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Speed Control of Brushless Dc Motor In Four Quadrant Operation Using Dsp

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Abstract

Brushless DC motor (BLDC) drives are becoming more popular in industrial, and several applications because of their higher efficiency and power density. This makes the control of BLDC motor in all the four quadrants very vital. This paper deals with the conventional control of three phase BLDC motor in all four quadrant operation. The BLDC motor is controlled in all four quadrant operation without any loss of power and conserving energy during regenerative period by charging the battery. The conventional controller uses Digital Signal Processor which has advantages as the microcontroller and offers higher speed, higher resolution, and capabilities to implement the simple algorithms to lower the system cost.

Keywords: BLDC motor, digital control processor, four quadrants, regenerative braking..

Introduction

Brushless DC (BLDC) motors have been widely used in a variety of applications in industrial automation and consumer appliances because of their higher efficiency and power density. Brushless DC motor is one of the motor types rapidly gaining popularity. The stator of a BLDC motor consist of a stacked steel laminations with winding placed in the slots that are axially cut along the inner periphery or around stator salient poles. The rotor is made up of permanent magnets and can vary from two to eight pole pairs with alternate north and south poles. In order to rotate a BLDC motor, the stator windings should be energized in a sequence. Brushless DC motor with their trapezoidal electromotive force (EMF) profile requires six discrete rotor position information for the inverter operation. These are typically generated by Hall-effect sensors placed within the motor.

In the brushless DC motor, polarity reversal is performed by power transistors switching in synchronization with the rotor position. Therefore, BLDC motors often incorporate either internal or external position sensors to sense the actual rotor position.This paper is organized as follows:

Section II describes the three phase BLDC motor, its features, and also the controller TMS320LF2407A, with its special features. In section III, the realization of four quadrant control operation of the BLDC motor is presented. The complete drive system is reviewed in Section IV. PI Controller is presented in section V. Experimental setup and the hardware results are presented for four-quadrant operation in Sections VI and VII. Section VIII concludes the proposed work.

BLDC Motor and Digital Controller

A. BLDC Motor

Brushless DC Motor [1] is driven by DC voltage but current commutation is controlled by solid state switches. The commutation instants are determined by the rotor position. The rotor shaft position is sensed by a Hall Effect sensor, which provides signals as represented in Table I. Whenever the rotor magnetic poles pass near the Hall sensors [2], they give a high or low signal, indicating either N or S pole is passing near the sensors. Based on the combination of these three Hall sensor signals, the exact sequence of commutation can be determined. These signals are decoded by combinational logic to provide the firing signals for 120°conduction on each of the three phases. The rotor position decoder has six outputs which control the upper and lower phase leg MOSFETs of Fig.1.

Table 1: Clockwise Hall Sensor Signals, Phase Voltages and Drive Signals

H_a	H_b	H_c	EMF_A	EMF_B	EMF_C	S_1	S_2	S_3	S_4	S_5	S_6
0	0	0	0	0	0	0	0	0	0	0	0
0	0	1	0	-1	+1	0	0	0	1	1	0
0	1	0	-1	+1	0	0	1	1	0	0	0
0	1	1	-1	0	+1	0	1	0	0	1	0
1	0	0	+1	0	-1	1	0	0	0	0	1
1	0	1	+1	-1	0	1	0	0	1	0	0
1	1	0	0	+1	-1	0	0	1	0	0	1
1	1	1	0	0	0	0	0	0	0	0	0

B. Digital Controller

Many papers have been published in hybrid [3] and reluctance motors. The digital pulse width modulation control of BLDC motor will be efficient and cost effective [4-5]. The digital control of the four quadrant operation of the three phase BLDC motor is planned with TMS320LF2407A. This digital controller combines the Digital Signal Processor features and PIC microcontroller features, making it versatile.

