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Practical Implementation of Four Quadrant Operation of Three Phase Bldc Motor with Fuzzy Logic Controller Using Fpga

Julin K Austine, Dr. A.K. Parvathy

Abstract— Brushless DC (BLDC) motor drives are becoming more popular in industrial, traction applications. This makes the control of BLDC motor in all the four quadrants very vital. This paper deals with the digital control of three phase BLDC motor. The motor is controlled in all the four quadrants without any loss of power; in fact energy is conserved during the regenerative period. The FPGA controller is used for the implementation of four quadrant operation of BLDC motor .Fuzzy logic controller is used to achieve precise speed control.

Index Terms— BLDC motor, digital control, four quadrants, fuzzy logic, regenerative braking , speed control, traction application

1 INTRODUCTION

The absence of brushes and commutator, makes the brushless dc motors more advantageous compared to conventional dc motors. They require practically no maintenance. It have high reliability , low inertia and friction, and low radio frequency interference and noise as a result it have long life. Due to low inertia and friction , they have faster acceleration. It can be run upto 100,000 rpm and higher [1] . Since 1970's BLDC have been used in different applications such as automotive, industrial automation, aerospace, instrumentation and appliances [2]. Brushless DC (BLDC) motors can replace conventional DC motors in many cases. They are driven by dc voltage and the current commutation is done by solid state switches. That is the commutation is done electronically. BLDC motors are available in different power ratings, from very small motors as used in hard disk drives to large motors in electric vehicles. Three phase motors are more common. Two phase motors are also found in many applications.

In this paper a fuzzy based control technique is adopted for the speed regulation of BLDC motors for the application of Electric Vehicles.

This paper is organized as follows:

Section II describes the four quadrant operation of the three phase BLDC motor. Section III describes the digital controller. Section IV describes the complete drive system. Section V describes Simulation results. Experimental setup and the results are presented in Sections VI. Section VII concludes the proposed work.

2 FOUR QUADRANT OPERATION

2.1 BLDC Motor

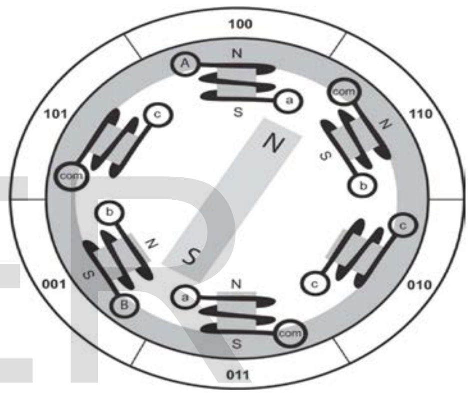

Fig1.BLDC Motor Star connected

A brushless motor is constructed with a permanent magnet rotor and wire wound stator poles. Electrical energy is converted to mechanical energy by the magnetic attractive forces between the permanent magnet rotor and the rotating magnetic field induced in the wound stator poles. Brushless DC Motors are driven by DC voltage.The BLDC Motor with star connected stator windings is shown in figure1.The current commutation is controlled by six solid state switches. The commutation instants are determined by the rotor position which is sensed by a Hall Effect sensor. Hall Effect sensor provides signals to the respective switches [3] and [4]. Whenever the rotor magnetic poles pass near the Hall sensors, they produce a high or low signal, indicating either North or South pole passing near the sensors. The numbers shown around the peripheral of the motor diagram in figure 1 represent the sensor position code. The north pole of the rotor points to the code that is output at that rotor position. The numbers are the sensor logic levels where the Most Significant bit is sensor C and the Least Significant bit is sensor A. The commutation sequence for clockwise and counter clockwise rotation is shown in tables 1 and 2 respectively.

