SPEED CONTROL OF DC BRUSHLESS MOTOR FED BY SIX STEP INVERTER USING MATLAB

1Asst.Prof. Bishnu Prasad Panda, Dept.of Electrical Engineering
2Asst.Prof. Surabhi Tripathy, Dept. of Electrical Engineering
3Asst Prof. Smrutirekha Maharana, Dept. of Electrical Engineering
4 Student.Mr. Bibek Das, Dept. of Electrical Engineering

ABSTRACT

This project proposed a control scheme of a neural network for the brushless direct current (BLDC) permanent magnet motor drives. Brushless DC motors rely on semiconductor switches to turn stator windings on and off at the appropriate time. The process is called electronic commutation. The behavior of BLDC motor drive is nonlinear, cause it is complex to handle by using conventional proportional-integral (PI) controller. In order to overcome this main problem, artificial neural network controller technique is developed. The neural network control learned continuously and gradually becomes the main effective control. Performances of the proposed neural network are compared with the conventional PI controller. Neural network improves speed response and also reduces torque ripples. The controller is intended to tracks variations of speed references and stabilizes the output speed during load variations. The mathematical model of BLDC motor and neural network algorithm is derived. The effectiveness of the proposed method is established by developing simulation model in MATLAB/ Simulink. The simulation results show that the proposed artificial neural network controller construct substantial improvement of the control performance.

1. INTRODUCTION

Permanent magnet Brushless DC motors are becoming very popular rapidly in industries such as automotive, aerospace, medical, industrial automation equipment and instrumentation because of their high efficiency, high power factor, silent operation, compact form, reliability, and low maintenance. Brushless Direct Current (BLDC) motors comprise several attractive properties such as smooth speed control and torque -speed characteristics. It is a rugged three-phase synchronous motor due to the use of permanent magnet rotor. The commutation in a permanent magnet brushless DC motor is accomplished by solid state switches of a three-phase voltage-source inverter (VSI). A permanent magnet BLDC motor has developed torque proportional to its phase current and its back electromotive force, which is proportional to the speed. Therefore, a constant current in its stator windings with variable voltage across its terminals maintains constant torque in a PMBLDC motor under variable speed operation. A speed control scheme is proposed which uses a reference voltage at dc link proportional to the desired speed of the permanent-magnet brushless direct current motor. However, the control of VSI is only used for electronic commutation based on the rotor position signals of the PMBLDC motor. Moreover, the control of DC motor also simple and does not require complex Hardware. But DC motors have main disadvantages regarding to lifetime of brushes are the limited. A lower reliability occurs caused by the brushes and the operation need time to time maintenance of replacement. The behaviour of BLDC motor drive is nonlinear, cause it is complex to handle by using conventional proportional-integral (PI) controller. In order to overcome this main problem, artificial neural network controller technique is developed. BLDC motors recommend a few advantages such as structure is simple and compact size, robust and highly efficient and reliable performance. BLDC motors also offer additional advantages such as greater speed capabilities and better speed versus torque characteristics. Due to the BLDC operate without brushes its lifetime spent can be increased and maintenance operation can be reduced.

The controller performs the same power distribution found in a brushed DC motor, but using a solid-state circuit rather than a commutator or brush system. In this motor, the mechanical "rotating switch" or commutator or brush gear assembly is replaced by an external electronic switch synchronized to the rotor's position. Brushless motors are typically 85-90% efficient, whereas DC motors with brush gear are typically 75-80% efficient. BLDC motors also have several advantages over brushed DC motors, including higher efficiency and reliability, reduced noise, longer lifetime caused by no brush erosion in it; elimination of ionizing sparks from the commutator, and overall reduction of electromagnetic interference (EMI). With no windings on the rotor, they are not subjected to centrifugal forces, and because the electromagnets are located around the perimeter, the electromagnets can be cooled by conduction to the motor casing, requiring no airflow inside the motor for cooling. This means that the motor's internals can be entirely enclosed and protected from dirt or other foreign matter.

