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Control Strategy for Four Quadrant Operation of Modular Brushless DC Motor Drive Using Hall Effect Sensors

G. Pranay Kumar[1], P. Pradyumna[2]

PG Student [PE&ED], Dept. of EEE, Mahatma Gandhi Institute of Technology, Hyderabad, Telangana, India[1]

Associate Professor, Dept. of EEE, Mahatma Gandhi Institute of Technology, Hyderabad, Telangana, India[2]

ABSTRACT: In this paper, design of modular brushless dc motor drive and its operation in four quadrants is described. In this design, each permanent magnet BLDC motor is powered by an inverter and number of motors and inverter sets are stacked together in order to give the required power rating and to have good reliability. The four quadrant operation of this design is also done in this paper to operate the motor clockwise and counter clockwise i.e., in motoring mode and regenerative braking mode. This is essential in saving the power as in the regenerative braking mode of operation, the power is fed back to the supply mains. The speed control of the drive system is also studied in this paper.

KEYWORDS: BLDC motor, digital control, four quadrants, regenerative braking, Modular Design

I.INTRODUCTION

Almost all the adjustable speed drives require three phase induction motors for their operation. If there is any fault in any phase, the drive system has to be shut down. If six- phase induction motors which are supplied by two current source inverters are used, the reliability of the system will be increased [9]. An induction motor having multiple independent phases with separate inverter for each phase requires a specially wound multiphase motor but enables the machine to operate at failure of any single drive unit, although the performance of the motor is degraded [6].

The permanent magnet motors have superior performance as compared to the induction motors as the magnetizing component of current and copper losses are eliminated. Particularly, the brushless type permanent magnet DC Motors has high performance torque control easily. Permanent magnet motors are widely used in a number of applications such as industrial automation, consumer electronics, hybrid electric vehicle, traction applications [7] [8].

If there is any fault in the machine under operation, or there is a need to extend or decrease the rating of the machine in terms of its operating voltage or power to be handled, the existing machine cannot be operated and the machine has to be replaced by a new machine with the required ratings. To overcome this, a new modular design construction is proposed which is the interconnection or group of such machines where the machines can be added or disconnected depending upon the rating of the loads. A four quadrant operation is necessary in utilizing the electricity effectively during regenerative braking mode of operation of a machine.

A four quadrant operation for the true modular motor drive employed with axial gap permanent magnet motors is presented in this paper. The motor modules are mounted on a common shaft and inverter modules are used to power each motor separately, thus independent drive units are formed with the combination of the motor and inverter. There are number of advantages achieved by modular design for both inverter and motor such as reducing the occurrence of faults, power rating scalability i.e., to increase or decrease the rating of the drive system simply adding or removing the inverter and motor modules which reduces the cost of the redesign and repairs can also be done easily by replacing the faulted module, without disturbing the unfaulted modules. Each set of stator coils are driven by each inverter separately and the permanent magnet motor id normally operated in Brushless DC motor mode. The effect of PWM strategies for four quadrant operation of the drive system is analysed in this paper.

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The rotor of the BRUSHLESS DC Motor is made with the permanent magnets and the stator is with windings. It's construction is similar to the DC motor where the brushes and the commutator are replaced with a control electronics such as a phase controlled converter. The control electronics energize the proper windings of the stator of the BLDC motor and replaces the function of the commutator. It is easy to start and stop as and when required since the motor has less inertia. These motors have great efficiency, good reliability, clean operation, produces less noise and very fast. Trapezoidal and/or voltages along with the rotor position are used to drive a BLDC motor. In order to maintain to gain maximum developed torque, the angle between the stator flux and rotor flux is maintained 90 by aligning the voltage spikes properly between phases. To detect the actual rotor position, position sensors such as Hall Effect sensors are used externally or internally or the position of the rotor can also be sensed without sensors. In Industrial Automation equipments, Aerospace, Consumer electronics, electric vehicles, Medical, Automotive and instrumentation BLDC motors can be used.