TABLE 1

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COMMUTATION SEQUENCE FOR CLOCKWISE ROTATION

Sequence	Hall Sensor Input			Active PWMs		Phase Current		
	A	B	C			A	B	C
1	1	0	0	PWM(Q3)	PWM(Q2)	-V	+V	-
2	1	0	1	PWM(Q5)	PWM(Q2)	-V	-	+V
3	0	0	1	PWM(Q5)	PWM(Q4)	-	-V	+V
4	0	1	1	PWM(Q1)	PWM(Q4)	+V	-V	-
5	0	1	0	PWM(Q1)	PWM(Q6)	+V	-	-V
6	1	1	0	PWM(Q3)	PWM(Q6)	-	+V	-V

TABLE 2.
COMMUTATION SEQUENCE FOR COUNTERCLOCKWISE ROTATION

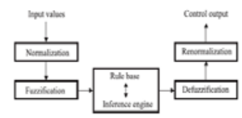
Sequence	Hall Sensor Input			Active PWMs		PhaseCurrent		
	A	B	C			A	B	C
1	1	0	0	PWM(Q3)	PWM(Q2)	-V	+V	-
2	1	1	0	PWM(Q3)	PWM(Q6)	-	+V	-V
3	0	1	0	PWM(Q1)	PWM(Q6)	+V	-	-V
4	0	1	1	PWM(Q1)	PWM(Q4)	+V	-V	-
5	0	0	1	PWM(Q5)	PWM(Q4)	-	-V	+V
6	1	0	1	PWM(Q5)	PWM(Q2)	-V	-	+V

2.2 Four quadrant operation

There are four possible modes or quadrants of operation using a Brushless DC Motor. In X-Y plot of speed versus torque plane, Quadrant I is forward speed and forward torque. Here the torque is propelling the motor in the forward direction. Conversely, Quadrant III is reverse speed and reverse torque. Now the motor is "motoring" in the reverse direction, spinning backwards with the reverse torque. In Quadrant II the motor is spinning in the forward direction, but torque is being applied in reverse as a result torque is being used to "brake" the motor and the motor is now generating power. Finally, Quadrant IV is exactly the opposite to quadrant II. The motor is spinning in the reverse direction, but the torque is being applied in the forward direction. Here again torque is being applied to attempt to slow the motor to change its direction to forward direction and again power is generated by the motor. 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 [7], which brings the rotor to the standstill position. Continuous energization of the main phase is attempted instead of waiting for the absolute standstill position. 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. Hall-effect sensors are used to determine the rotor position.

3 DIGITAL CONTROLLER

The four quadrant control of three phase BLDC motor is achieved with 250,000-gate Xilinx Spartan-3E XC3S250E FPGA in a 144-Thin Quad Flat Pack package (XC3S250E-TQ144) .The position signals from the three Hall sensors are read through the I/O lines. The PWM module consists of six input output pin, which is used for producing the PWM pulses for the MOSFET switches. Hall sensor inputs from the motor are fed to the microcontroller. The reference speed and the actual speed are fed to the controller. The closed loop control is



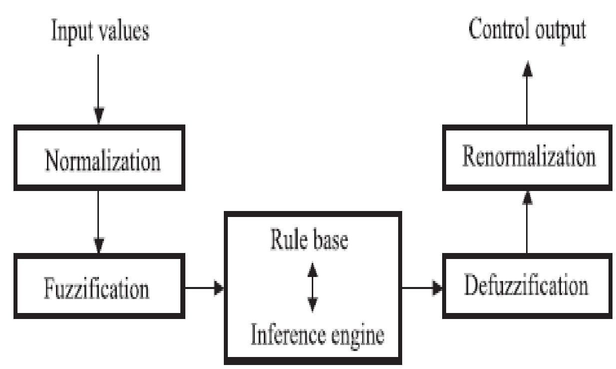


Fig2.Block diagram of fuzzy logic controller

NORMALIZATION:

Normalization performs the scale transformation, which maps the physical values of the speed (input) variable into a normalized universe of discourse[7]. The speed error (e) is taken in the disclosure [-100 100] and the change in error (Δe) in speed is taken in the disclosure [-50 50].
Speed error (e) = reference speed - actual speed; change in er-

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ror (Δe) = present speed error - previous speed error.

