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Axial Flux Permanent Magnet BLDC Motor for Electric Vehicles

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***Abstract*— Axial flux permanent magnet (AFPM) brushless direct current (BLDC) motors are an interesting solution, where shape flexibility, compactness, robustness, high efficiency, wide speed range and high torque are required. Different topologies of AFPM BLDC motor are discussed. In most of the applications of AFPM BLDC motors, control over a speed is very important. To achieve accurate speed of a motor, closed loop control using proportional integral (PI) controller is proposed in this paper. Micro controller is used to drive the motor by sensing rotor position using Hall sensor. This paper gives the result of simulation based on AFPM BLDC motor and its various applications.**

Keywords— Axial flux machines, permanent magnet motors, BLDC motors, PI controller

I. INTRODUCTION

Axial flux permanent magnet (AFPM) brushless direct current (BLDC) motors have gained much interest in recent years. The search for more efficient and eco-friendly machines makes this an interesting field of research. Investigations in the field of electrical machines have included a wide variety of matters and concepts. The design, control and thermal aspects are some examples of commonly studied issues. From the first DC machines to the current leading induction machines, there is no doubt that high level of technological development has been achieved. Development of new materials and concepts as well as new needs and applications has placed permanent magnet machines in a prominent position. The inherent features of PMSM, such as high efficiency, high compactness and wide operation speed range, make these machines suitable for direct drive applications. In direct drive applications, the shaft of the machine is directly coupled to the shaft of the application, thus avoiding the gearbox, which leads to more efficient and compact solutions. Furthermore, PM machines have a magnetized motor, so that the consumption of electrical energy is decreased. These machines are able to work at low speed, which is very interesting for direct drive low speed applications; however, high speeds are also reachable, giving the PM machine a wide speed range.

For the past two decades, several Asian countries, which have been under pressure for high pressure for high energy prices, have implemented the use of variable speed permanent magnet motor drives for energy saving applications. On the other hand, the United States has kept on using low cost induction motor drives which have around 10 % lower efficiency than adjustable permanent magnet (PM) motor drives for energy saving applications. Therefore, recently the increase in energy prices spurs higher demand of variable speed PM motor drives. Also recent rapid proliferation of motor drives into the automobile industry, based on hybrid drives, generates a serious demand for high efficiency PM motor drive and this was the beginning of interest in BLDC motor.

II. TOPOLOGIES

Constructional wise BLDC motor can be classified into two types, Radial flux motor and Axial Flux Motor. In radial flux motor the magnetic field travels in a radial direction across the air gap between the stator and rotor. When magnetic flux travels in radial direction and interacts with the current flowing in axial direction, torque is produced.

The motor, in which the magnetic field between the rotor and stator travels in axial direction, is called axial flux motor. When the magnet flux travels in axial direction and interacts with radial current it produces torque. Following are the different types of AFPM BLDC motors,

A. *Single Side*

This is the simplest topology in the axial flux machines range. The stator core may be either slotted or spotless. The axle and the bearings must withstand attraction force, so they have to be properly dimensioned.

B. *Double Side*

Double side machines consist of three elements in two possible configurations, interior rotor is placed between two stators and the interior stator is placed between two rotors.

C. *Multistage*

The connection between the winding of different stages could be done in either series or parallel. Furthermore, a connection/disconnection of stages could be done depending on the temporary requirements of the application.

III. PRINCIPLE OF OPERATION

BLDC motor is an electronically switched motor. It requires information about rotor position to generate appropriate gating signal for its power electronic controller. This is as shown in Fig.1. The commutation is done electrically. To know the position of rotor is very important for electrical commutation. Usually the hall sensors are placed in 120 degree in space. When the magnet poles of rotor come to hall sensor, the signal is generated as in Fig.2.

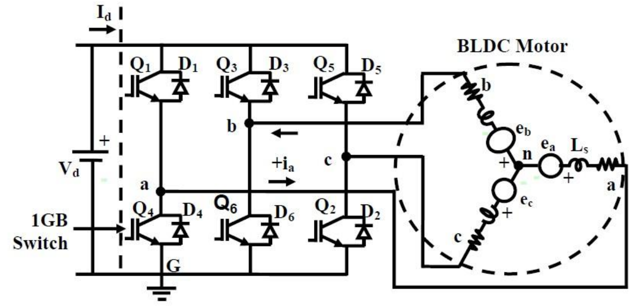

Fig.1. Three-phase Equivalent Circuit of BLDC motor

According to six steps, the commutation sequence is performed. The motor phases are supposed to conduct for 120 electrical degrees one time per cycle. The two phases are only conducted at one time. The hall sensor signal has the rising edge and the falling edge for each phase. That is, the six trigger signals are generated per cycle. Using these trigger signals, motor control is carried out.

