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State of the Art on 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 sensorless control of these motors. The operation of PMBLDC motors requires rotor-position sensing for controlling the winding currents. The sensorless 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 an emphasis on sensorless control of these motors.

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

1. 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 [1-137]. 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 [8, 24].

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 commutatorless synchronous motors which have PM excitation on the rotor [1-30].

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.

Amongst the available PM materials, Alnico magnets can have flux densities equivalent to soft magnetic irons but they get easily demagnetized due to lower values of

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coercive force as compared to ceramic magnets [21]. Ceramic magnets are economical but their maximum energy density product is low due to lower values of retentivity. Rare earth and samarium cobalt alloys have relatively good magnetic properties, but they are expensive. Other than polymer bonded rare earth magnets, for example, ferrite and cobalt based metallic magnets are physically hard and brittle. Therefore, selection of the particular PM material is application specific; however, Neodymium-Iron-Boron (Nd-Fe-B) rare earth magnets are more in demand because they provide the highest energy density and higher residual flux density than others [21].

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. This paper is organized in nine sections as follows. A state of the art PMBLDC motor application is reviewed in Section 2. The classification of permanent magnet brushless (PMBL) motors is presented in Section 3. The construction of PMBLDC motors and controllers for PMBLDC motors are discussed in Sections 4 and 5, respectively. The position sensorless control methods of PMBLDC motors are discussed in Section 6. The applications, power quality aspects and future trends of PMBLDCM drives are highlighted in Sections 7, 8 and 9, respectively. The concluding remarks and recommendations are given in Section 10.

2. 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 [1-137]. 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 motors have been reported in the literature [113-137].

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 [36-137].

The cost of a PMBLDCM drive has two main components; one is the motor and other is the controller. Extensive research attempts [13-29] have been made to reduce the cost and to increase the efficiency of these motors. 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.

3. Classification of PMBL Motors

Permanent magnet brushless motors can be divided into two subcategories. The first category uses continuous rotor-position feedback for supplying sinusoidal voltages and currents to the motor. The ideal motional EMF is sinusoidal, so that the interaction with sinusoidal currents produces constant torque with very low torque ripple. This called a Permanent Magnet Synchronous Motor (PMSM) drives, and is also called a PM AC drive, brushless AC drive, PM sinusoidal fed drive, sinusoidal brushless DC drive, etc.

The second category of PMBL motor drives is known as the brushless DC (BLDC) motor drive and it is also called a trapezoidal brushless DC drive, or rectangular fed drive. It is supplied by three-phase rectangular current blocks of 120° duration, in which the ideal motional EMF is trapezoidal, with the constant part of the waveform timed to coincide with the intervals of constant phase current. These machines need rotor-position information only at the commutation points, e.g., every 60°electrical in three-phase motors [1-29].

The PMBLDC motor has its losses mainly in the stator due to its construction; hence the heat can easily be dissipated into the atmosphere. As the back EMF is directly proportional to the motor speed and the developed torque is almost directly proportional to the phase current, the torque can be maintained constant by a stable stator current in a PMBLDC motor. The average torque produced is high with fewer ripples in PMBLDC motors as compared to PMSM [1-15]. Amongst two types of PMBL motors, PMSM is, therefore, preferred for applications where accuracy is desired e.g. robotics, numerical controlled machines, solar tracking etc. However, the PMBLDCM can be used in general and low cost applications. These motors are preferred for numerous applications, due to their features of high efficiency, silent operation, compact in size and low maintenance.

4. Construction of PMBLDC Motors

The stator of a PMBLDC motor usually has three phase concentrated windings; however, the rotor construction varies according to desired requirements. Various geometries for PM rotors have been reported in the literature [21], for improved power density and efficiency by adopting flux enhancement, armature reaction reduction or high-speed operation. Two main configurations of PM rotors are surface mounted magnet type where magnets are mounted on the outer surface of the rotor, and the buried magnet type where the magnets are mounted inside the magnetic structure of the rotor.

Another type of PMBL motor is the axial field machine where the direction of the magnetic field is axial instead of radial. The configurations of axial field PMBL motors include a single stator and single rotor, a single stator sandwiched between two rotors (double air gaps), a single rotor sandwiched between two stators (double air gaps) and a variety of multiple stators and rotors (multiple air gaps) [21].

Any of these PMBLM rotor configurations can be selected on the basis of application and power rating. Various other configurations of PMBL machines include Axial Flux Permanent Magnet (AFPM) machines, PM alternators and torous alternators with different rotor geometries like surface type, interior type, radial and axial field machines in two, three and multi phase PMBLDC machines.

5. 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.

Reduced cost controllers for PMBLDC motors are more in demand and many schemes and algorithms for reduced cost controllers have been reported in the literature [82-102]. 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 [92, 95]. 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 work.

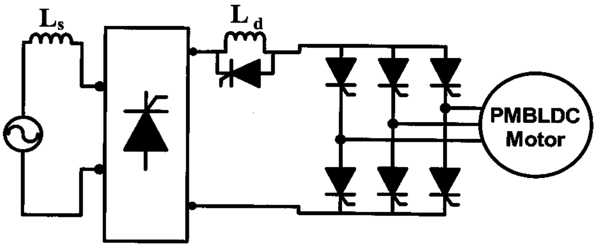


Fig. 1 Load commutated converter topology [92]

A single phase AC mains input based thyristorised load commutated converter topology as shown in Fig. 1, has been reported [92] based on a current source inverter. Four-quadrant operation, current sensorless 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.

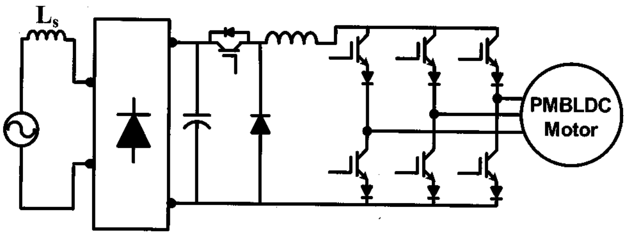


Fig. 2 Buck converter-CSI based topology [95]

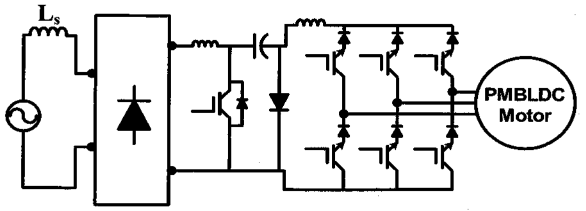


Fig. 3 Ćuk converter-CSI based topology [95]

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 [95] for reduction of harmonics and cost as well.

The topologies with switches less than one per phase reported in the literature [82-83, 85, 89-91, 94, 99-102] are modified from the basic VSI topology [1-16] (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 [90-91]. It has been modified for power factor correction [91, 94] 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) [102].

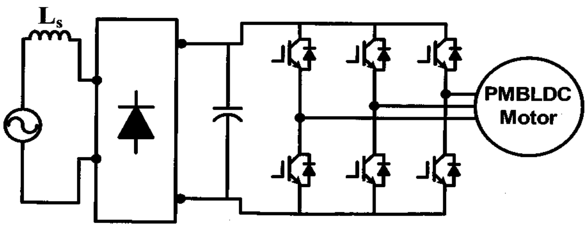


Fig. 4 Conventional VSI based topology [1-16]

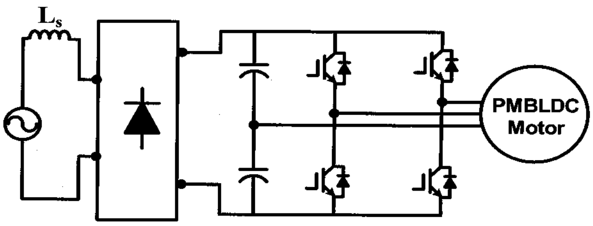


Fig. 5 Three phase four switch topology [90, 91]

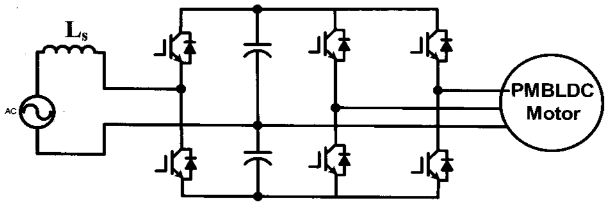


Fig. 6 3-ph. 4 switch topology without input rectifier [91, 94]

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 [82, 89]. 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 [82].