The controller has a modified Harvard architecture, with a 16×16 bit working register array. It has two 40 bit wide accumulators. All the DSP instructions are performed in a single cycle. The three external interrupt sources, with eight user selectable priority levels for each interrupt source helps to get the hall sensor inputs from the motor. The reference speed and the required duty cycle can be fed into the controller. The closed loop control is achieved with the PID controller.

A. 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 glitch less 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.

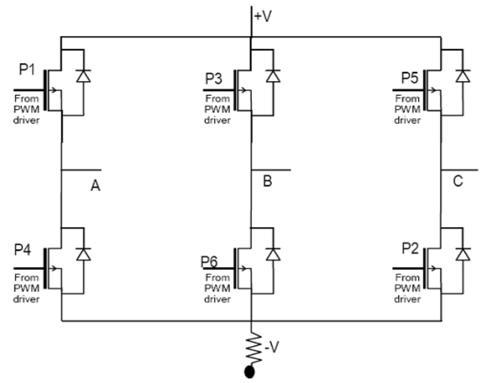

Figure 1: Three Phase Inverter Circuit To BLDC Motor

B. ADC Module

The 10 bit high speed analog to digital converter (A/D) allows conversion of an analog input signal to a 10 bit digital number. This module is based on Successive Approximation Register (SAR) architecture, and provides a maximum sampling rate of 500 kbps. The A/D converter has a unique feature of being able to operate while the device is in sleep mode.

Four Quadrant Control Operation

There are four possible modes or quadrants of operation[6-7] using a Brushless DC Motor in Fig.(2) In an X-Y plot of speed versus torque, Quadrant I is forward speed and forward torque. 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. Quadrant II is where the motor is spinning in the forward direction, but torque is being applied in reverse. Torque is being used to "brake" the motor, and the motor is now generating power as a result. Finally, Quadrant IV is exactly the opposite. The motor is spinning in the reverse direction, but the torque is being applied in the forward direction. Again, torque is being applied to attempt to slow the down motor and change its direction to forward again. Once again, power is being generated by the motor.

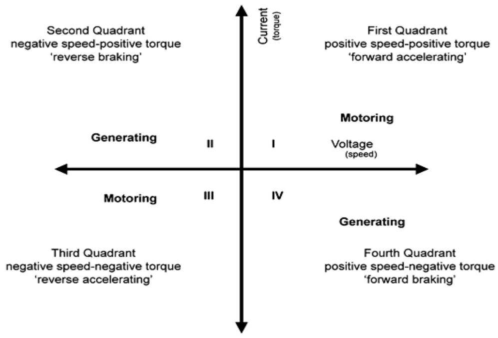

Figure 2: Four Quadrants of operation

When BLDC motor (Fig.3) 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. 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 waiting for the absolute standstill position, continuous energization of the main phase is attempted. This rapidly slows down the rotor to a stand-still position. Therefore, there is a necessity for determining the instant when the rotor of the machine is ideally positioned for reversal.

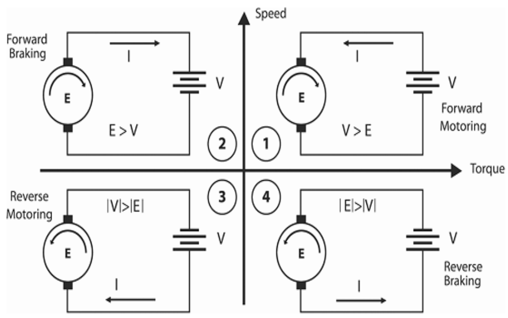

Figure 3: Operating Modes

The Brushless Dc Drive System

Four quadrants Zero current transition converter [8] was implemented for DC motor and single controllable switch for four quadrant operation was implemented for SRM drive. The common regenerative braking methods include adding an extra converter, or adding an extra ultra-capacitor, or switching sequence change of power switches. But the method of adding a converter not only increases cost but also reduces conversion efficiency. The method of adding an ultra capacitor doesn’t require extra DC-DC converter, but it needs a sensor to detect the ultra-capacitor voltage. This makes the circuit very complex and hard to implement. Moreover ultra-capacitor is very expensive.