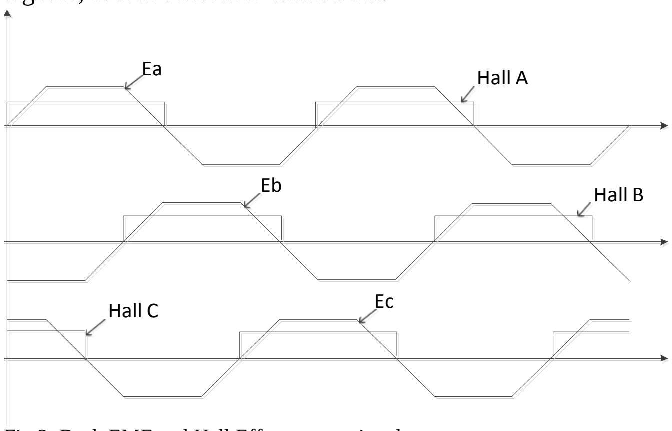

Fig.2. Back EMF and Hall Effect sensor signal

IV. PROPOSED CLOSED LOOP CONTROLING TECHNIQUE

Many applications, such as robotics and factory automation, require precise control of speed and position. Speed control systems allow one to easily set and adjust the speed of a motor. The control system consists of a speed feedback system, a motor, an inverter, a controller and a speed setting device. A properly designed feedback controller makes the system insensible to disturbance and changes of the parameters. In closed loop control the speed of BLDC motor can be controlled using proportional integral (PI) controller, PI controller can regulate the duty cycle hence control the voltage applied to BLDC motor. Speed of BLDC motor is directly proportional to applied voltage. Speed of BLDC motor can be set to reference speed. Any diversion from this speed will be given as an error signal to PI controller. PI controller will take appropriate signal on receiving of this error signal and then increase as well as decrease the duty cycle of applied gate signal.

The purpose of a motor speed controller is to take a signal representing the demanded speed and to drive a motor at that speed. Closed loop speed control systems have fast response, but become expensive due to the need of feedback components such as speed sensors. A Hall sensor can also used as a speed sensing device [6]. Speed controller calculates the difference between the reference speed and the actual speed producing an error, which is fed to the PI controller. PI controllers are used widely for motion control systems. They consist of a proportional gain that produces an output proportional to the input error and an integral gain to make the steady state error zero for a step change in the input.

V. PROPOSED SCHEME

Proposed scheme shows that single phase AC supply is converted into DC supply using single phase controlled bridge rectifier. To have a commutation action, three phase bridge inverter is used. DC power from rectifier is supplied to the three phase bridge inverter. Three phase AC supply from inverter is then fed to the AF BLDC motor.

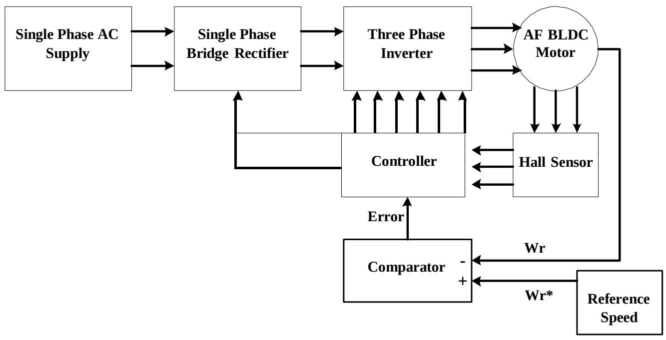

Fig.3. Proposed scheme for closed loop control of AF BLDC motor

Hall sensors detect the rotor position and provide position signal to the controller which energies the appropriate winding of the three phases motor and motor starts running at Wr speed. To have a closed loop control, a reference speed Wr* is fixed at particular value. This value is compared with the actual speed with comparator. Error signal generated by comparator is then given to the controller which takes corrective action and gives the triggering pulses to the rectifier circuit.