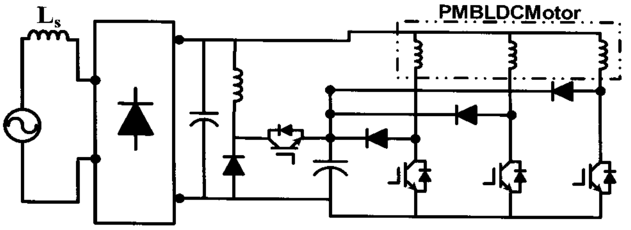


Fig. 7 C-dump topology [82]

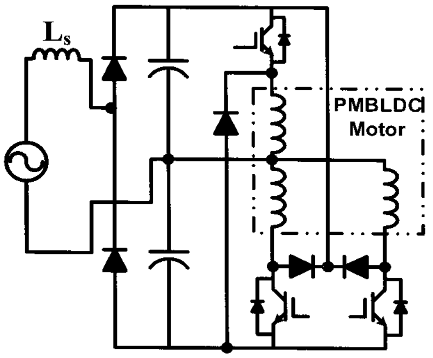


Fig. 8 Split supply converter topology [83]

A half bridge power converter topology known as a split supply converter topology (shown in Fig.8) has also been used for PMBLDCM [83] having one switch per phase and only two diodes for rectification. This topology can be used with bifilar winding after incorporating some modifications; however it reduces motor utilization [2, 13].

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 [85] for the control of PMBLDCM. 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 [91, 94-95, 102] which provide power factor correction (PFC) as well while controlling the operation of PMBLDC motors. A SEPIC converter based unipolar control has been reported [102] as one such topology (shown in Fig.11). These topologies have also been claimed as low cost controllers for PMBLDC motors.

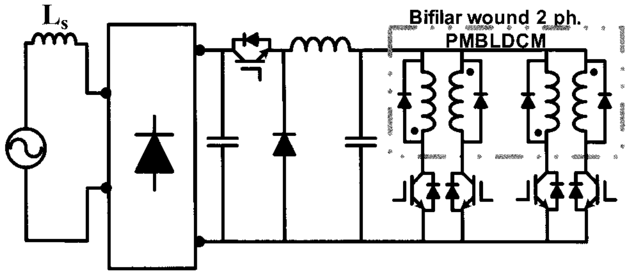


Fig. 9 Buck converter based topology for bifilar wound two phase PMBLDC Motor [2, 13]

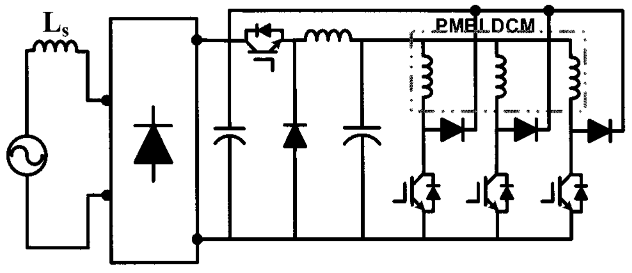


Fig. 10 Variable DC link converter topology [85]

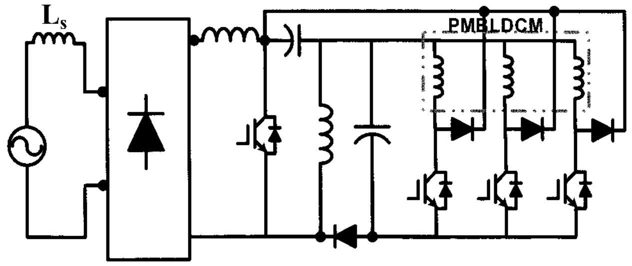


Fig. 11 SEPIC converter based topology [99]

Some of researchers [99, 132] 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. 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 sensorless schemes may be employed in which rotor position information is deduced from the voltages and currents in the motor windings.

6. Position Sensorless Control Methods

The basic idea of position sensorless control methods is to eliminate the position sensors (usually three Hall sensors). To accomplish this task, additional circuitry and computational efforts are required to estimate the commutation instances of the PMBLDC motor from the voltage and current signals which can easily be sensed. Therefore, sensorless 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 sensorless schemes [17-20, 49-81, 131-136]. The position sensorless 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 sensorless techniques may be broadly categorized as: back electromotive force (BEMF) sensing, inductance or flux-linkage variation sensing [17-20, 49-81]. Closed-loop observer based methods to address position sensing in PM machines and sensorless schemes for permanent magnet synchronous motors have also been reported in the literature [17-20, 30, 127, 131], which can be extended to brushless dc motors in the same fashion or with some modifications.

6.1 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 120° 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” [17-20, 49, 131-136], 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. 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 [49, 100].

The detection of the third harmonic component in back EMF [59, 72], direct current control algorithm [100] and phase locked loops [66] 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 [74, 124] while ignoring these problems.

6.2 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 [17-20, 55, 60, 75]. 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 [135]. 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 [17-20, 77] 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 sensorless 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.

6.3 Flux Linkage Variation Sensing

Another method reported in the literature [17-20] is 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 [17-20]. 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 [17-20].

7. Application Potential of PMBLDC Motors

Classic electric motors are mostly preferred for motion control, in general and household appliances, in particular. The most common motors for household appliances are single phase AC induction motors, including split phase, capacitor start, capacitor run types and universal motors. These motors operate at constant speed directly from AC mains irrespective of efficiency; however, consumers now demand appliances with low energy consumption, improved performance, reduced acoustic noise, and many more convenience features. Therefore, household appliances are expected to be one of largest end product market for PMBLDC motors over the next few years. The major household appliances include fans, blowers, washing machines, room air-conditioners, refrigerators, vacuum cleaners, food processors, etc.

The possibilities of cost reduction have to be explored to commercialize PMBLDCM drives, apart from technological advancements. The cost of a PMBLDCM drive has two main components; one is motor and other is the controller. Extensive research attempts [13-29] have been made to reduce the cost and increase the efficiency of the motor. Comparative analysis has also been presented in the literature [36, 117] for the choice of the motor to suit a particular application.

Recently, there has been growing research interest for use of PMBLDC motors in electric vehicles (EVs) and hybrid electric vehicles (HEVs) due to environmental concerns of vehicular emissions. An electric drive is one of the main parts of an EV/HEV and requires multidisciplinary power electronic technologies, including motors, converter topologies, switching devices, microprocessors/DSPs, and control strategies. The PMBLDC motor is more suitable for EVs/HEVs and low power applications, due to high power density, less volume, high torque, high efficiency, easy to control, simple hardware and software, and low maintenance. It is very difficult to identify a unique drive solution for all kinds of electric vehicles (i.e. bikes, cars, vans, trucks, etc.). For many applications, the motor should have shape flexibility, compactness, robustness, high efficiency and high torque [113-137].