Section II describes about the configuration and design of the modular brushless DC Motor drive. Section III explains about the four quadrant operation of the drive. Section IV is about the controller in which Hall Effect sensors, PWM Module and PI controller are briefly explained. Section V deals with the design of the proposed system using MATLAB/ SIMULINK and the results obtained from this designed circuit. Section VI gives the conclusion of the project and some of applications of this project.

II. MODULAR BRUSHLESS DC MOTOR DRIVE CONFIGURATION

A true modular design with axial gap permanent magnet motors can be realized although a single rotor and multiple sets of stator windings can form a modular motor drive. In this design, a common shaft is used for all motor modules and every motor module has separate stator and rotor, as shown in the Fig 1. Separate inverters are used to power each motor module, so that independent drive unit is formed. The common DC power can be shared by the inverter modules so that the cost reduces or the fault tolerance level can be increased by having a separate DC source. Required number of the stack of the inverter and motor modules can be used depending on the power requirement of the specific applications which leads to considerable savings in redesigning of the module for different applications. Even if there is any failure in any unit, the drive system is continue in operation but at reduced power. The information about the position of the rotor gives the controlling a PM motor properly and this information can be known by using Hall Effect sensors or optical encoders. Position sensorless schemes can also be employed in certain applications where the starting of the motor doesn't require the inverters. If each drive unit is employed with its own position sensor, the reliability will be increased and if only one set of position sensors are used, the system is formed with less cost [4].

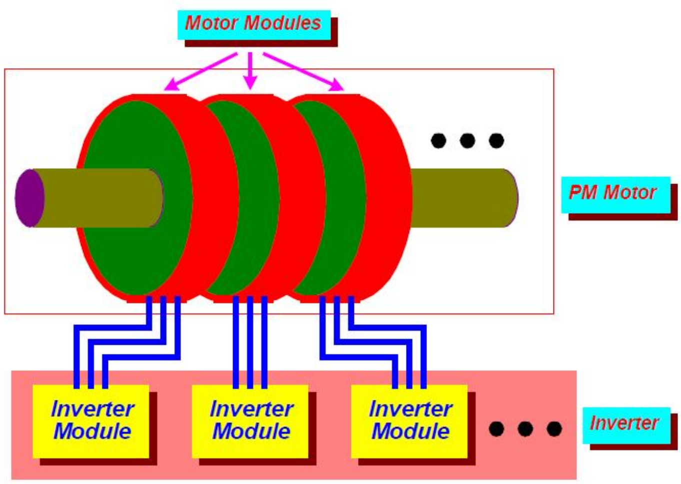

Fig 1. Modular inverter and modular motor drive system configuration.

The permanent magnet motors are excited mainly two ways. First, the motor is given sinusoidal current which has a sinusoidal back emf, which is called driving the motor in synchronous ac mode. Second, the BLDC motors, which is

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very attractive for high power drive systems and is thus the choice for the traction motor drive. Three phase Permanent magnet motor with a trapezoidal back EMF excited by quasi square current waveforms is used for this purpose, which is given by three phase fully controlled converter. Inverter phase commutation is the simplicity of this approach. A voltage source inverter produces quasi square wave current waveform which is well matched to the flat top of the trapezoidal back EMF waveform, so that the cost of the drive system is going to be less. Requirement for accurate stator current commutation control is the disadvantage of the trapezoidal back EMF waveform. The torque developed in a PM motor with a trapezoidal back EMF is very sensitive to the relative phase of the quasi square wave currents imposed by the inverter with respect to the back EMFs. Pulsating torque can be developed in these drives because of a small phase error in commutation. Thus the information of the back emf should be accurate for proper commutation of stator currents with an inverter [9].