The method proposed in this paper is simple and reliable. It conserves energy in a rechargeable battery during the regenerative [9-11] braking mode. Relay circuits are employed to run the motor during the accelerating mode and charge the battery during the regenerative mode.

The schematic diagram of the drive arrangement of the three phase BLDC motor is shown in Fig.4. The position signals obtained from the Hall sensors of the motor are read by the I/O lines of the TMS 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, which are applied to the three phase inverter.

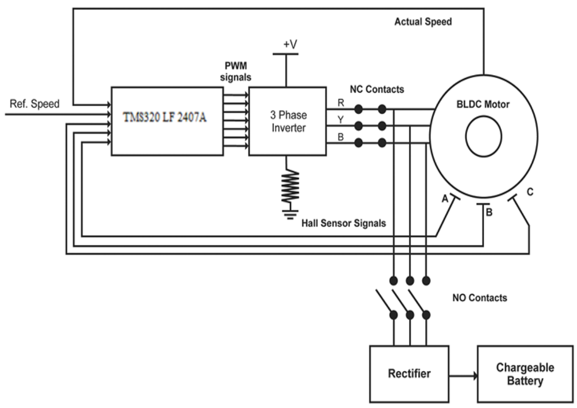

Figure 4: Closed Loop Drive

Whenever there is a reversal of direction of rotation it implies there is a change in the quadrant. When the motor is operating in the motoring mode, in the clockwise direction, the relay contacts are normally open. The relay circuit is shown in Fig.5. 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 and stored in a chargeable battery. The braking energy can be given back to the power source. But it increases the complexity of the circuit; the DC power generated has to be inverted to be given back to the mains.

Paper [12] discusses the FPGA-based novel digital PWM control scheme for BLDC motor.

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.

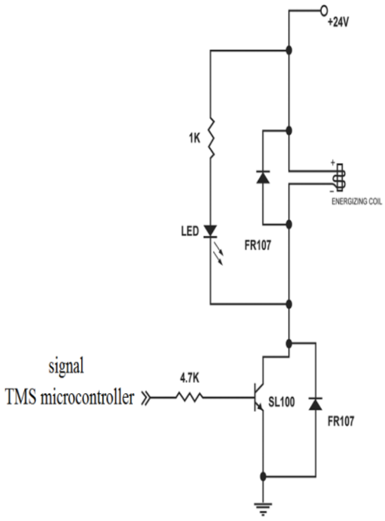

Figure 5: Relay Circuit

The actual speed of the motor is fed back to the conventional controller, which compares with the reference speed and gives the relevant output to the inverter circuit feeding power to the bldc motor. The difference in speed generates an error signal which aids the motor to run at a constant speed. Any sudden speed reduction (which is obtained from the Hall sensor signals of the motor) indicates that the brake is applied. The capture module of controller generates an interrupt signal, which closes the normally open contacts of the rectifier block and opens the normally closed contacts of the motor so that the power available can be fed to the battery for charging.

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. 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. Tuning process is done by trial and error method.

Experimental Setup

Figure 6: Hardware Implementation

The practical implementation of the four quadrant control of the three phase BLDC motor is shown in Fig.6. The set up includes mainly the DSP trainer kit TMS 320LF2407A, BLDC motor, three phase inverter with battery and relay. This DSP includes the advantages as the microcontroller but also offers higher speed, higher resolution, and capabilities to implement the math intensive algorithms to reduce the system cost. The high speed is attributable mainly to the dual bus of the Harvard architecture as well as single-cycle multiplication and addition instructions. One bus is used for data and the other is used for program instructions. This saves time because each is utilized simultaneously. Traditionally, cost has been a potential disadvantage of the DSP solution, but this aspect has diminished with the continuing decline of DSP costs. DSP controllers enable enhanced, real-time algorithms as well as sensor less control. The combination reduces the number of components and optimizes the design of silicon to achieve a system cost reduction.