VI. PERFORMANCE OF MOTOR

Transient period for any machine should be less to have a better transient performance. AF BLDC motor has low inertia, that's why it has more transient stability. To study the performance of AF BLDC motor, simulation is carried out for different operating conditions. Fig.4 gives the speed characteristic of reference speed Wr* and actual rotor speed Wr with respect to time. The reference speed Wr is set for three thousand rpm. The motor comes to the steady state condition by achieving reference speed near 0.1 second.

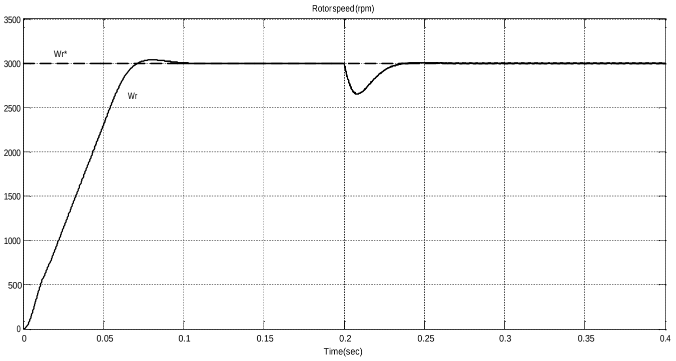

Fig.4. Comparison of reference speed and actual speed

A mechanical load of 7 Nm is connected to the motor at 0.2 sec and due to this load there is a drop in speed. For an equilibrium condition, electromagnetic torque should be equal to mechanical motor and acceleration torque will be zero. To achieve equilibrium condition motor will raise its torque to 7 Nm as shown in Fig.5.

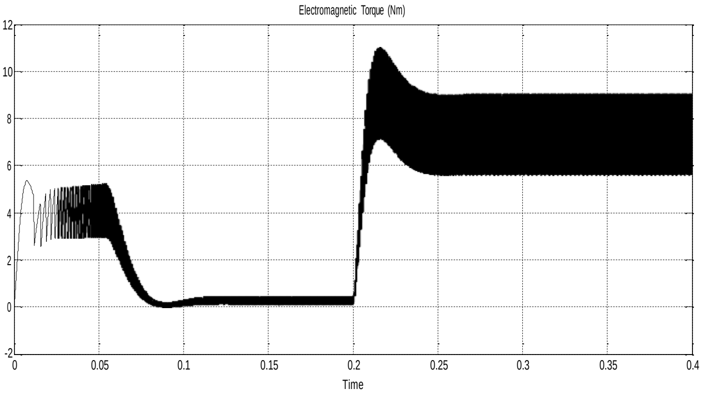

Fig.5. Characteristic of electromagnetic torque of motor

In BLDC motor, back electromotive force (emf) is directly proportional to the speed of the motor. As there is a drop in speed for some certain time, not only the magnitude but also frequency of back electromotive forces (emf) decreases. As seen in Fig.6, there is a decrease in the frequency of back emf near 0.2 second.

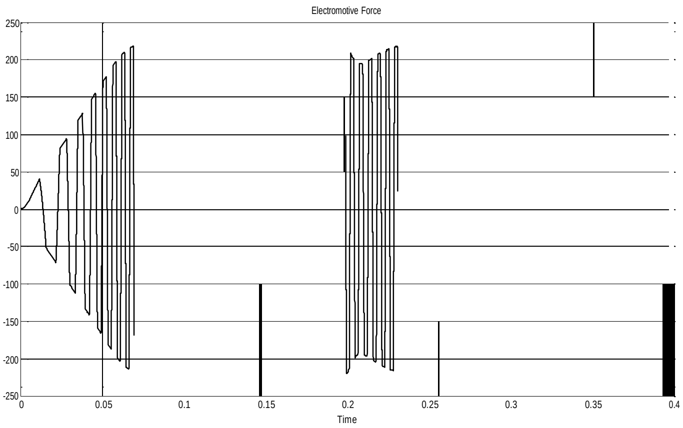

Fig.6. Electromotive force at three thousand rpm speed

Closed loop control will come in action to take care the drop in speed. Error between the actual speed and reference speed is calculated by PI controller and appropriate triggering is given to the six switches to reduce this error. At some particular instant, the error is zero and motor regain its original speed.