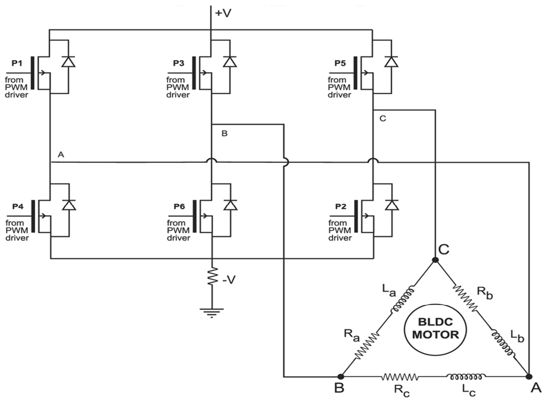

Fig. 2. Equivalent Circuit of power stage of BLDC motor.

III. FOUR QUADRANT OPERATION

There are four possible modes or quadrants of operation using a Brushless DC Motor which is depicted in Fig. 3. When BLDC motor (Fig. 4) is operating in the first and third quadrant, the supplied voltage is greater than the back emf which is forward motoring and reverse motoring modes respectively, but the direction of current flow differs. When the motor operates in the second and fourth quadrant the value of the back emf generated by the motor should be greater than the supplied voltage which are the forward braking and reverse braking modes of operation respectively, here again the direction of current flow is reversed [3].

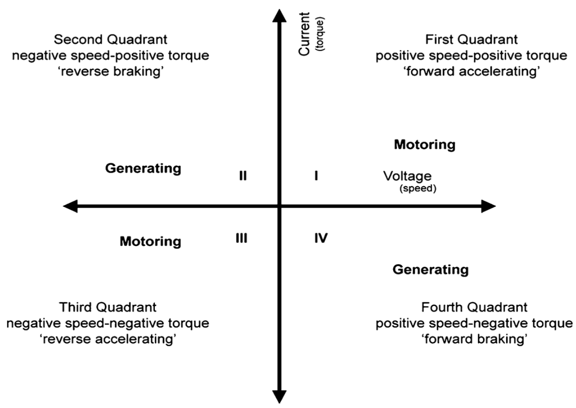

Fig. 3. Four Quadrants of operation.

The BLDC motor is initially made to rotate in clockwise direction, but when the speed reversal command is obtained, the control goes into the clockwise regeneration mode, which brings the rotor to the standstill position. Instead of

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waiting for the absolute standstill position, continuous energization of the main phase is attempted. This rapidly slows down the rotor to a standstill position. Therefore, there is the necessity for determining the instant when the rotor of the machine is ideally positioned for reversal.

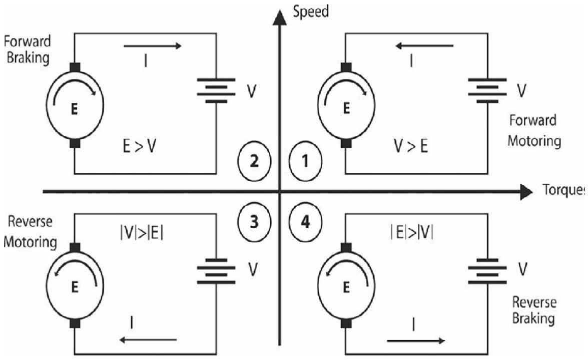

Fig. 4. Operating Modes.

Hall effect sensors are used to ascertain the rotor position and from the Hall sensor outputs, it is determined whether the machine has reversed its direction. This is the ideal moment for energizing the stator phase so that the machine can start motoring in the counter clockwise direction.

IV. CONTROLLER

Modelling of a controller is depicted in the Fig 5. The controller consists the Proportional and Integral (PI) controller, Hall Effect sensor signals, and the PWM module for the generation of the Gate signals to drive the controlled converter. The Hall Effect sensor signals are first decoded by the decoder and then the PWM module is used for the generation of the Gate pulses.