The maximum power that can be applied to a BLDC motor is exceptionally high, limited almost exclusively by heat, which can damage the magnets. BLDC motors are considered to be more efficient than brushed DC motors. This means that for the same input power, a BLDC motor will convert more electrical power into mechanical power than a brushed motor, mostly due to the absence of friction of brushes. The enhanced efficiency is greatest in the no load and low-load region of the motor’s performance curve . Under high mechanical loads, BLDC motors and high quality brushed motors are comparable in efficiency. Brushless DC motors are commonly used where precise speed control is necessary, as in computer disk drives or in video cassette recorders, the spindles within CD, and etc. Brushless dc (BLDC) motors have been desired for small horsepower control motors due to their high efficiency, silent operation, compact form, reliability, and low maintenance. However, the control complexity for variable speed control and the high cost of the electric drive hold back the widespread use of brushless dc motor. Over the last decade, continuing technology development in power semiconductors, microprocessors/logic ICs, adjustable speed drivers (ASDs) control schemes and combined to enable reliable, cost-effective solution for a broad range of adjustable speed applications. Brushless DC motor has a rotor with permanent magnets and a stator with windings. It is essentially a DC motor turned inside out. The brushes and commutator have been laminated and the windings are connected to the control electronics. The control electronics replace the function of the commutator and energize the proper winding. The motor has less inertia, therefore easier to start and stop. BLDC motors are potentially cleaner, faster, more efficient, less noisy and more reliable. The Brushless DC motor is driven by rectangular or trapezoidal voltage strokes coupled with the given rotor position. The voltage strokes must be properly aligned between the phases, so that the angle between the stator flux and the rotor flux is kept close to 90 to get the maximum developed torque. BLDC motors often incorporate either internal or external position sensors to sense the actual rotor position or its position can also be detected without sensors.

2. FUNDAMENTAL CONCEPT OF BLDC MOTOR

Background

Brushless dc (BLDC) motors are preferred as small horsepower control motors due to their high efficiency, silent operation, compact form, reliability, and low maintenance.

However, the problems are encountered in these motor for variable speed operation over last decades continuing technology development in power semiconductors, microprocessors, adjustable speed drivers control schemes and permanent-magnet brushless electric motor production have been combined to enable reliable, cost-effective solution for a broad range of adjustable speed applications.

Household appliances are expected to be one of fastest-growing end-product market for electronic motor drivers over the next five years. The major appliances include clothes washer's room air conditioners, refrigerators, vacuum cleaners, freezers, etc. Household appliance have traditionally relied on historical classic electric motor technologies such as single phase AC induction, including split phase, capacitor-start, capacitor–run types, and universal motor. These classic motors typically are operated at constant-speed directly from main AC power without regarding the efficiency. Consumers now demand for lower energy costs, better performance, reduced acoustic noise, and more convenience features. Those traditional technologies cannot provide the solutions.

General Motor Principles

Motors convert electrical energy into mechanical energy using electromagnetic principles. The energy conversion method is fundamentally the same in all electric motors. This document starts with a general overview of basic electromagnetic physics before entering discussing the details of motor operation.

Left-Hand Rule

Extend the left hand with the thumb and four fingers on the same plane with the thumb pointing out. Face the palm towards the north pole of the external magnetic field and the four fingers in the direction of the current; the thumb points in the direction of the force.

The magnitude of the force can be calculated from the equation below:

$F=BIL\sin\theta$

Where F is the electromagnetic force, B is the magnetic field density, I is the conductor current, L is the length of the conductor, and θ is the angular difference between B and I.