Axial flux motors can be an interesting option for EVs, because it can be directly coupled, to or inside, the vehicle wheels. With this kind of solution known as a "wheel motor," the mechanical differential and reduction gear can both be avoided. Among the available types of axial flux motors, the axial flux interior permanent magnet (AFIPM) motor in which the stator windings are allocated in slots, has some very attractive characteristics for application as wheel motors e.g. robust construction and ability to deliver the desired torque in the flux-weakening region, too. It has higher output torque as compared to other motors due to the cumulative effects of field and reluctance [36-48].

PMBLDC motors have been used in various high-speed applications such as the hard disk drive (HDD) of computers which run at very high speed to reduce the access time of the data written on the surface of a rotating disk. In order to run the motor at high speed, back electromotive force (EMF) constant is designed to be small to reduce the voltage drop due to back EMF. But, it results in small starting torque, thereby a long transient period. It is one of the drawbacks of a PMBLDC motor in high-speed applications. Therefore a combination of unipolar and bipolar drives has been used which utilizes the advantage of the large starting torque of a bipolar drive and the high operating speed of a unipolar drive. A DSP/FPGA based controller can be used to drive the PMBLDC motor with the bipolar or unipolar method and to switch from one method to the other at any speed [132].

Many other applications of PMBLDC motors have been reported which include, tread mills [124], washers [127], dexterous robotic hands [128], wheelchairs [130], compressors of household air conditioners [107, 120], automotive HVACs [113, 133] and commercial freezers [136], fans [123, 129] and pumps [44, 116, 118, 125]. The use of an application specific integrated circuit (ASIC) such as ML-4425 [22, 23] for generating the commutation pulses based on back-EMF sensing, has the flexibility of adding desired features through software modifications rather than with additional hardware.

8. Power Quality Considerations

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. 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 [103-112].

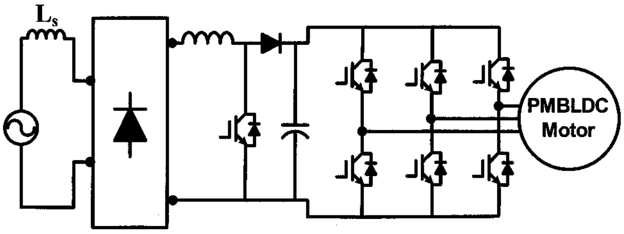
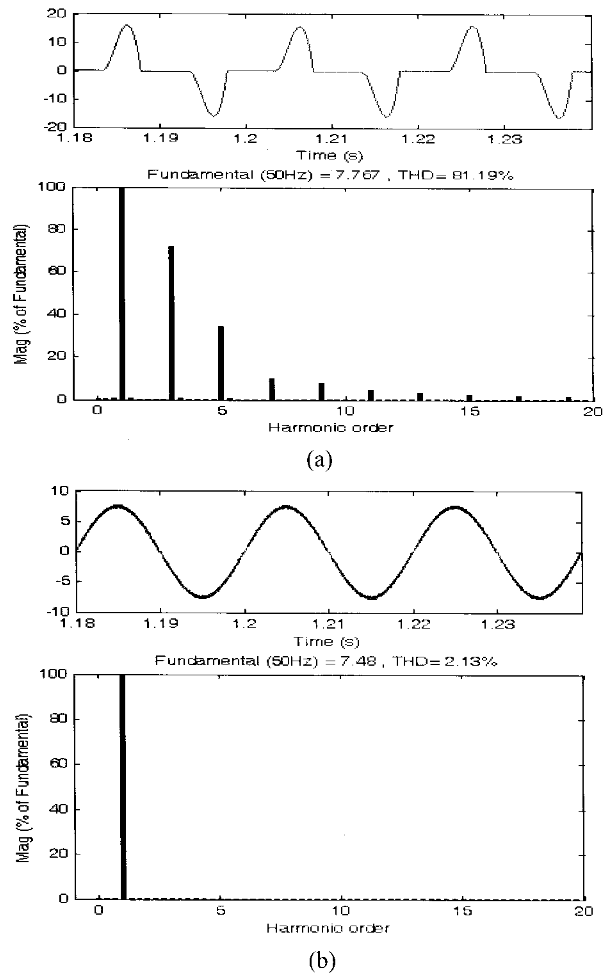


Fig. 12 Boost converter based PFC topology [94,99]

Despite increased awareness about power quality improvements, in general, the topologies for power quality improvement in PMBLDC motors have been reported less frequently in the literature [91, 94-95, 99, 104-106, 112]. 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 at input mains of PMBLDCM drive. Conventional six switch converters have been reported [94-95, 99, 106] with various PFC converters. A six switch single phase to three phase converter has been reported [91, 94, 102] which draws sinusoidal input current at close to unity power factor. Some of these topologies are designed and modeled for a PMBLDC Motor of 1.5 kW (data is given in Appendix) in the MATLAB/Simulink environment.



(a)

(b)

Fig. 13 The source current (i_s) 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)

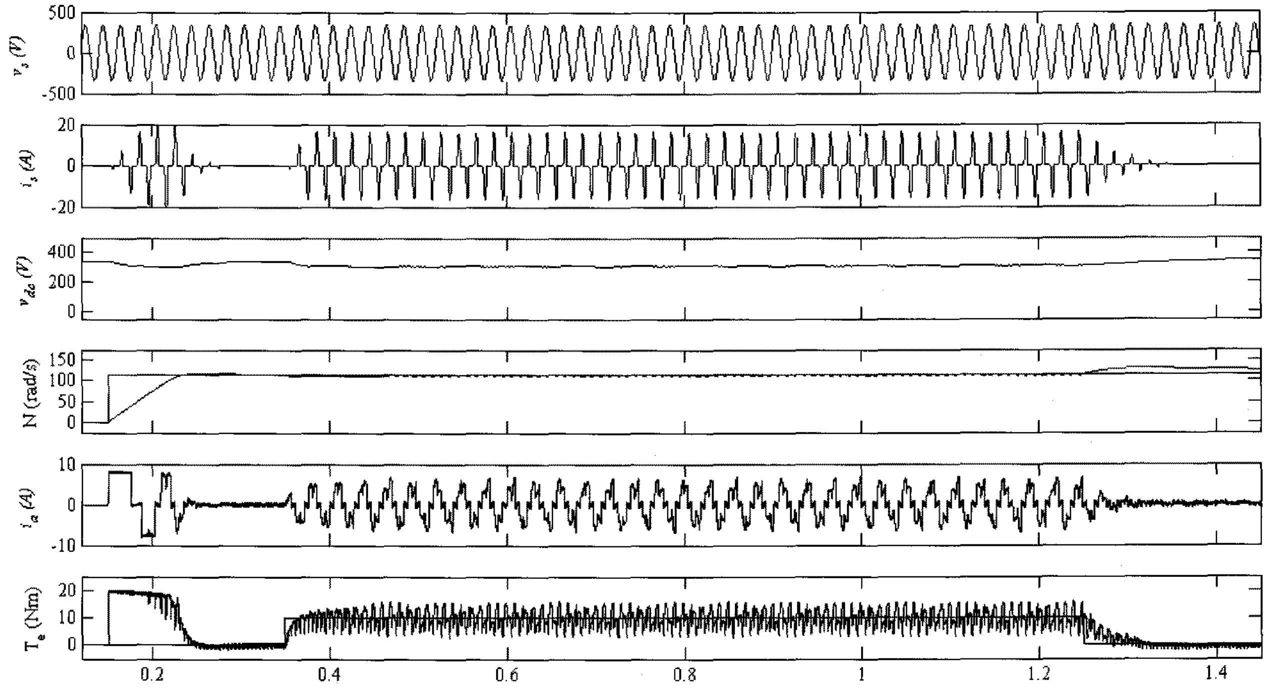
Fig. 13 shows the supply currents and harmonic spectra of the conventional PWM VSI fed PMBLDC motor drive with and without PFC converter. The harmonic spectra shows 81.19% THD in the AC mains current at rated torque with a crest factor (CF) of 2.95 for conventional VSI. The THD of AC mains current is reduced to 2.13% with the boost PFC topology with a crest factor of 1.45 at same load on the motor.