A. PI controller

The regulation of speed is accomplished with PI Controller. By increasing the proportional gain of the speed controller, the controller's sensitivity is increased to have faster reaction for small speed regulation errors. This allows a better initial tracking of the speed reference by a faster reaction of the current reference issued by the speed controller. This increased sensitivity also reduces the speed overshooting. The armature current reduces faster, once the desired speed is achieved. An increase of the integral gain will allow the motor speed to catch up with the speed reference ramp a lot faster during sampling periods. This will indeed allow a faster reaction to small speed error integral terms that occur when a signal is regulated following a ramp. The controller will react in order to diminish the speed error integral a lot faster by producing a slightly higher accelerating torque when following an accelerating ramp. On the other hand, too high increase of the proportional and integral gains can cause instability, and the controller becoming insensitive. Too high gains may also result in saturation.

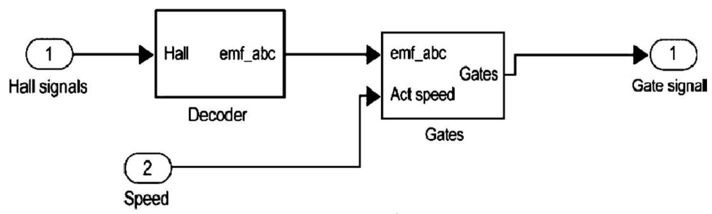

Fig 5. Modelling of Controller.

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B. PWM Module

The PWM module simplifies the task of generating multiple synchronized Pulse Width Modulated (PWM) outputs. It has six PWM I/O pins with three duty cycle generators. The three PWM duty cycle registers are double buffered to allow glitchless updates of the PWM outputs. For each duty cycle, there is a duty cycle register that will be accessible by the user while the second duty cycle register holds the actual compared value used in the present PWM period.

C. Hall Effect sensors

A Hall Effect sensor is a transducer that varies its output voltage in response to a magnetic field. Hall Effect sensors are used for proximity switching, positioning, speed detection, and current sensing applications.

In its simplest form, the sensor operates as an analog transducer, directly returning a voltage. With a known magnetic field, its distance from the Hall plate can be determined. Using groups of sensors, the relative position of the magnet can be deduced.

Frequently, a Hall sensor is combined with circuitry that allows the device to act in a digital (on/off) mode, and may be called a switch in this configuration. Commonly seen in industrial applications such as the pictured pneumatic cylinder, they are also used in consumer equipment; for example some computer printers use them to detect missing paper and open covers. When high reliability is required, they are used in keyboards.

Hall sensors are commonly used to time the speed of wheels and shafts, such as for internal combustion engine ignition timing, tachometers and anti-lock braking systems. They are used in brushless DC electric motors to detect the position of the permanent magnet. In the pictured wheel with two equally spaced magnets, the voltage from the sensor will peak twice for each revolution. This arrangement is commonly used to regulate the speed of disk drives.

V. SIMULATION AND RESULTS

The closed loop controller for a three phase brushless DC motor is modelled using MATLAB/Simulink [2] and is shown in Fig 6. Permanent Magnet Synchronous motor with trapezoidal back EMF is modelled as a Brushless DC Motor. The model of the controller receives the Hall signals as its input, converts it in to appropriate voltage signals. The gate signals are generated by comparing the actual speed with the reference speed. Thus a closed loop speed control is achieved with the help of PI control, present in the controller block