FUZZIFICATION:

Fuzzy logic controllers have experimentally shown excellent results, especially when faced with nonlinear control systems [8-11].The process of converting numerical measurements to grades of membership of fuzzy set members is called fuzzification. Hence fuzzification block matches the input data with the conditions of the rules to determine how well then condition of each rule matches that particular input instance. There is a degree of membership for each linguistic term that applies to that input variable[7]. Triangular membership function is used for inputs and output. Seven membership functions are defined for speed error. For seven clusters in the membership functions, seven linguistic variables are defined as: Negative Big (NB), Negative Medium (NM), Negative Small (NS), Zero (Z), Positive Small (PS), Positive Medium (PM), and Positive Big (PB).

RULE BASE:

TABLE 3
RULE BASE

e/Δe	**NB**	**NM**	**NS**	**ZE**	**PS**	**PM**	**PB**
NB	NB	NB	NB	NM	NS	NS	ZE
NM	NB	NM	NM	NM	NS	ZE	PS
NS	NB	NM	NS	NS	ZE	PS	PM
ZE	NB	NM	NS	ZE	PS	PM	PB
PS	NM	NS	ZE	PS	PS	PM	PB
PM	NS	ZE	PS	PM	PM	PM	PB
PB	ZE	PS	PS	PM	PB	PB	PB

Table 3 shows the rule base used for the speed control of BLDC motor.

INFERENCE ENGINE:

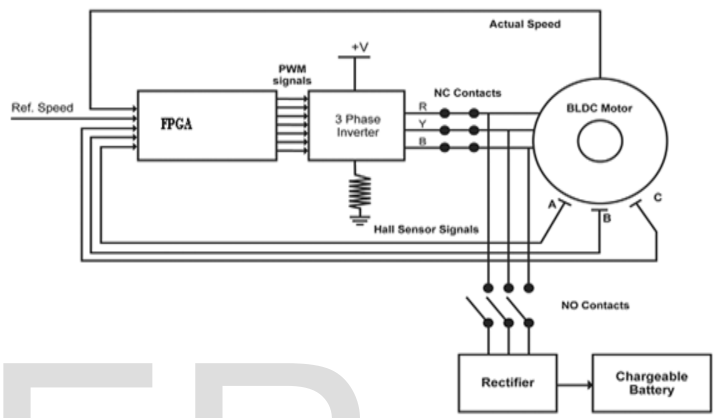
The rules corresponds the strategy that the control signal should be a combination of the error and the change in error. For each rule, the inference engine looks up the membership values in the condition of the rule. As the fuzzy logic controller receives inputs, the rule base is evaluated. The antecedent (IF e AND Δe) blocks test the inputs and produce decisions and the consequent (THEN an integer) blocks of some rules are satisfied while others are not. The final decisions are combined to form logical sums. These conclusions feed into the inference process where each response output member function (-9 to 9) is determined.

The resulting fuzzy set must be converted into a number that can be sent to the process as a control signal. This operation is called defuzzification. The resulting fuzzy set is thus defuzzified into a crisp control signal. The defuzzification of the data into a crisp output can be obtained by combining the results of the inference process and then computing the "fuzzy bisector" of the area.

DENORMALIZATION:

The crisp output of the fuzzy logic controller is in the range of -9 to 9. In order to get the desired pulse width, the number that have gotten is compared with that of triangular wave. Thus the voltage is controlled so as to obtain the desired speed.