Fig. 14 shows the variation of source voltage (v_s), source current (i_s), DC link voltage (v_{dc}), speed (N), motor phase current (i_a) and torque (T_e) for conventional VSI based topology fed PMBLDCM drives with and without PFC during starting and load perturbation (i.e. load application and load removal). 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. Other attempts [107-111] have been reported on various wave shaping techniques, which can be used with PMBLDC motor drives after careful analysis and evaluation.

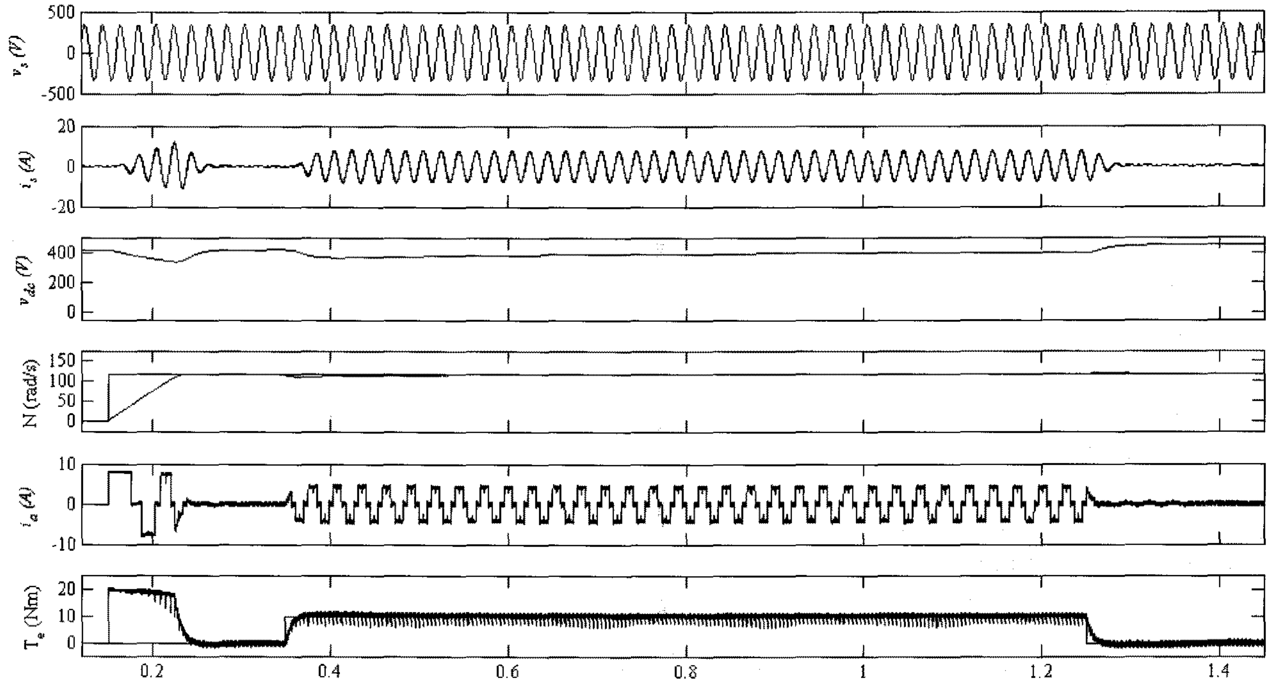
9. Future Trends

In spite of being a most promising machine, PMBLDC motors have faced many hurdles in order to come to their present stage in terms of cost, torque ripple, noise, vibration, reliability, operational constraints such as temperature rise etc. Numerous applications of PMBLDC motors have been discussed with emphasis on low cost topologies and sensorless techniques. The applications of PMBLDC motors, as reported in the literature [1-16, 101-123], are mostly in EVs/HEVs, some household and commercial appliances and very few industrial drives. However these motors may be employed in a number of such applications, if cost reduction with sensorless operation is possible. The power quality improvement at AC mains adds to the benefits of the drive in many applications. Investigations are being made in the direction of controller cost reduction using various topologies with and without position/speed sensors.

Many additional applications of PMBLDCMs may be explored in ceiling and pedestal fans, domestic juicers, mixers and grinders, industrial and domestic pumps, dryers and many more small appliances.



(a) Conventional VSI topology (Fig. 4)



(b) Conventional VSI based boost PFC topology (Fig.12)

Fig. 14 Variation of source voltage (v_s), source current (i_s), dc link voltage (v_{dc}), speed (N), motor phase current (i_a) and torque (T$_e$) for PMBLDCM drive during starting (0.15 sec.), load application (0.35 sec) and load removal (1.25 sec.)

Moreover, PMBLDCM drives can be employed for people carriers in airport lobbies, golf carts, freezers, automobiles, hand tools, and small-process drives with precise control for packaging, bottling, food processing and other similar applications. However, in most of these applications, the role of controller and operating conditions are different, therefore, the controller design for a particular application plays a major role in the performance and efficiency of the drive. The cost of the controller and complexity of control become the key factor for the commercialization of these drives. Hence the acceptability of PMBLDC motors in a variety of applications solely depends upon the research in the area of simplified and low cost controller design. Therefore, general or application specific controller topologies have to be designed for PMBLDC motors with prime consideration of simple and low cost controllers having improved power quality at the input mains of the drive.

The future research in PMBLDCM drives is expected to focus on sensorless starting, reduction of motor cost, controller cost reduction, comprehensive sensorless control, application specific controller design, improved PQ controllers, reduced cost controllers with PFC features. With the above objectives of PMBLDCM drives, the economic viability and performance of PMBLDC motors in a wide range of applications is expected to grow in the future.

10. Conclusions

An exhaustive overview of PMBLDCM drives has been presented to provide a clear perspective on various aspects of these drives to the researchers and engineers working in this field. The PMBLDCM drives are suitable for many applications; however, the choice of the motor (i.e. rotor configuration), control scheme (i.e. sensorless or with sensors) and controller topology depends on the accuracy, cost, complexity and reliability of the system. ASICs are one step in the direction of low cost controllers and many more such ICs with cost effective solutions will be developed in the near future. A customer can select a PMBLDCM drive with their desired features, however, there is a tradeoff between the number of parameters (e.g. sensorless or with sensors, accuracy, complexity, reliability and cost of controller). It is hoped that this investigation on PMBLDCM drives will be a useful reference for users and manufacturers.

Appendix

Motor data:

Rated Power: 1.5 kW, Rated Voltage: 400 V, Rated Speed: 1500 rpm, Rated Current: 4.0 A, Rated torque: 10 Nm, No of poles: 4, Resistance: 2.8 ohm/ph., Inductance (L_s+M): 0.00521 H/ph., back EMF constant : 1.23 Vsec/rad, Moment of Inertia = 0.013 Kg-m^2. The Circuit Parameters used for simulations: Source impedance: 0.03 pu, DC link capacitance: 1100 μF, dc link inductance for PFC: 5 mH, The switching frequency of boost switch = 20 kHz.

References

[1] T. Kenjo and S. Nagamori, *Permanent Magnet Brushless DC Motors*, Clarendon Press, oxford, 1985.

[2] J. M. D. Murphy and F. G. Turnbull, "Power Electronic Control of AC Motors", Pergamon Press, Oxford, 1988.

[3] G. K. Dubey, "Power Semiconductor Controlled Drives", Prentice Hall, New Jersey, 1989.

[4] T. J. E. Miller, *Brushless Permanent Magnet and Reluctance Motor Drive*, Clarendon Press, oxford, 1989.