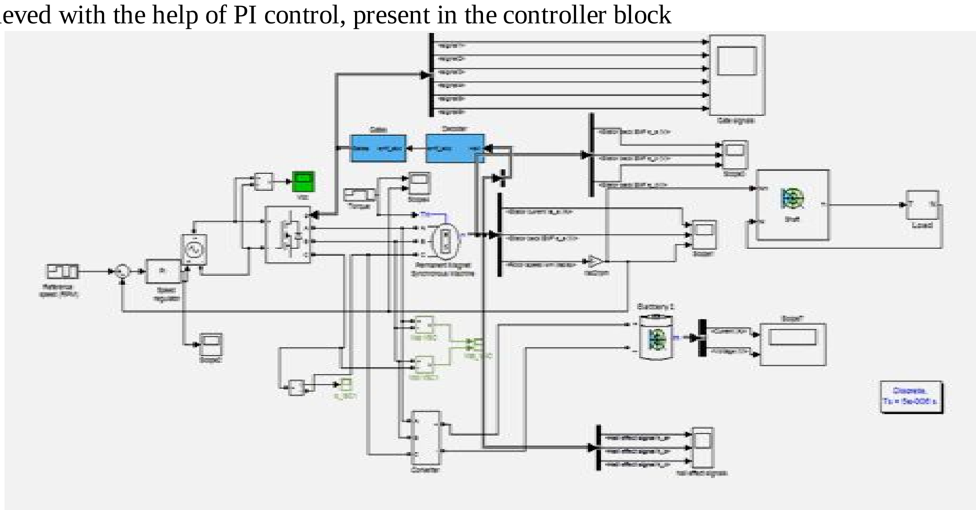

Fig 6. Simulink Model of Proposed System

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The phase current wave forms are shown in the fig 7. The phase current for the brushless DC motor is normally trapezoidal or rectangular in nature.

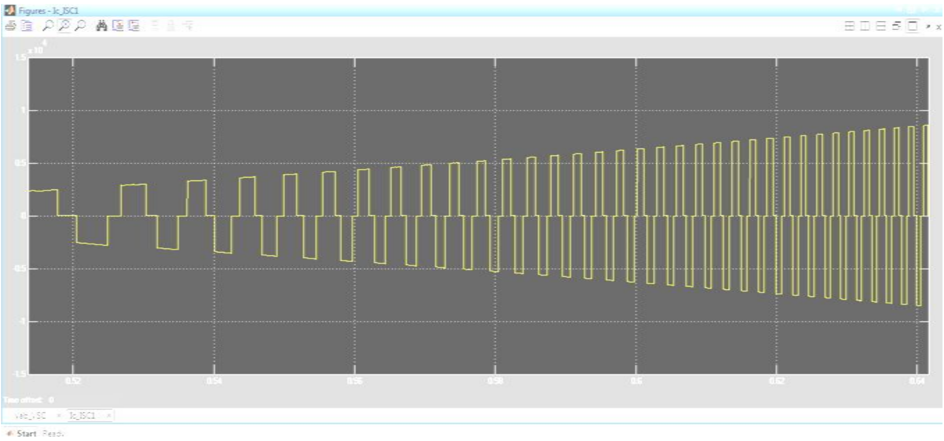

Fig 7. Phase current I_c

The Hall Effect sensor signals are decoded and given to the PWM module, which gives the required PWM signals to drive the gates of the controlled converter switches. The PWM signals which are applied to the Gates of the inverter are shown in the Fig 8. Depending upon these PWM signals, the ON and OFF time periods of switches varies, i.e., there will be a variation of the duty cycle and hence the output voltage of the electronic commutator is changed which is applied to the motor.