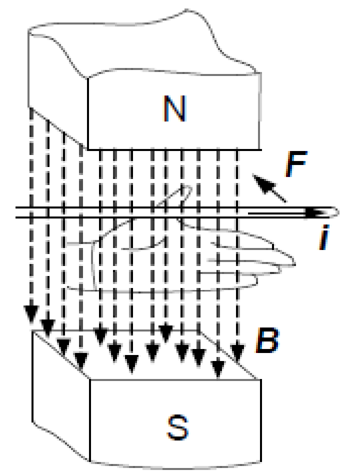

Figure 2.1. Left-hand rule

Structure of BLDC Motor

The stator of a BLDC motor consists of stacked steel laminations with windings placed in the slots that are axially cut along the inner periphery as shown in Figure 2. Traditionally, the stator resembles that of an induction motor; however, the windings are distributed in a different manner. Most BLDC motors have three stator windings connected in star fashion. Each of these windings are constructed with numerous coils interconnected to form a winding. One or more coils are placed in the slots and they are interconnected to make a winding. Each of these windings is distributed over the stator periphery to form an even numbers of poles.

The rotor is made of permanent magnet and can vary from two to eight pole pairs with alternate North (N) and South (S) poles as shown in figure 2. Based on the required magnetic field density in the rotor, the proper magnetic material is chosen to make the rotor. Ferrite magnets are traditionally used to make permanent magnets. As the technology advances, rare earth alloy magnets are gaining popularity. The ferrite magnets are less expensive but they have the disadvantage of low flux density for a given volume. In contrast, the alloy material has high magnetic density per volume and enables the rotor to compress further for the same torque. Also these alloy magnets improve the size-to-weight ratio and give higher torque for the same size motor using ferrite magnets. Neodymium (Nd), Samarium Cobalt (SmCo) and the alloy of Neodymium, Ferrite and Boron (NdFeB) are some examples of rare earth alloy magnets. Continuous research is going on to improve the flux density to compress the rotor further.

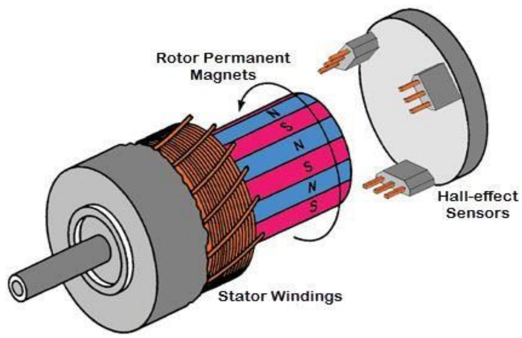

Figure 2.2 Schematic View of BLDC

3. ARTIFICIAL NEURAL NETWORK

Artificial Neural Network Controller

The structure of the proposed neural network control of a BLDC motor is shown in figure 3.1 and figure 3.2 which is based on the number of neurons in each layer of the proposed ANN architecture.

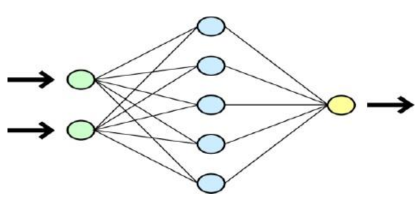

Figure 2.1 Architecture of the proposed ANN controller

Neural network is an interconnected group of nodes like vast network of neurons in the human brain.

It is an efficient method for controlling the speed of brushless dc motor because it can take multiple inputs Simultaneously and gives the computational results quickly.The Block diagram of BLDC motor by artificial neural network controller is shown in the figure 3.2.

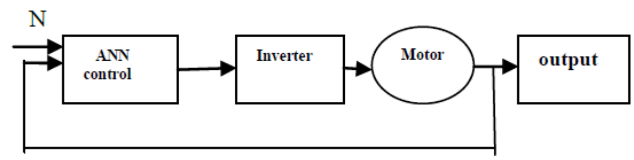

Figure 3.2 Block diagram of BLDC motor by ANN controller

ANN based controller for the BLDC motor drive which requires minimal offline training yet precisely and accurately follows command speed with insensitivity to load and parameter variations. The system is simplified to a single artificial neuron (SAN) to minimize complexity and computational burden requirements. By using sensor less speed measuring system we can find out the Speed error and conditionally used at each iteration to adaptively modify the SAN parameters to produce the precise command torque to minimize speed error. BLDC is widely used because of its high mechanical power density, simplicity and cost effectiveness. A mathematical model of ANNs are mathematical systems consisting of many weighted interconnected operation elements (neurons). A processing element is an equation, which is often termed a transfer function. This processing element receives signals from other neurons; combines and converts them; and produces a numerical result. In general, processing elements roughly correspond to real neurons, they are interconnected via a network and this structure constitutes neural networks.