[5] T. J. Sokira and W. Jaffe, *Brushless DC Motors: Electronic Commutation and Control*, Tab Books USA, 1989.

[6] Y. Dote and S. Kinoshita, *Brushless Servomotors - Fundamentals and Applications*, Clarendon Press, oxford, 1990.

[7] Y. Dote, *Servo Motor and Motion Control using Digital Signal Processors*, Prentice Hall, Englewood Cliffs, New Jersey, 1990.

[8] J. R. Hendershort Jr and T. J. E. Miller, *Design of Brushless Permanent-Magnet Motors*, Clarendon Press, Oxford, 1994.

[9] D. C. Hanselman, *Brushless Permanent Magnet Motor Design*, McGraw hill, New York, 1994.

[10] B. K Bose, *Power Electronics and Variable Frequency Drives, Technology and Applications*, IEEE Press, 1997.

[11] C. M. Ong, *Dynamic Simulation of Electric Machinery using MATLAB / SIMULINK*, Prentice Hall USA, 1998.

[12] I. Bolden and S. A. Nasar, *Electric Drives*, CRC Press, New York, 1998.

[13] R. Krishnan, *Electric Motor Drives: Modeling, Analysis and Control*, Pearson Education, New Delhi, 2001.

[14] J. F. Gieras and M. Wing, *Permanent Magnet Motor Technology – Design and Application*, Marcel Dekker Inc., New York, 2002.

[15] J. F. Gieras, R. J. Wang and M. J. Kamper, *Axial Flux Permanent Magnet Brushless Machines*, Kluwer Academic Publishers, Dordrecht/Boston/London, 2004.

[16] B. Singh, "Recent advances in permanent magnet brushless DC motors", *Sadhana*, Vol. 22, Part 6, pp. 837-853, Dec. 1997.

[17] J. P. Johnson, M. Ehsani and Y. Giizelgiinler, "Review of sensorless methods for brushless DC", in *Proc. IEEE Ind. Appl. Conf.*, Vol. 1, pp. 143-150, 1999.

[18] T. H. Kim, H. W. Lee and M. Ehsani, "State of the art and future trends in position sensorless brushless DC motor/generator drives", in *Proc. IEEE Industrial Electronics Society Conf.*, pp. 1718-1725, 2005.

[19] D. Montesinos, S. Galceran, F. Blaabjerg, A. Sudria and O. Gomis, "Sensorless control of PM synchronous motors and brushless DC motors - an overview and evaluation", in *Proc. European Conf. Power Electronics and Applications*, pp. 1-10, 2005.

[20] P. P. Acarnley and J. F. Watson, "Review of position sensorless operation of brushless permanent magnet machines", *IEEE Trans. Ind. Electron.*, Vol. 53, No. 2, pp. 352-361, April 2006.

[21] B. Singh, B. P. Singh and S. K. Dwivedi, "A state of art on different configurations of permanent magnet brushless machines", *IE (I) Journal – EL*, Vol. 78, pp. 63-73, June 2006.

[22] *ML4425 Sensorless BLDC Motor Controller*, Product Specification, Micro Linear, 2000.

[23] *ML4425 Sensorless BLDC Motor Controller*, Product Specification, Fairchild Semiconductor, 2001.

[24] C. L. Puttaswamy, "Analysis, Design and Control of Permanent magnet Brushless Motors," PhD. Thesis, IIT Delhi, 1996.

[25] S Anantha, "Dedicated Controller for Permanent Magnet Brushless DC Motor Drive" M.Tech. Thesis, IIT Delhi, 1997.

[26] Sunita Singh, "DSP based Permanent Magnet Brushless Motor Drive", M.Tech. Thesis, IIT Delhi, 1998.

[27] Kavita Jain, "Implementation DSP based Digital Speed controller for Permanent Magnet Brushless DC Motor", M.Tech. Thesis, IIT Delhi, 1999.

[28] J. Shao, "Direct back EMF detection method for sensorless brushless DC (BLDC) motor drives", Diploma Thesis, Virginia Polytechnic Institute and the State Univ., 2003.

[29] M. Kumar, "Analysis and Control of Permanent Magnet Brushless Motor Drives", PhD. Thesis, IIT Delhi, 2005.

[30] S. K. Dwivedi, "Power Quality Improvements and Sensor Reductions in Permanent Magnet Synchronous Drives", PhD. Thesis, IIT Delhi, 2006.

[31] H. T. Kawaji and M. R. White, "Low voltage start up circuit for brushless DC motors", U.S. Patent 6741049 B2, May 25, 2004.

[32] X. Junnan and M. Konno, "Brushless direct current monophase motor drive circuit", U.S. Patent 6933688 B2, Aug. 23, 2005.

[33] X. Junnan, M. Konno and S. Yamamoto, "Drive circuit for brushless DC fan motor", U.S. Patent 7091681 B2, Aug. 15, 2006.

[34] J. X. Lee, "Brushless dc fan motor driving circuit", U.S. Patent 7177124 B2, Feb. 13, 2007.

[35] J. L. Lassen, "Sensorless control of two phase brushless dc motor", U.S. Patent 7183734 B2, Feb. 27, 2007.

[36] C. C. Chan, "Axial field electrical machines –design and applications", IEEE *Trans. Energy Conv.*, Vol. 2, No. 2, pp. 294 -300, June 1987.

[37] M. M. Elmissiry and S. Chari, "Performance of toroidal stator, axial flux brushless DC motor under dynamic conditions of operation", in *Proc. IEE ICEMD'93*, pp. 612-618, 1993.

[38] F. Caricchi, F. Crescimbini, E. Fedeli and G. Noioa, "Design and construction of a wheel-directly-coupled axial-flux PM motor prototype for Evs", in *Proc. IEEE-IAS Conf.*, pp. 254-261, 1994.

[39] D. Patterson and R. Spee, "The design and development of an axial flux permanent magnet brushless DC motor for wheel drive in a solar powered vehicle", *IEEE Trans. Ind. Appl.*, Vol. 31, No. 5, pp. 1054-1060, Sep., 1995.

[40] F. Caricchi, F. Crescimbini and A.D. Napoli, "Prototype of innovative wheel direct drive with water-cooled axial-flux PM motor for electric vehicle applications", in *Proc IEEE APEC*, pp. 764 –770, 1996.

[41] F. Caricchi, F Crescimbini, F. Mezzetti and E. Santini, "Multistage axial flux PM machine for direct wheel drive", *IEEE Trans. Ind. Appl.*, Vol. 32, No. 4, pp. 882-888, July 1996.

[42] L. Soderlund, A. Koski, H. Vihriala, J.T. Eriksson and R.Perala, "Design of an axial flux permanent magnet wind power generator", in *Proc. IEE ICEMD*, pp. 224 -228, 1997.

[43] F. Profumo, Z. Zhang and A. Tenconi, "Axial flux machines drives: A new viable solution for electric cars", *IEEE Trans. Ind. Electron.*, Vol. 44, No. 1, pp. 39-45, Feb. 1997.

[44] F. Caricchi, F. Crescimbini and O. Honorati, "Low cost compact permanent magnet machine for adjustable speed pump application", *IEEE Trans. Ind. Appl.*, Vol. 34, No. 1, pp. 109-116, Jan./Feb.1998.

[45] E. Muljadi, C. P. Butterfield and W. Yih-Huie, "Axial-flux modular permanent-magnet generator with a toroidal winding for wind-turbine applications", *IEEE Trans. Ind. Appl.*, Vol. 35, No. 4, pp. 831 -836, July 1999.

[46] F. Caricchi, F.Crescimbini and O. Honorati, "Modular, axial-flux, permanent-magnet motor for ship propulsion drives", *IEEE Trans. Energy Conv.*, Vol. 14, No. 3, pp. 673 -679, Sep. 1999.