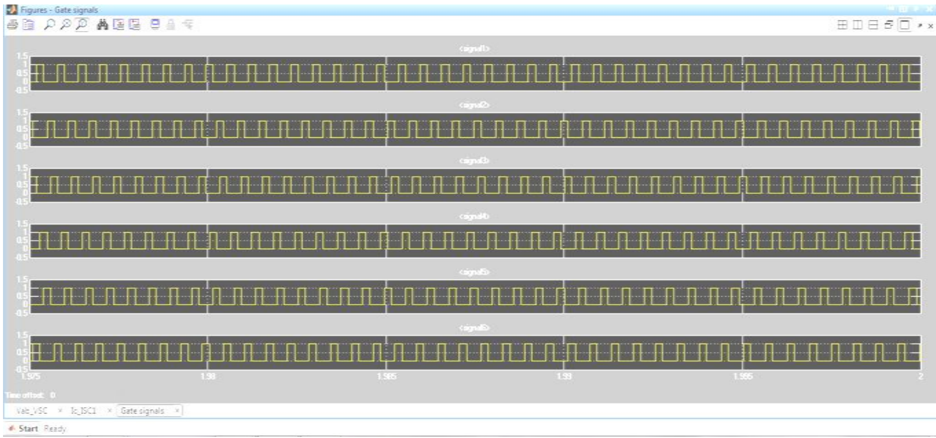

Fig 8. PWM signals applied to gates of the inverter

The Hall Effect sensor signals are shown in fig 9, which gives the information about the position of the rotor The position signals obtained from the Hall sensors of the motor are read by the I/O lines of the Digital controller. The Hall sensor inputs give the position of the rotor which is fed to the controller. The controller compares it with the reference speed and generates an error signal. The required direction of rotation either clockwise or counter clockwise can also be fed to the digital controller. The PWM module of the controller generates appropriate PWM signals.

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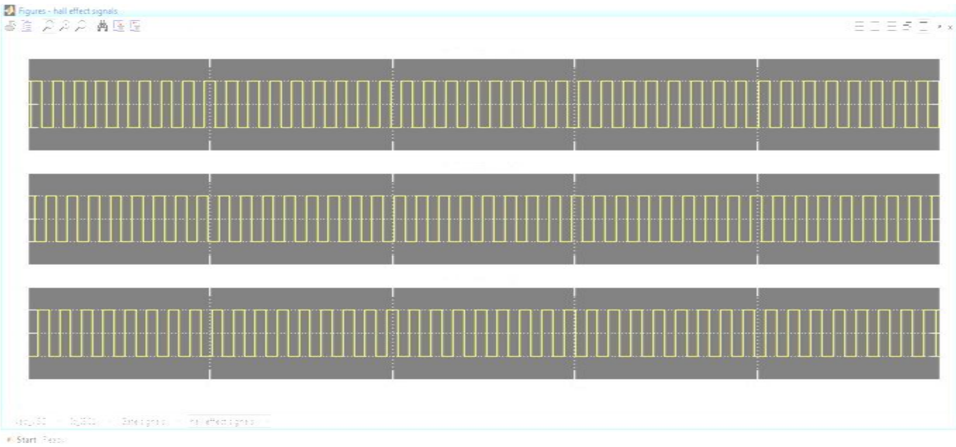

Fig 9. Hall Effect signals

The simulation results shown in the Fig 10 depicts the sinusoidal stator current, trapezoidal voltages applied to the motor and the speed of the rotor. The stator current of the machine under operation (BLDC Motor) is sinusoidal in nature, it is having the trapezoidal back EMF waveforms and the motor speed is almost constant after reaching its reference or set speed.

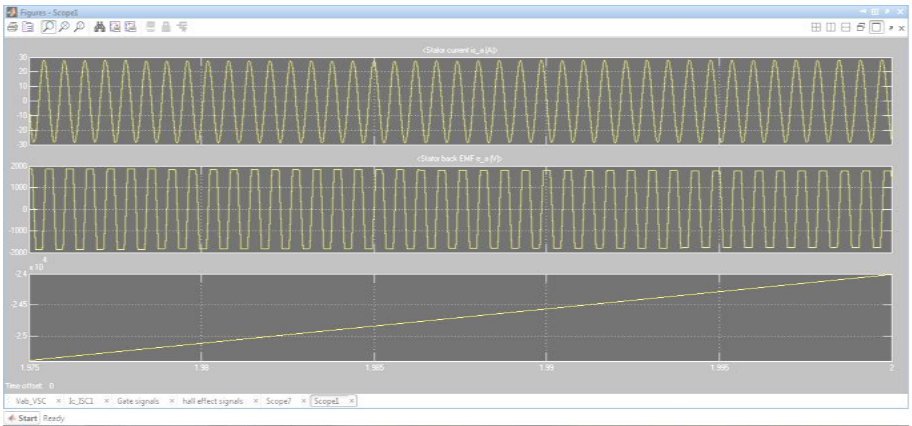

Fig 10. Stator current, stator back emf and rotor speed (rpm)

Fig 11. Shows voltages between the phases RY and YB, which are trapezoidal. These trapezoidal wave forms of voltages are given to the BLDC motor for its operation. To operate a brushless DC motor, rectangular pulses can also be given in general.