$$X = \sum_{i=0}^{n} W_i A_i + \theta$$

Equation 1 shows Single Artificial Neuron. The structure of ANNs contains three main elements neurons, the connection providing input and output route, and connection weights indicating the strength of these connections. Typically, the architecture (structure) of an ANN is formed and weight values required to optimize the accuracy of the outputs are determined using one of several mathematical algorithms. The ANNs unravel a relationship between the input variables and estimated variables by determining the weights using previous examples. In other words, ANNs are "trained". Once these relationships are determined (in other words, once the network is trained), an ANN can be operated with new data and estimations can be produced. The performance of a network is measured by the aimed signal and error criterion. The error margin is obtained by the comparison of the output of the network and the aimed output. A back-propagation algorithm is used to adjust the weights in such a way to reduce the error margin. The network is trained by repeating this processing many times. The aim of training is to reach an optimum solution based on performance measurements. ANNs have an extensive range of applications in real life problems. They are currently used successfully in many industries.

3.2 Control Algorithm

Conventionally, proportional integral(PI) and proportional integral derivative (PID) speed controllers have been utilized to meet these control challenges controller has an advantages that it is very simple, inexpensive, have applications in most systems, faster response. But the disadvantages are the set point offset, delay if gain is lower. So this P Controller needs the gain adjustment. Then the PI controller is preferred. And it has an advantages that there is no offset, have applications in many processes.

The disadvantage of this controller are more costly, little complex, slow response, oscillations and overshoot. In PID controller it has no offset, faster, no or very less oscillations, and it has low overshoot. It has disadvantages that it was costly and it is used for limited applications, it is more difficult to configure and tune the functions. FLC (fuzzy logic controllers) based systems typically require extensive initial tuning and may impose significant computational burden. So, here I go with Artificial Neural Network and sensor less speed control of BLDC motor the drive system is developed to analyze the performance of the proposed drive

3.3 PI speed control of the BLDC motor

The PI control drive consists of speed controller, reference current generator, PWM current controller, position sensor, the motor and MOSFET based current controlled voltage source inverter (CC-VSI). The motor speed is compared with its reference value and the speed error is developed in Proportional- integral (PI) speed controller.

$$e(t) = w_{ref} - w_m(t)$$

$w_m(t)$ is compared with reference speed
w_{ref} and resulting error is estimated at the nth sampling instant as

$$T_{ref}(t) = T_{ref}(t-1) + K_p e(t) - e(t-1) + K_I e(t)$$

Where K_p and K_I are the gains of PI controller.
The controller output is considered as the reference torque. A limit is put on the speed controller output depending on permissible maximum winding currents. The reference current generator block generates the three phase reference currents i_a, i_b, i_c using the limited peak current magnitude decided by the controller and the position sensor

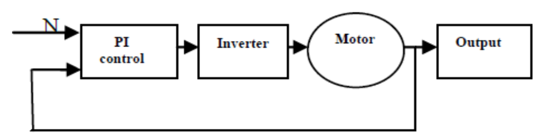

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Figure 3.3. Block diagram of BLDC motor by PI controller

4. OPERATION AND METHODOLOGY

Operational Motor Theory

Motor operation is based on the attraction or repulsion between magnetic poles. Using the three-phase motor shown in Figure 4.1, the process starts when current flows through one of the three stator windings and generates a magnetic pole that attracts the closest permanent magnet of the opposite pole. The rotor will move if the current shifts to an adjacent winding. Sequentially charging each winding will cause the rotor to follow in a rotating field. The torque in this example depends on the current amplitude and the number of turns on the stator windings, the strength and the size of the permanent magnets, the air gap between the rotor and the windings, and the length of the rotating arm.