[47] F. Profumo, F. J. Eastham, A. Tenconi, and G. Gianolio, "Plastic electric motors: a viable solution for axial flux machines", in *Proc. IEEE International Sympo. Ind. Electron.*, Vol. 1, pp. 1-10, 2002.

[48] O. Ronghai, M. Aydin and T. A. Lipo, "Performance comparison of dual-rotor radial-flux and axial-flux permanent-magnet BLDC machines", in *Proc. IEEE IEMDC*, pp.1948-1954, 2003.

[49] N. Matsui, "Sensorless PM brushless DC motor drive", *IEEE Trans. Ind. Electron.*, Vol. 43, No. 2, pp. 300-308, April 1996.

[50] T. Takeshita and N. Matsui, "Sensorless control and initial position estimation of salient-pole brushless DC motor", in *Proc. International Workshop Advanced Motion Control*, Vol. 1, pp. 18-23, 1996.

[51] J. P. Johnson and M. Ehsani "Sensorless brushless DC control using a current waveform anomaly", in *Proc. IEEE IAS Conf.*, Vol. 1, pp.151-158, 1999.

[52] Z. Chen, M. Tomita, S. Doki and S. Okuma, "New adaptive sliding observers for position-and velocity-sensorless controls of brushless DC motors", *IEEE Trans. Ind. Electron.*, Vol. 47, No. 3, pp.582-591, June 2000.

[53] D. H. Jung and I. J. Ha, "Low-cost sensorless control of brushless DC motors using a frequency-independent phase shifter", *IEEE Trans. Power Electron.*, Vol. 15, No. 4, pp. 744-752, July 2000.

[54] S. Shan, L. Quingfu, X. Wie, and W. Xinghua, "A novel starting method for the sensorless salient-pole brushless DC motor", in *Proc. ICEMS*, Vol. 2, pp. 895-897, 2001.

[55] G. H. Jang, J. H. Park and J. H. Chang, "Position detection and start-up algorithm of a rotor in a sensorless BLDC motor utilising inductance variation", *IEE Proc –Elec. Power Appl*, Vol. 149, No. 2, pp. 137-142, March 2002.

[56] S.G. Han and A.C Renfrew, "Sensorless torque vector speed control of a brushless DC motor", in *Proc. IEEE Conf. Power Electron., Machines and Drives*, pp.510-514, 2002.

[57] K. H. Kim and M. J. Youn, "Performance comparison of PWM inverter and variable DC link inverter schemes for high-speed sensorless control of BLDC motor", *Electronics Letters*, Vol. 38, No. 21, pp. 1194-1295, Oct. 2002.

[58] T. H. Kim, B. K. Lee and M. Ehsani, "Sensorless control of the BLDC motors from near zero to high speed", in *Proc. IEEE Applied Power Electronics Conf. and Expo.*, Vol. 1, pp. 306-312, 2003.

[59] J. X. Shen, Z. Q. Zhu and D. Howe, "Sensorless flux-weakening control of permanent magnet brushless machines using third-harmonic back-EMF", in *Proc. IEEE IEMDC*, Vol. 2, pp.1229-1235, 2003.

[60] J. H. Jang, S. K. Sul and Y. C. Son "Current measurement issues in sensorless control algorithm using high frequency signal injection method", in *Proc. IEEE Ind. Appl. Conf.*, Vol. 2, pp. 1134-1141, 2003.

[61] T. H. Kim and M. Ehsani, "An error analysis of the sensorless position estimation for BLDC motors," in *Proc. of IEEE Industry Applications Conference*, Vol. 1, pp. 611-617, 2003.

[62] M. Tursini, R. Petrella and F. Parasiliti, "Initial rotor position estimation method for PM motors", *IEEE Trans. Ind. Appl.*, Vol. 39, No. 6, pp. 1630-1640, Nov./Dec. 2003.

[63] G. J. Su and J. W. McKeever, "Low-cost sensorless control of brushless DC motors with improved speed range", *IEEE Trans. Power Electron.*, Vol. 19, No. 2, pp. 296-302, March 2004.

[64] Y. S. Lai, F. S. Shyu and Y. H. Chang, "Novel sensorless PWM controlled BLDCM Drives without using position and current sensors, Filter and center tap voltage", in *Proc. IEEE Industrial Electronics Society Conf.*, Vol. 3, pp. 2138-2143, 2003.

[65] Y. S. Lai, F. S. Shyu and Y. H. Chang, "Novel sensorless PWM controlled BLDCM drives without using position and current sensors, Filter and center tap voltage", in *Proc. IEEE Industrial Electronics Society Conf.*, Vol. 3, pp. 2144-2149, 2003.

[66] Y. Amano, T. Tsuji, A. Takahashi, S. Ouchi, K. Hamatsu and M. Iijima, "A sensorless drive system for brushless dc motors using a digital phase-locked loop", *Electrical Engineering in Japan*, Vol. 142, No. 1, pp. 57-66, 2003.

[67] K. Y. Cheng and Y. Y. Tzou, "Design of a sensorless commutation IC for BLDC motors", IEEE *Trans. Power Electron.*, Vol. 18, No. 6, pp. 1365-1375, Nov. 2003.

[68] W. J. Lee and S. K. Sul, "A New Starting Method of BLDC Motors without Position Sensor", in *Proc. IEEE Industry Applications Conference,* Vol. 4, pp. 2397-2402, 2004.

[69] T. H. Kim and M. Ehsani, "Sensorless control of the BLDC motors from near-zero to high speeds", *IEEE Trans. Power Electron.*, Vol. 19, No. 6, pp. 1635-1645, Nov. 2004.

[70] H. W. Lee, T. Kim and M. Ehsani, "Performance improvement of the linear BLDC generator in a deep space explorer", in *Proc. IEEE Industrial Electronics Society Conf.*, pp. 2497-2501, 2004.

[71] H. W. Lee, T. Kim and M. Ehsani, "Performance improvement of the linear BLDC generator in a deep space explorer", in *Proc. IEEE Power Electronics Specialists Conf.*, Vol. 4, pp. 2627-2631, 2004.

[72] J. X. Shen, Z. Q. Zhu and D. Howe, "Sensorless flux-weakening control of permanent-magnet brushless machines using third harmonic back EMF", *IEEE Trans. Ind. Appl.*, Vol. 40, No. 6, pp. 1629-1636, Nov./Dec. 2004.

[73] C. G. Kim, J. H. Lee, H. W. Kim and M. J. Youn, "Study on maximum torque generation for sensorless controlled brushless DC motor with trapezoidal back EMF", *IEE Proc.-Electr. Power Appl.,* Vol. 152, No. 2, pp. 277-291, March 2005.

[74] J. Shao and D. Nolan, "Further improvement of direct back EMF detection for sensorless brushless DC (BLDC) motor drives", in *Proc. IEEE Applied Power Electronics Conf. and Expo.*, Vol. 2, pp. 933-937, 2005.

[75] X. Yunxiang, Z. Ping and N. Haiqing, "A study on high frequency signal injection method of aiming at detecting the rotor position of the salient-pole brushless DC motor", in *Proc. International Conf. Electrical Machines and Sys.*, Vol. 3, pp. 2369-2372, 2005.

[76] C. H. Chen and M. Y. Cheng, "A new sensorless control scheme for brushless DC motors without phase shift circuit", in *Proc. IEEE Power Electron. and Drives Sys. Conf.*, pp. 1084-1089, 2005.

[77] H. Qingxin and L. Hui "DSP control system of brushless DC motor without position sensor", in *Proc. IEEE Conf. Electrical Machines and Systems*, Vol. 1, pp. 371-375, 2005.