Fig 3.Closed Loop drive



4. COMPLETE DRIVE SYSTEM

Figure 3 shows the block diagram of the BLDC motor drives system used. The hall sensors give the rotor position. The actual speed of the motor is fed back to the Fuzzy Logic controller, which is compared with the reference speed. The difference in speed generates an error signal which aids the motor to run at a constant speed. The required direction of rotation either clockwise or counter clockwise can also be fed to the controller. The PWM module of the controller generates appropriate PWM signals, which are applied to the three phase inverter. When the motor is operating in the motoring mode, in the clockwise direction, the relay contacts are normally opened. But when braking is applied or when a speed reversal command is received, the relay contacts are closed. The kinetic energy which will be wasted as heat energy is now converted into electric energy which is rectified .The rectified energy can be stored in a rechargeable battery. The braking energy can be given back to the power source. But it increases the complexity of the circuit as the DC power generated has to be inverted to be given back to the mains. The frequent reversal of direction of rotation will result in the continuous charging of the battery. The energy thus stored can be used to run the same motor when there is an interruption of power supply. When the speed reduces to zero (which is obtained from the Hall sensor signals of the motor) it implies that the brake is applied. The capture module of controller generates an interrupt signal, which closes the normally opened contacts of the rectifier block and opens the normally closed contacts of the motor.

5. SIMULINK MODEL

The closed loop controller for a three phase brushless DC motor is modeled using MATLAB/Simulink [12] and [13] is shown in Fig. 4. Bogacki Shampine numerical integration method is used to get the solution of the equations.

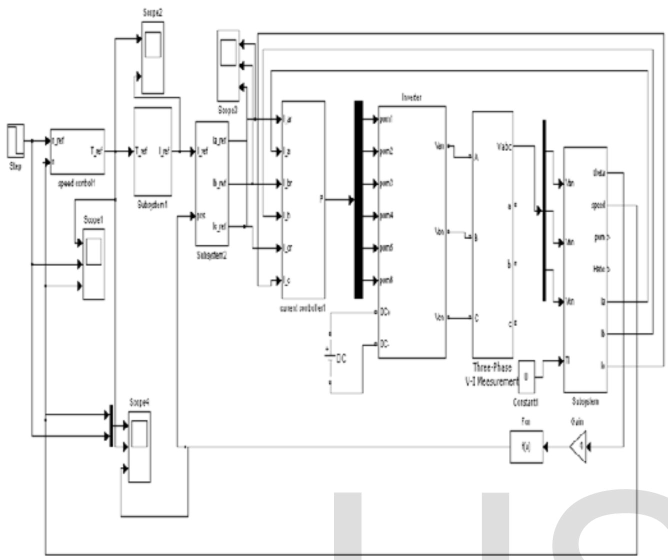


Fig. 4. Simulink Model of Four Quadrant Drive.

The reference speed is 3000 rpm. The rotor speed output obtained during forward and reverse motoring mode is shown in figure 5. Variation in back emf as the mode changes from forward motoring mode to reverse motoring mode is show in fig 6.

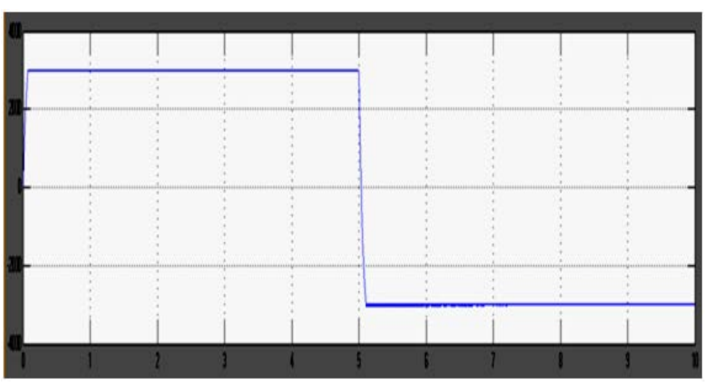


Fig 5. Rotor speed output (rpm)