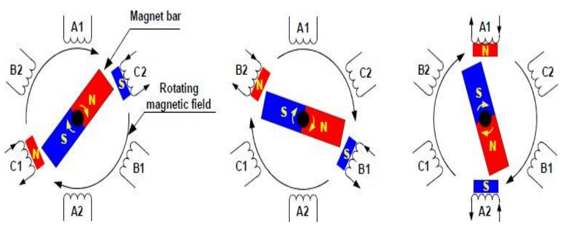

Figure 4.1 Rotor rotation

Electronic Commutation

The process of continually switching current to different motor coils to produce torque on the rotor is called *commutation.*

Brushless motors rely on semiconductor switches to turn stator windings on and off at the appropriate time. The process is called electronic commutation that switches current from winding to winding, forcing the rotor to turn. The rotor in a typical brushless motor incorporates a four-pole permanent magnet and a smaller "sensor" magnet. The stator on the other hand consists of a three-phase Y-connected winding and three Hall-effect sensors. The sensor magnet turns the Hall Effect sensors "on" and "off," indicating the position of the shaft. With this information the controller is able to switch current to each winding at the optimum timing point. The brushless dc motor drive system is shown in the figure 4.1.

Methodology

Figure 4.2 shows block diagram of Sensor less speed control of BLDC motor. DC input is given to the inverter. This will generates three phase output which can be fed to the BLDC motor. PWM generator generates controlled gate pulse from the Back Emf of the motor. Then the controlled voltage can be generates by using ANN controller by comparing actual speed and reference speed. BLDC motors are a type of synchronous motor. This means the magnetic field generated by the stator and the magnetic field generated by the rotor rotates at the same frequency. BLDC motors do not experience the "slip" that is normally seen in induction motors. BLDC motors come in single-phase, 2-phase and 3-phase configurations. Corresponding to its type, the stator has the same number of windings. Out of these, 3-phase motors are the most popular and widely used. This application note focuses on 3-phase motors.

Stator

The stator of a BLDC motor consists of stacked steel laminations with windings placed in the slots that are axially cut along the inner periphery. Traditionally, the stator resembles that of an induction motor; however, the windings are distributed in a different manner. Most BLDC motors have three stator windings connected in star fashion. Each of these windings are constructed with numerous coils interconnected to form a winding. One or more coils are placed in the slots and they are interconnected to make a winding. Each of these windings are distributed over the stator periphery to form an even number of poles.

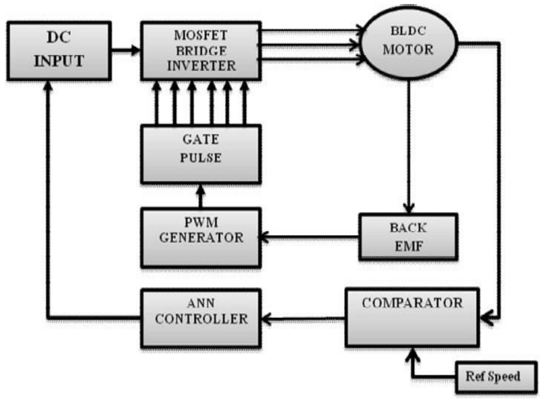

Figure 4.2 Block Diagram of Speed Control of BLDC motor

There are two types of stator windings variants: trapezoidal and sinusoidal motors. This differentiation is made on the basis of the interconnection of coils in the stator windings to give the different types of back Electromotive Force (EMF). As their names indicate, the trapezoidal motor gives a back EMF in trapezoidal fashion and the sinusoidal motor's back EMF is sinusoidal, as shown in Figure 8 and 9. In addition to the back EMF, the phase current also has trapezoidal and sinusoidal variations in the respective types of motor. This makes the torque output by a sinusoidal motor smoother than that of a trapezoidal motor. However, this comes with an extra cost, as the sinusoidal motors take extra winding interconnections because of the coils distribution on the stator periphery, thereby increasing the copper intake by the stator windings.