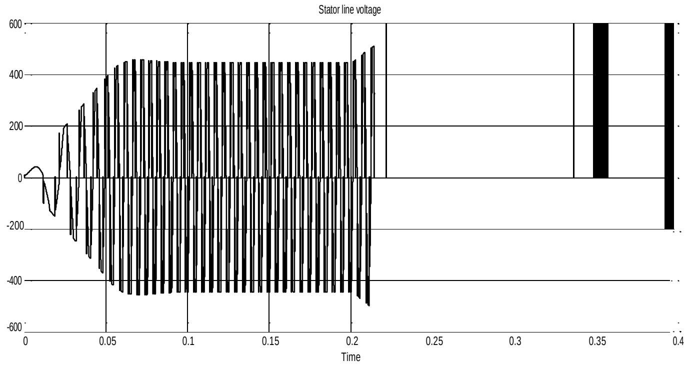

Fig.7. Characteristic of stator line voltage of motor

A characteristic of stator line voltage is shown in above Fig.7. It is clearly seen that after the load is connected to the motor, the stator line voltage is increased. The increased in the stator line voltage is to compensate the error between reference speed and actual speed. The respective stator line current is shown in Fig.8. During transient period, there is a change in stator current and when load is applied to the motor stator current increases to have an electromagnetic torque.

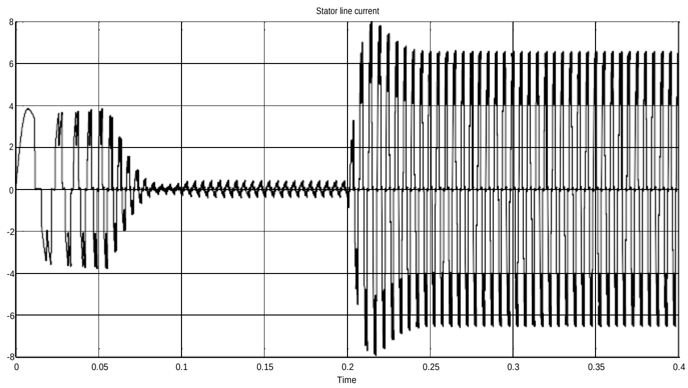

Fig.8. Waveform of stator line current

VII. Applications

Throughout the history, induction machines have been the most frequently used topologies in common industries. However, in recent years, because of ecological thinking and the rise low-speed applications, permanent magnet synchronous machines have become more popular. Furthermore, the development of new applications, such as electrical vehicles and renewable energy has pushed the development of high-performance, direct-drive electrical machines.

AFPM BLDC motors can be a good choice because of their disk shape, multi stage capability, and characteristic high torque density. These features make axial flux machines a real alternative to classical radial flux machines. In that sense, it is possible to find companies that commercialize axial machines. Nowadays the majority of applications share the same requirements: high efficiency, saving of space, and economic feasibility, among other characteristics.

However, three applications may be the most relevant due to the numbers of documents and amount of research a review of the literature reveals in the search for information about axial flux machines: wind power, electric vehicles, blowers and elevation.

A. Electric Vehicles

For electric car propulsion systems, the wheel motor is an application that requires the electrical machine has shape flexibility, compactness, robustness, high efficiency, and high torque. Axial flux machines are an interesting solution, where the motor is directly coupled to, or inside, the drive wheels [2]-[6].

B. Wind Power Systems

For low-speed wind turbine applications, AFPM synchronous generator has been studied and designed in [1]. To get low- cost, low weight and simple manufacture, which are highly desirable characteristics of the design, a slotless machine has been designed in order to exploit at the best the mechanical manufacture work reduction allowed by this configuration. Simulation of the system has been carried out into two conditions: steady state wind flow, variable wind speed with the fluctuation assigned by certification standards for wind turbine application.

C. Blowers

In [4], AFPM BLDC motor is fabricated for blowers in vacuum cleaners. Motor design and velocity control of the self-tuning fuzzy proportional-differential-integral (PID) control and a soft-switching mechanism combined with the sensorless drive method have been demonstrated effectively and successfully for the present slim sensorless AFPM BLDC. The system characteristics of the designed slim sensorless AFPM BLDC motors have been enhanced and satisfied the demand of blowers for applying in vacuum cleaners.

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