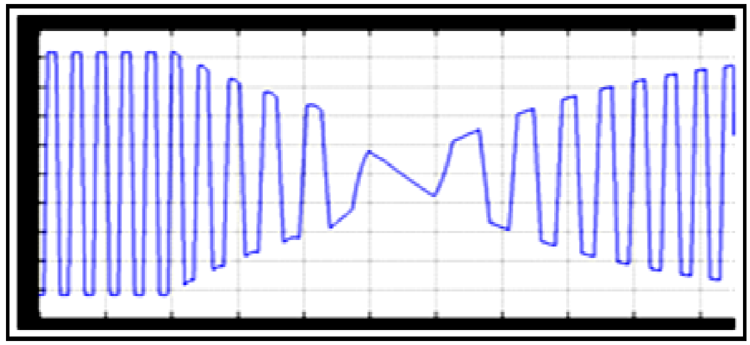


Fig 6. Variation in back emf as the mode changes from forward motoring mode to reverse motoring mode

6 EXPERIMENT RESULT AND SETUP

The practical implementation of the four quadrant control of the three phase BLDC motor is shown in Fig.7. The specifications of the motor are listed in Table 4. The relay coil has three normally open and three normally closed contacts. The RY voltage given to the BLDC motor from inverter is shown in the figure 8.

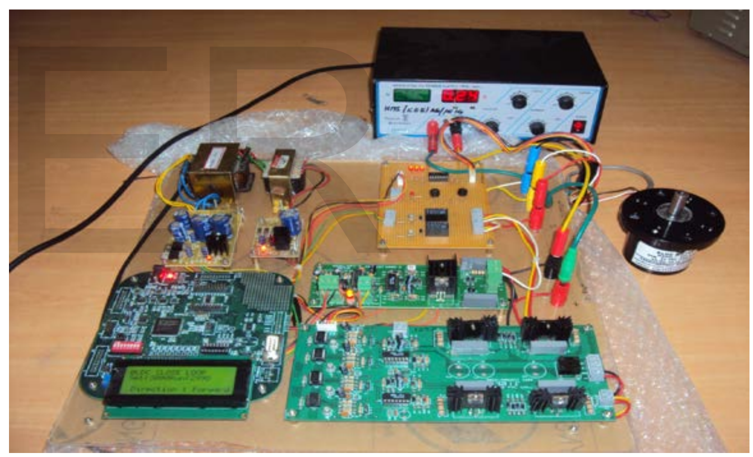


Fig.7. Practical implementation

TABLE 4
MOTOR SPECIFICATIONS

Description	Value
Rated voltage	24V
Rated current	2.4A
Rated speed	3000rpm
Rated power	60W

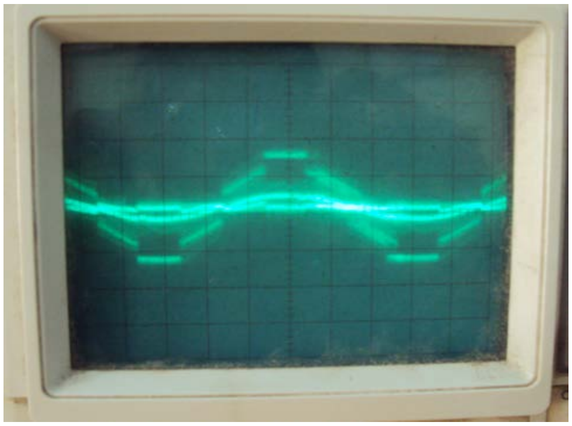


Fig 8.RY voltage of BLDC motor

7. CONCLUSION

In this paper, the proposed control scheme made the motor to change the direction from CW to CCW without going to standstill position. The time taken to achieve this braking is comparatively less. This concept can be well utilized in the rotation of spindles, embroidery machines and electric vehicles where there is frequent reversal of direction of rotation of the motor required. The prototype model thus designed can be implemented even for higher rating motors. The generated voltage during the regenerative mode can be returned back to the supply mains which will result in considerable saving of power.

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