[78] Y. Kang, S. B. Lee and J. Yoo, "A microcontroller embedded AD converter based low cost sensorless technique for brushless DC motor drives", in *Proc. IEEE Industry Applications Conf.*, Vol. 4, pp. 2176-2181, 2005.

[79] Y. Liu, Z. Q. Zhu and D. Howe, "Instantaneous torque estimation in sensorless direct-torque-controlled brushless DC motors", *IEEE Trans. Ind. Appl.*, Vol. 42, No. 5, pp. 1275-1283, Sep.-Oct., 2006.

[80] B. G. Park, T.S.Kim, J.S. Ryu and D.S. Hyun, "Fuzzy back-EMF observer for improving performance of sensorless brushless DC motor drive", in *Proc. Applied Power Electronics Conf. and Expo.*, pp. 674-678, 2006.

[81] M. Kumar, B. Singh and B.P. Singh, "Reversible permanent magnet brushless dc motor drive without mechanical sensors", *International Journal of Power and Energy Systems*, Vol. 27, No. 4, pp. 346-352, 2007.

[82] R. Krishnan and S. Lee, "PM brushless DC motor drive with a new power-converter topology", *IEEE Trans. Ind. Appl.*, Vol. 33, No. 4, pp. 973-982, Jul./Aug., 1997.

[83] R. Krishnan, "A novel single-switch-per-phase converter topology for four-quadrant pm brushless dc motor drive", *IEEE Trans. Ind. Appl.*, Vol. 33, No. 5, pp. 1154-1161, Sep./Oct., 1997.

[84] F. Blaabjerg, J. K. Pedersen, U. Jaeger and P. Thoegersen "Single current sensor technique in the DC link of three-phase PWM–VS inverters: a review and a novel solution", *IEEE Trans. Ind. Appl.*, Vol. 33, No. 5, pp. 1241-1253, Sep./Oct., 1997.

[85] R. Krishnan and P. Vijayraghavan, "A new power converter topology for PM Brushless dc motor drives", in *Proc. IEEE IECON*, Vol. 2, pp. 709–714, 1998.

[86] F. Blaabjerg, D. O. Neacsu and J. K. Pedersen, "Adaptive SVM to compensate DC-link voltage ripple for four-switch three-phase voltage-source inverters", *IEEE Trans. Power Electron.*, Vol. 14, No. 4, pp.743-752, July 1999.

[87] Bhim Singh, S S Murthy and A H N Reddy, "A Micro controller Based Speed Controller for Permanent Magnet Brushless DC Motor", *IETE Technical Review*, Vol. 17, No. 5, pp. 299-310, Sep.-Oct., 2000.

[88] Bhim Singh, AHN Reddy and S S Murthy, "Hybrid Fuzzy Logic Proportional plus Conventional Integral- Derivative Controller for Permanent Magnet Brushless DC Motor", in *Proc. IEEE ICIT*, pp. 185-191, 2000.

[89] F. L. Luo and H. G. Yeo, "Advanced PM brushless DC motor control & system for electric vehicles", in *Proc. IEEE Industry Applications Conference*, Vol. 2, pp. 1336-1343, 2000.

[90] B. K. Lee and M. Ehsani, "Advanced BLDC motor drive for low cost and high performance propulsion system in electric and hybrid vehicles", in *Proc. IEEE Electric Machines and Drives Conf.*, pp. 246-251, 2001.

[91] B. K. Lee, T. H. Kim and M. Ehsani, "On the feasibility of four-switch three-phase BLDC motor drives for low cost commercial applications: topology and control", in *Proc. IEEE Applied Power Electronics Conf. and Expo.*, Vol. 1, pp. 428-433, 2001.

[92] S. P. Waikar, H. A. Toliyat, A. S. B. Thunya, Z. Zhang and J. C. Moreira, "A novel thyristor-based brushless DC motor drive for low cost applications", in *Proc. IEEE Applied Power Electron. Conf. and Expo.*, Vol. 1, pp. 434-439, 2001.

[93] K. H. Kim and M. J. Youn, "DSP-based high-speed sensorless control for a brushless DC motor using a DC link voltage control", *Electric Power Components and Sys.*, Vol. 30, pp. 889-906, 2002.

[94] S. M. Madani, H. Lei and H. A. Toliyat, "A low-cost four-switch BLDC motor drive with active power factor correction," in *Proc. IEEE Annual Ind. Electron. Soc. Conf.*, Vol. 1, pp. 579-584, 2002.

[95] R. Khopkar, S. M. Madani, M. Hajiaghajani and H. A. Toliyat, "A low-cost BLDC motor drive using buck-boost converter for residential and commercial applications", in *Proc. IEEE International Electric Machines and Drives Conf.*, Vol. 2, pp. 1251-1257, 2003.

[96] Bhim Singh, SS Murthy, BP Singh, M Kumar and S Anantha, "A low Cost Analog Controller for Permanent Magnet Brushless Motor Drive System", *IE(I) Journal-EL*, Vol. 83, pp. 296-301, March 2003.

[97] Bhim Singh, B.P. Singh and K Jain, "Implementation of DSP Based Digital Speed Controller for Permanent Magnet Brushless dc Motor", *IE(I) Journal-EL*, Vol. 84, pp. 16-21, June 2003.

[98] Bhim Singh, AHN Reddy and S S Murthy, "Gain Scheduling Control of Permanent Magnet Brushless DC Motor", *IE(I) Journal-EL*, Vol. 84, pp. 52-62, Sep., 2003.

[99] T. Gopalarathnam and H. A. Toliyat, "A new topology for unipolar brushless dc motor drive with high power factor", *IEEE Trans. Power Electron.*, Vol. 18, No. 6, pp. 1397-1404, Nov. 2003.

[100] C. T. Lin, C. W. Hung and C. W. Liu, "Sensorless control for four-switch three-phase brushless DC motor drives", in *Proc. IEEE Ind. Appl. Conf.*, Vol. 4, pp. 2048-2053, 2006.

[101] A. H. Niasar, H. Moghbeli and A. Vahedi, "A novel sensorless control method for four-switch, brushless dc motor drive without using any 30° phase shifter", in *Proc. IEEE Conf. Elect. Machines and Sys.*, pp. 408-413, 2007.

[102] C. T. Lin, C. W. Hung and C. W. Liu, "Position sensorless control for four-switch three-phase brushless dc motor drives", *IEEE Trans. Power Electron.*, Vol. 23, No. 1, pp. 438-444, Jan., 2008.

[103] P. S. Frederiksen, J. Birk and F. Blaabjerg, "Comparison of two energy optimizing techniques for PM-machines", in *Proc. IECON*, Vol. 1, pp. 32-37, 1994.

[104] A. M. Tuckey and D. J. Patterson, "The design and development of a high power factor current source controller for small appliance brushless DC motors", in *Proc. IEEE APEC*, Vol. 2, pp. 778-781, 1996.

[105] V K Sharma, M A Khan, B Singh and S S Murthy, "Comparison of power quality aspects of switched reluctance and permanent magnet brushless DC motor", in *Proc. IEEE TENCON*, Vol.3, pp. III-300-III-333, 2000.

[106] Bhim Singh, B.P. Singh and M Kumar, "PFC converter fed PMBLDC motor drive for air conditioning", *IE(I) Journal-EL*, Vol. 84, pp. 22-27, June 2003.

[107] B. Singh, SS Murthy, BP Singh and M. Kumar, "Improved power quality converter fed permanent magnet AC motor for air conditioning", *Electric Power System Research*, Vol. 65, No.3, pp 239-245, 2003.

[108] B. Singh, B. P. Singh and S. Dwivedi, "Improved power quality converter fed direct torque controlled permanent magnet synchronous motor drive", in *Proc. IEEE Petroleum and Chemical Ind. Conf.*, pp. 261-266, 2004.