The specifications of the motor and chargeable battery are listed in Table II. Chargeable battery of rating 6V and 1.3A/hr is used to store energy during regenerative mode. The relay coil has a resistance of 640 ohms. It has three normally open and three normally closed contacts.

Table 2: Specification of Brushless Dc Motor and Battery

Description	Value
Rated Votage	24V
Rated Current	2.4A
Rated Speed	3000rpm
Rated Power	60w
No.of Poles	8

No. of Phases	3
Rated Batter voltage	12V
Charging Current	1.3A/h

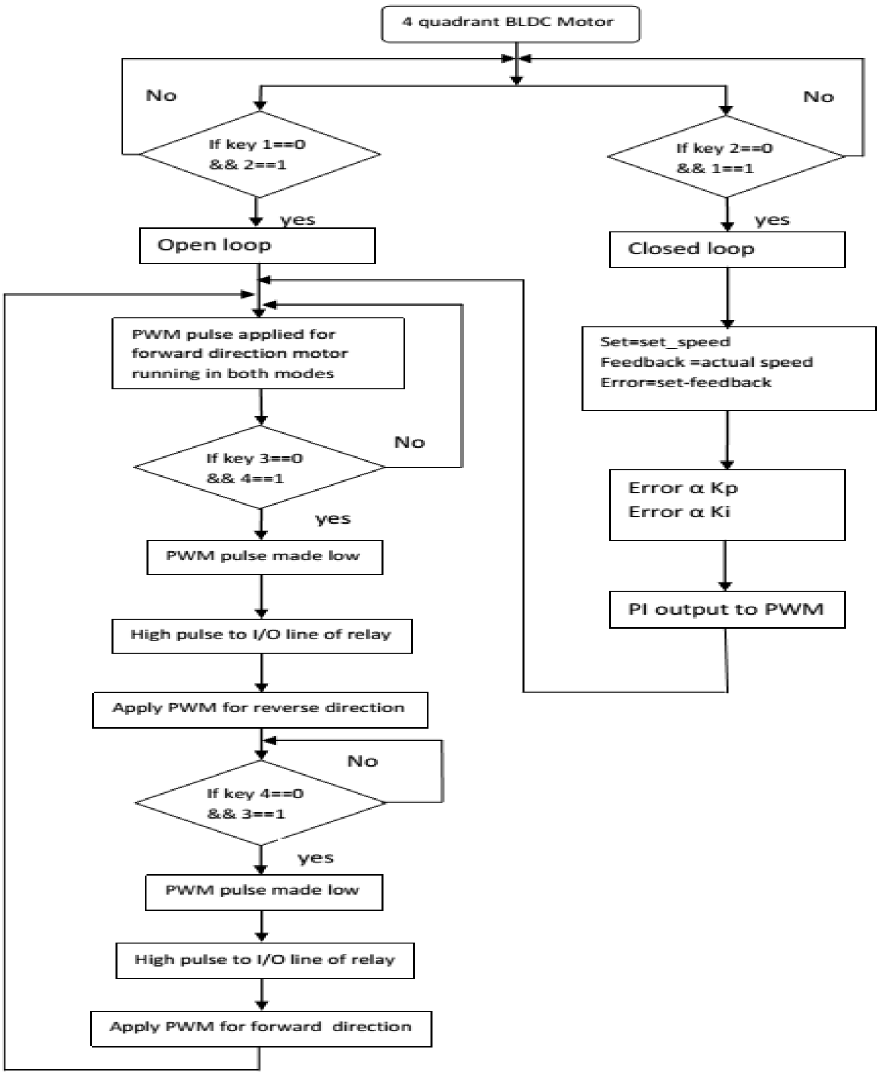

Figure 7: Flowchart for four quadrant controller

The flowchart for the four quadrant controller is presented in Fig 7. This describes the complete control algorithm designed for reaching the desired speed of the brushless dc motor in four quadrant operation using conventional technique with Digital Signal Processor TMS 320LF2407A.