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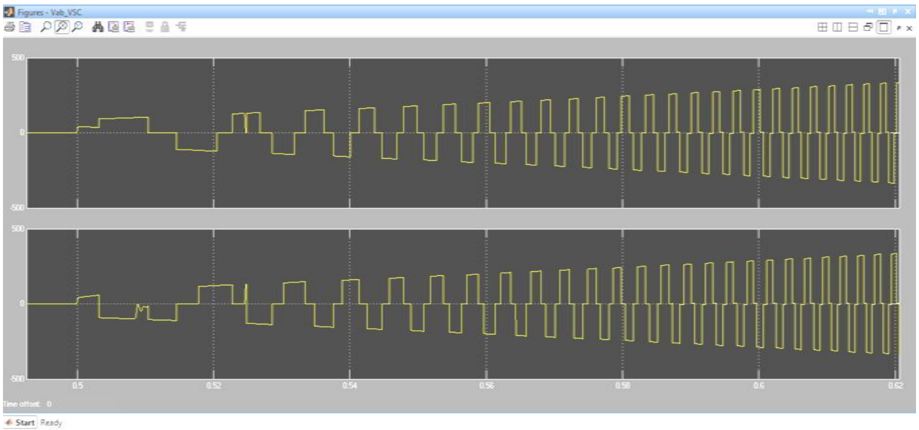

Fig 11. Trapezoidal voltages V_{RY} and V_{YB}

VI. CONCLUSION

A modular design is described for both the inverter and the permanent magnet BLDC motor and a control scheme is proposed for the modular brushless dc motor drive for changing its direction instantaneously. The transition from clockwise to counter clockwise rotation of the motor is too quick. In the regenerative mode of operation, the generated voltage is fed back to the supply, so that there will be a saving of power. The modular design of the inverter and the BLDC motor is very advantageous and economical as the power rating of the drive can be changed by removing or adding the inverter and motor modules. The effect of PWM strategies and the results can be achieved by the variation of Proportional and Integral constants of the PI controller. For best results, Tuning process is done by trial and error method and the Proportional Constant and Integral Constant are 0.1 and 0.03 respectively.

The simulation results have shown that the four quadrant operation of BLDC motor drive employing modular design is well suited for applications such as hybrid electric vehicles, traction system. The advantages of this proposed project is reliability of controlling techniques, superior performance in speed control, efficient conservation of energy on load and no load conditions, quicker and smooth transition from braking to motoring and vice-versa. The disadvantage of this model is arcing might occur when a proto type model is designed for higher rating motors, and if the motor rating is small, this is not a serious issue and hence, can be negligible.

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BIOGRAPHY

G. PRANAY KUMAR received his B.Tech degree in Electrical and Electronics Engineering From Sree Chaitanya College of engineering, affiliated to Jawaharlal Nehru Technological University, Hyderabad and Currently pursuing his M.Tech in Power Electronics and Electric Drives From Mahatma Gandhi Institute of Technology, affiliated to Jawaharlal Nehru Technological University, Hyderabad. He has participated in various Paper presentations, workshops and his areas of interests include the Electric Drives and control, Nonconventional Energy sources

P. PRADYUMNA received his M.Tech degree in Micro Electronics and control systems from Visvesvaraya Technological University in 2004 and has working as an Associate Professor in Electrical and Electronics Engineering Department at Mahatma Gandhi Institute of Technology. He has over 12 years of experience in teaching field and has guided more than 45 under Graduate students and about 10 Post Graduate students for their academic Projects. Currently he is doing his research in the area of Non- Conventional Energy resources.