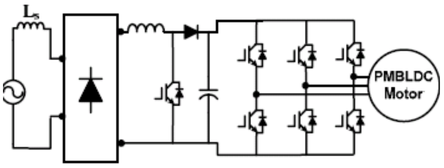

Fig. 12 Boost converter based PFC topology [7, 9]

Fig. 6 shows a three phase four switch topology voltage source inverter (VSI) having total six switches including rectifier for PFC and Fig. 12 shows a conventional six switch VSI topology with single phase PFC[15-18] at input mains of PMBLDCM drive. Conventional six switch converters have been reported with various PFC converters. A six switch single phase to three phase converter, which draws sinusoidal input current at close to unity power factor. In papers, some of these topologies are designed and modeled for a PMB LDC Motor of 1.5 kW in the MATLAB/Simulink environment.

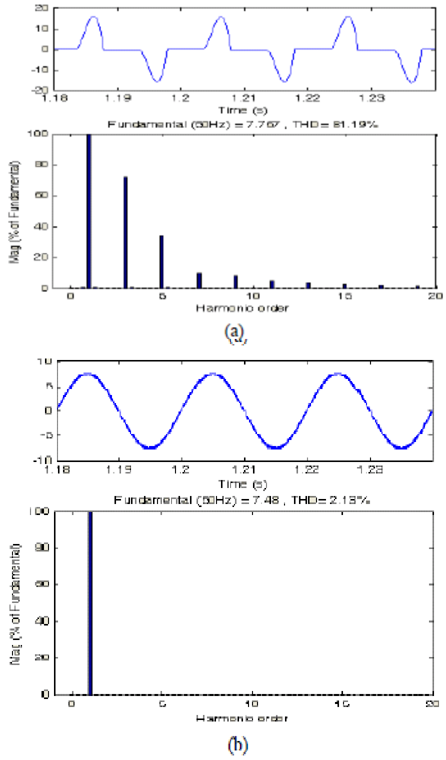

Fig. 13 The source current (*is*) waveform and its THD during steady state at rated torque for (a) conventional VSI based topology fed PMBLDCM drive (Fig.4) and (b) conventional VSI based boost PFC topology fed PMBLDCM drive (Fig.12)

Fig. 13 shows the supply currents and harmonic spectra of the conventional PWM VSI fed PMBLDC motor drive with and without PFC converter. The harmonic spectra shows 81.19% THD in the AC mains current at rated torque with a crest factor (CF) of 2.95 for conventional VSI. The THD of AC mains current is reduced to 2.13% with the boost PFC topology with a crest factor of 1.45 at same load on the motor[16,20]. The performance of the PMBLDCM drive is improved with boost PFC topology in terms of low torque ripples, smooth speed variation and unity power factor at AC mains.

CONCLUSIONS

An exhaustive overview of PMBLDCM drives has been presented to provide a clear perspective on various aspects of these drives. The PMBLDCM drives are suitable for many applications; however, the choice of the motor (i.e. rotor configuration), control scheme (i.e. Sensor less or with sensors) and controller topology depends on the accuracy, cost, complexity and reliability of the system. A customer can select a PMBLDCM drive with their desired features, however, there is a tradeoff between the number of parameters (e.g. Sensor less or with sensors, accuracy, complexity, reliability and cost of controller).The performance of the PMBLDCM drive is improved with boost PFC topology in terms of low torque ripples, smooth speed variation and unity power factor at AC mains.

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