Rotor

The rotor is made of permanent magnet and can vary from two to eight pole pairs with alternate North (N) and South (S) poles. Based on the required magnetic field density in the rotor, the proper magnetic material is chosen to make the rotor. Ferrite magnets are traditionally used to make permanent magnets. As the technology advances, rare earth alloy magnets are gaining popularity.

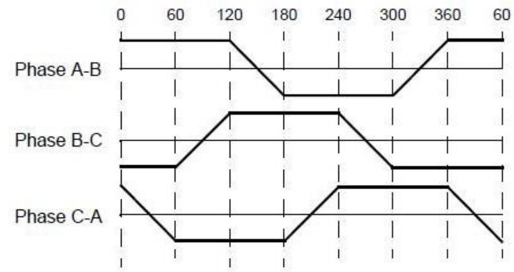

Figure 4.3 Trapezoidal back emf

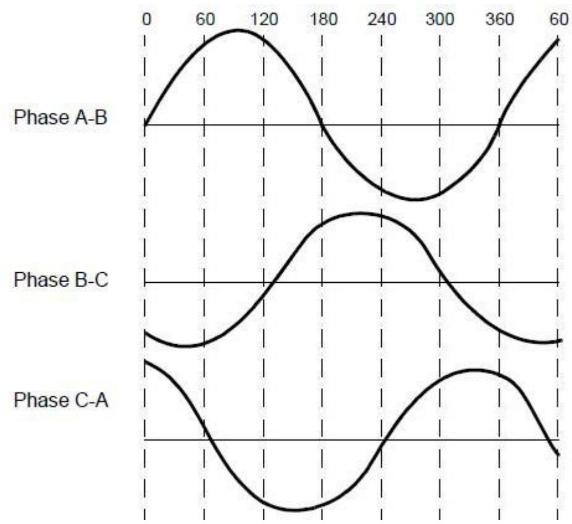

Figure 4.4 Sinusoidal back EMF

5. ADVANTAGE AND DISADVANTAGE

Advantages

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

- Less maintenance because there are no brushes
- High efficiency
- Long operating life
- Low friction loss since there are no brushes
- Noiseless operation
- Higher speed ranges
- Smaller and lighter

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

Disadvantages

There are some disadvantages of brushless dc motor. They are

- The need for a shaft position sensing device or some indirect rotor position sensing device and an electronic controller, both of which are essential, add to the cost.
- Increased complexity due to the electronic controller.
- With some types of permanent magnets there are severe temperature limits since the magnetic properties deteriorate with rise in temperature.
- Lack of simple method of field weakening for increasing the speed.
- High cost of magnets, particularly for large size machines.

6. APPLICATIONS

The applications of brushless are

- Compressor (air conditioner, refrigerator)
- Appliances (refrigerator, vacuum cleaner, food processor)
- Brushless DC motors are widely used as servomotors
- computer hard drives and CD/DVD players
- Industrial fan
- In manufacturing, brushless motors are primarily used for motion control, positioning or actuation systems
- The Segway Scooter and Vectrix MaxiScooter use brushless motors
- Automotive (fuel and water pumps, cooling fan, climate control)
- Brushless motors have been legal in North American radio controlled car racing
- Brushless motors are a popular motor choice for model aircraft including helicopters.

7. SIMULATION MODEL

Circuit Explanation

Figure 7.1 shows circuit diagram of Speed control of BLDC Motor. It shows when the dc input voltage is given to the MOSFET controlled switches it will generated three phase output and it will given to the BLDC motor. Back Emf will be generated in the motor. This will be taken as an advantage for such operation for generating controlled gate pulse from the PWM generator. Then the Speed can be sensed and it can be fed to ANN controller. This will found error signal and corrected then the output of the controller is given to input voltage. Drive parameters can be measured using simulation diagram. The sensor less drive is based on the detection of the Back Electro Magnetic Force (BEMF) induced by the movement of a permanent magnet rotor in front of stator winding. This method also requires the use of a trapezoidal signal in order to have a zero crossing of the BEMF. For a given fixed motor design (number of stator winding turns, mechanical rotor characteristics and rotor magnet characteristics) the BEMF Amplitude is proportional to the rotor speed. The sensor less method uses the zero crossing of BEMF to synchronize phase commutations. To detect BEMF the specific 120° six-step drive is used. "120° sixstep drive" forces zero current twice in each phase during a six step period. This allows BEMF zero crossing to be detected and read.