Hardware Results

The tests for four quadrant drive of BLDC motor at various load and speed were conducted and some of the graphs for back emf speed, current have been shown in the following section.

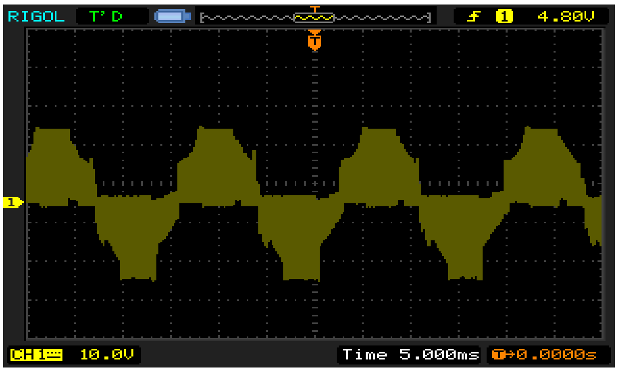

Figure 8: Trapezoidal Voltages of RY

The digital storage oscilloscope images shown in Fig. 8 indicate the trapezoidal voltage of phase R and Y.

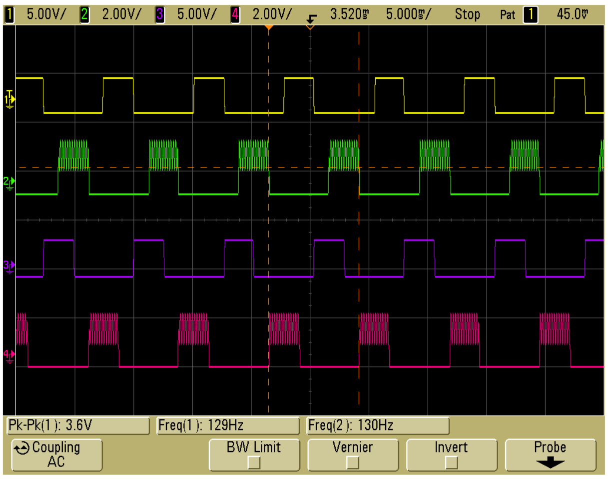

Figure 9: PWM Pulses—Control signals to the Inverter

The PWM pulses which are given as input to the inverter are shown in Fig.9.