[109] B. Singh, B. P. Singh and S. Dwivedi, "AC-DC boost bridge converter for power quality improvement of vector controlled PMSM drive", in *Proc. NPEC*, pp. 245-254, 2005.

[110] J. W. Kimball, P. T. Krein and Y. Chen, "Hysteresis and delta modulation control of converters using sensorless current mode", *IEEE Trans. Power Electron.*, Vol. 21, No. 4, pp. 1154-1158, July 2006.

[111] B. Singh, B. P. Singh and S. Dwivedi, "Active wave shaping of AC mains current in direct torque controlled permanent magnet synchronous motor drive", *International Journal Energy Tech. and Policy.*, Vol. 4, No. 1/2, pp. 179-204, 2006.

[112] A. Barkley, D. Michaud, E. Santi, A. Monti and D. Patterson, "Single stage brushless DC motor drive with high input power factor for single phase applications", in *Proc. IEEE PESC*, pp. 1-10, 2006.

[113] L. E. Unnewehr, P. Piatkowski and G. Giardini, "A brushless DC motor for vehicular AC/heater applications", in *Proc. IEEE Vehicular Tech. Conf.*, Vol. 26, pp. 8-15, 1976.

[114] G. Amaratunga and P. Mclaren, "Permanent magnet generators for aerospace applications: optimization of power to weight ratio", in *Proc. IEE-ICEM*, pp. 335-339.

[115] R. M. Crowder, "The application and control of brushless DC motors in high power robotic joints", in *Proc. IEE PEVSD*, pp. 253-257, 1988.

[116] C L Putta Swamy, Bhim Singh, B P Singh and S S Murthy, "Experimental Investigations on a Permanent Magnet Brushless DC Motor fed by PV Array for Water Pumping System", in *Proc. IEEE IECEC*, pp. 1663-1668, 1996.

[117] M. Ehsani, K. M. Rahman and H. A. Toliyat, "Propulsion system design of electric and hybrid vehicles", *IEEE Trans. Ind. Electron.*, Vol. 44, No. 1, pp. 19-27, Feb., 1997.

[118] C L Putta Swamy, Bhim Singh, B P Singh and S S Murthy, "Experimental Investigations on a Permanent Magnet Brushless DC Motor Fed by a PV Array for a Water Pumping System", *ASME-Journal of Solar Energy Engineering,* Vol. 122, pp. 129-132, Aug., 2000.

[119] B. K. Lee and M. Ehsani, "Advanced BLDC motor drive for low cost and high performance propulsion system in electric and hybrid vehicles", in *Proc. IEEE Electric Machines and Drives Conf.*, pp. 246-251, 2001.

[120] Z. Wu, J. Wang, J. Ying and J. Zeng, "Sensorless brushless DC motor drive for air-conditioner compressor", in *Proc. Fifth Int. Conf. Electrical Machines and Systems*, Vol. 2, pp. 968-971, 2001.

[121] G. J. Su, J. W. McKeever and K. S. Samons "Modular PM motor drives for automotive traction applications", in *Proc. IECON*, Vol. 1, pp. 119-124, 2001.

[122] R. J. Hill-Cottingham, P. C. Coles, J. F. Eastham, F. Profumo, A. Tenconi and G. Gianolio, "Novel axial flux machine for aircraft propeller drive: design and modeling", *IEEE Trans. Magnetics.*, Vol. 38, No. 5, pp. 3003-3005, Sep., 2002.

[123] A. Lelkes, J. Krotsch and R. W. De-Doncke, "Low-noise external rotor BLDC motor for fan applications", in *Proc. IEEE Annual IAS Conf.*, Vol. 3, pp. 2036-2042, 2002.

[124] J. W. Ahn, H. S. Song and D. H. Lee "Brushless DC motor drive for tread mill application", in *Proc. IEEE Electric Machines and Drives Conf.*, Vol. 1, pp. 360-364, 2003.

[125] J. Shao, D. Nolan, M. Teissier and D. Swanson, "A novel microcontroller-based sensorless brushless DC (BLDC) motor drive for automotive fuel pumps", *IEEE Trans. on Ind. Appl.*, Vol. 39, No. 6, pp. 1734-1740, Nov./Dec. 2003.

[126] D. Jones, "A new buried magnet brushless PM motor for a traction application", in *Proc. Electrical Insulation Conf. and Electrical Manufacturing and Coil Winding Technology Conf.*, pp. 421-429, 2003.

[127] K. Y. Cho, S. B. Yang and C. H. Hong, "Sensorless control of a PM synchronous motor for direct drive washer without rotor position sensors", *IEE Proc.-Elect. Power Appl.,* Vol. 151, No. 1, pp. 61-69, Jan. 2004.

[128] P. He, M. H. Jin, L. Yang, R. Wei, Y. W. Liu, H. G. Cai, H. Liu, N. Seitz, J. Butterfass, and G. Hirzinger, "High performance DSP/FPGA controller for implementation of HIT/DLR dexterous robot hand", in *Proc. IEEE Robotics & Automation Conf.*, pp. 3397-3402, 2004.

[129] A. Lelkes, and M. Bufe, "BLDC motor for fan application with automatically optimized commutation angle", in *Proc. IEEE PESC*, Vol. 3, pp. 2277-2281, 2004.

[130] J. U. Chu, I. H. Moon, G. W. Choi, J. C. Ryu and M. S. Mun, "Design of BLDC motor controller for electric power wheelchair", in *Proc. IEEE Conf. Mechatronics*, pp. 92-97, 2004.

[131] T. Kosaka, M. Fujitsuna, T. Takahashi and N. Matsui, "Current polarity detection-based simple position sensorless drive of IPMSM for AC compressor in HEV", in *Proc. IEEE Industry Applications Conf.*, pp. 284-291, 2004.

[132] G. Jang and M. G. Kim, "A bipolar-starting and unipolar-running method to drive a hard disk drive spindle motor at high speed with large starting torque", *IEEE Trans. Magnetics*, Vol. 41, No. 2, pp. 750-755, Feb., 2005.

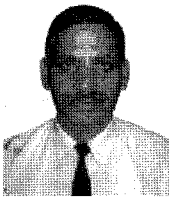
[133] M. Naidu, T. W. Nehl, S. Gopalakrishnan and L. Wurth, "Keeping cool while saving space and money: a semi-integrated, sensorless PM brushless drive for a 42-V automotive HVAC compressor", *IEEE Ind. Appl. Mag.*, Vol. 11, No. 4, pp. 20-28, Jul.-Aug., 2005.

[134] Q. Jiang, C. Bi and S. Lin, "Sensorless control of permanent magnet spindle motors used in hard disk drives", in *Proc. IEEE Conf. Electrical Machines and Sys.*, Vol. 1, pp. 177-182, 2005.

[135] J. Shao, "An improved microcontroller-based sensorless brushless DC (BLDC) motor drive for automotive applications", *IEEE Trans. Ind. Appl.,* Vol. 42, No. 5, pp. 1216-1221, Sep.-Oct., 2006.

[136] D. K. Kim, K. W. Lee, B. T. Kim and B. I. Kwon, "A novel starting method of the SPM-type BLDC motors without position sensor for reciprocating compressor", in *Proc. IEEE Industry Applications Conf.,* Vol. 2, pp. 861-865, 2006.

[137] T. Kim, H. W. Lee, L. Parsa and M. Ehsani, "Optimal power and torque control of a brushless DC (BLDC) motor/generator drive in electric and hybrid electric vehicles", in *Proc. IEEE Industry Applications Conf.*, Vol. 3, pp. 1276-1281, 2006.



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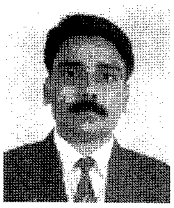

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