Back Emf=NlrB..(2)

Where, N = number of windings per phase

l = length of the rotor

r = internal radius of the rotor

B = rotor magnetic field

ω = angular velocity

Because the controller must direct the rotor rotation, the controller requires some means of determining the rotor's orientation/position (relative to the stator coils.) Some designs use Hall Effect sensors or a rotary encoder to directly measure the rotor's position. Others measure the back EMF in the undriven coils to infer the rotor position, eliminating the need for separate Hall Effect sensors, and therefore are often called sensor less controllers. Controllers that sense rotor position based on back-EMF have extra challenges in initiating motion because no back-EMF is produced when the rotor is stationary. This is usually accomplished by beginning rotation from an arbitrary phase, and then skipping to the correct phase if it is found to be wrong. This can cause the motor to run briefly backwards, adding even more complexity to the startup sequence. Other sensors less controllers are capable of measuring winding saturation caused by the position of the magnets to infer the rotor position.

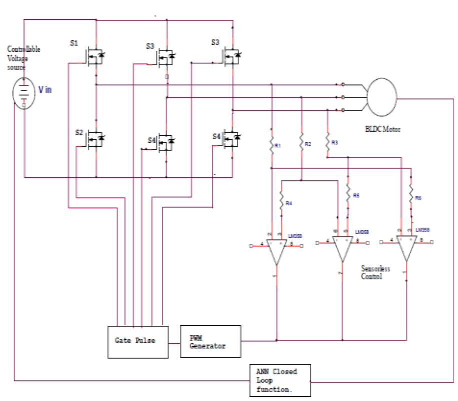

Figure 7.1 Circuit Diagram

8. SIMULATION RESULTS

Figure 8.1 shows simulation circuit diagram of the proposed system. The Simulation can be done by using MATLAB Simulink. Simulink, developed by Math Works, is a commercial tool for modeling, simulating and analyzing multi domain dynamic systems. Its primary interface is a graphical block diagramming tool and a customizable set of block libraries. It offers tight integration with the rest of the MATLAB environment and can either drive MATLAB or be scripted from it. Simulink is widely used in control theory and digital signal processing for multi domain simulation and design.

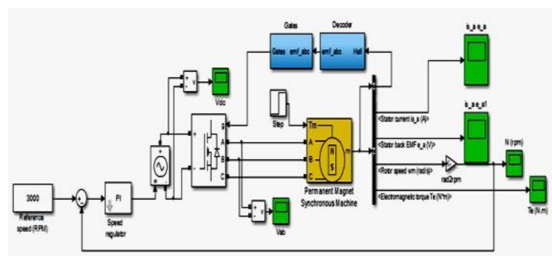

Figure 8.1 Simulation Circuit Diagram

The following figure shows simulation results of dc bus voltage, line voltage, Stator current, Electromagnetic Torque, Rotor speed and Controlled speed of motor.