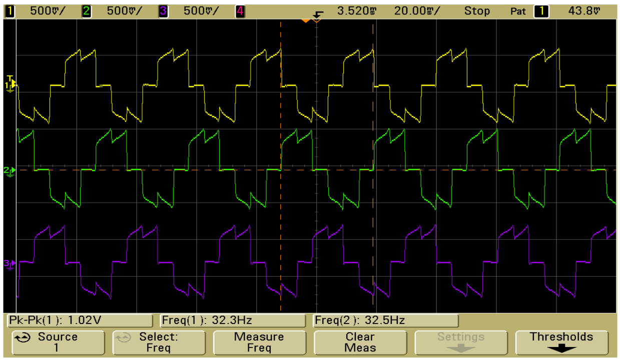

Figure 10: Current waveforms for phase-R,Y,B at 0.5kg & 1500rpm

Three phase currents (RYB) of the Brushless DC motor are shown in Fig. 10

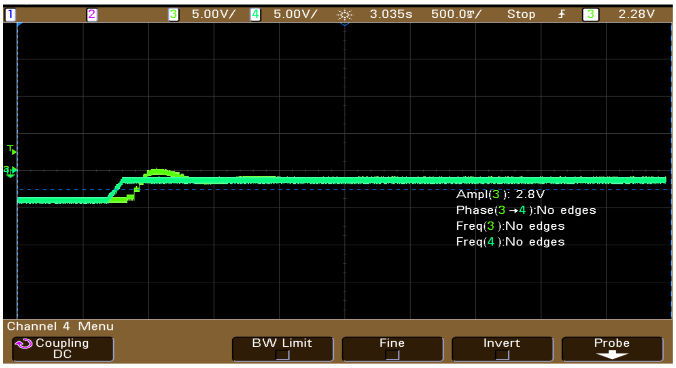

Figure 11: Speed Control For Step Change 500-1500 Rpm At 0.5kg

The speed wave form shown in Fig. 11 depicts that the actual speed nearing with the reference speed when changed from lower to higher speed (500 rpm to 1500 rpm).

Figure 12: Speed control for step change 2500-500 rpm at 0.5kg

The speed graph shown in Fig.12 depicts that the actual speed nearing with the reference speed when changed from higher to lower speed (2500 rpm to 500 rpm).

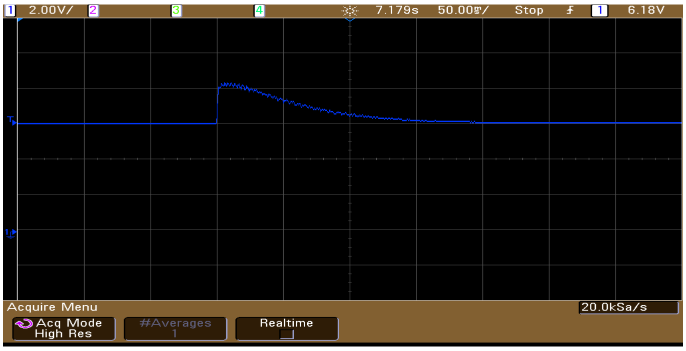

Figure 13: Energization of battery with load of 0.5Kg from 2500 rpm to -500rpm.

The energization of the batteries with loads of 0.5 kg and 0.75 kg are depicted in the plots of Figs. 13, 14 respectively.

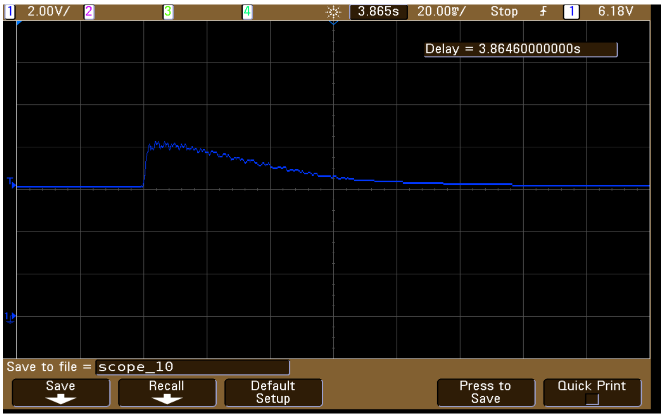

Figure 14: Energization of battery with load of 0.75Kg from 2500 rpm to -500rpm

In the Fig 13 and 14, voltage waveforms are shown which indicate the charging of battery due to switch over for same speed reversal at different load of the motor. Though the test was conducted for various speed and load only some graphs have been shown to analyze the performance of the motor for charging voltage of the battery. In the test conducted for higher speed reversal with light load gives more charging voltage for short duration. But for lower speed reversal with more loads gives less voltage for little longer duration. In both the cases battery gets the advantage of either high voltage for short duration or low voltage for longer duration.

Conclusion

In this paper, a control scheme has been proposed for BLDC motor to change the direction from CW to CCW and the speed control is achieved with the PI controller.

The controller performs really well for all the range of speed and load. Even for the changeover of the speed, controller is able track the reference speed quickly. The generated voltage during the regenerative mode can be given back to the supply mains which will result in considerable saving of power. This concept may well be utilized in the rotation of spindles, embroidery machines and electric vehicles where there is frequent reversal of direction of rotation of the motor.

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