DC Bus Voltage

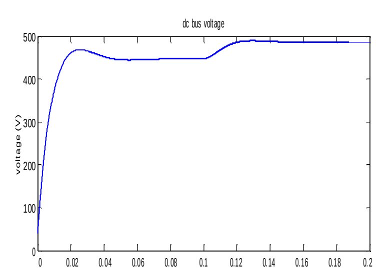

Figure 3. DC Bus voltage Waveform

Line Voltage

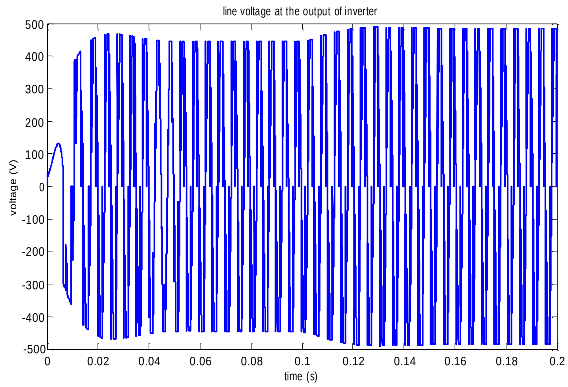

Figure 8.3. Line voltage at the output of Inverter

Stator Current

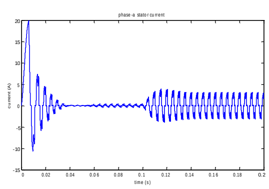

Figure 8.4. Stator Current Waveform

8.4 Electromagnetic Torque

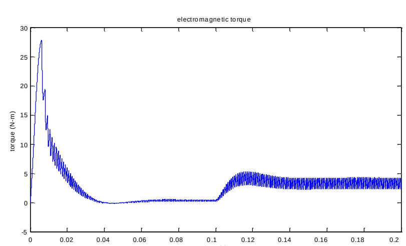

Figure 8.5. Electromagnetic torque Waveform

8.5 Rotor Speed

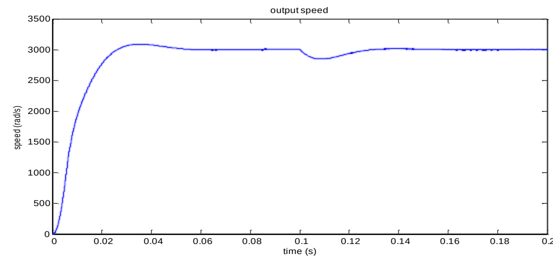

Figure 8.6. Rotor speed Waveform

8.6 Controlled Speed of Motor

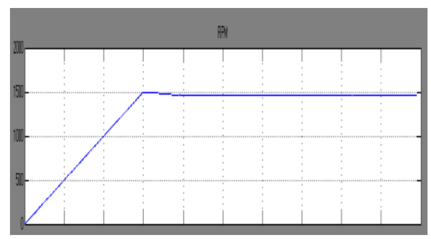

Figure 8.7. Controlled Speed Waveform

9. CONCLUSION

In view of the pulsation of three-phase BLDC motor with non-ideal back EMF, a new speed control method is proposed. When the motor works at low speed, the torque ripple is restrained by phase current through increasing the duty cycle of PWM. When the motor works at high speed, overlapping commutation scheme is used. The commutation times are given by the current controller in low and high speeds. Aiming at the non-ideal back EMF, the duty cycle is calculated in the current controller by measuring the angular position, speed, and the offline measured back EMF. By using this, the motor rpm is fed to the inverter and the regulated input voltage is generated automatically according to the output. Hence, speed is controlled of BLDC motor fed by six step inverter.

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AUTHOR BIBLIOGRAPHY

Mr. Bishnu Prasad Panda , was born in India. He received M.Tech degree in Electrical Engineering from Biju Patnaik University of Technology, Orissa. He is working as an Assistant Professor in Gandhi School of Engineering, Berhampur. His major research interests include Photovoltaic system and its application in power system

Mrs. Surabhi Tripathy ,was born in india .She received M.tech degree with specilization Energy system Engineering in I.G.I.T ,Sarang fromBiju Patnaik University of Technology, Orissa. She is working as an Assistant Professor in Gandhi School of Engineering, Berhampur.Her major research interests include Photovoltaic system with its MPPT tracking and application in power system.

Mrs.Smrutirekha Maharana ,was born in india .She received M.tech degree from Biju Patnaik University of Technology, Orissa. She is working as an Assistant Professor in Gandhi School of Engineering, Berhampur. Her major research interests include Photovoltaic system with its MPPT tracking

Mr.Bibek Das, was born in india .
He is pursuing Diploma in Gandhi School of Engineering. His major research interests include in power system operation and control.