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INTELLIGENT CONTROL METHODS FOR SENSOR LESS CONTROL OF BLDC MOTOR DRIVE USED IN HIGH SPEED APPLICATIONS

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ABSTRACT

Brushless dc (BLDC) motors and their drives are penetrating the market of home appliances, HVAC industry, and automotive applications in recent years because of their high efficiency, silent operation, compact form, reliability, and low maintenance. Traditionally, BLDC motors are commutated in six-step pattern with commutation controlled by position sensors. To reduce cost and complexity of the drive system, sensorless drive is preferred. In this paper, a fuzzy logic controller(FLC) for sensorless brushless dc (BLDC) motor. The proposedFLC is based on the terminal voltage measurement as thesensorless method for BLDC motor control. There are twomodules designed in the speed control of BLDC motor, i.e.command and regulating modules. Command module is to findand issue commutation period and PWM duty cycle to the BLDCmotor for desired speed. The regulating module is designed byapplying a FLC with sensorless technology and is used toregulate the speed of BLDC motor under various disturbances,such as loading effect. A new scheme is proposed for sensor-less control of PMBLDC motor for aligning its rotor at a known position.

Keywords: ack EMF; PMBLDC motor; position sensor-less, fuzzy logic controller (FLC).

I. INTRODUCTION

A. Background

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 permanent-magnet brushless electric motor production have 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 (EMDs) over the next five years [1]. The major appliances in the figure include clothes washers, room air conditioners, refrigerators, vacuum cleaners, freezers, etc. Water heaters, hot-water radiator pumps, power tools, garage door openers and commercial appliances are not included in these figures. 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. On the other hand, in recent year, the US government has proposed new higher energy-efficiency standards for appliance industry. In the near future, those standards will be imposed [2]. These proposals present new challenges and opportunities for appliance manufactures. In the same time, automotive industry and HVAC industry will also see the explosive growth ahead for electronically controlled motor system, the majority of which will be of the BLDC type [3,4]. For example, at present, the fuel pump in a car is driven by a dc brushed motor. A brush type fuel pump motor is designed to last 6,000 hours because of limit lifetime of the brush. In certain fleet vehicles this can be expended in less than 1 year. A BLDC motor life span is typically around 15,000 hours, extending the life of the motor by almost 3 times. It is in the similar situation for the air-conditioning blower and engine-cooling fan. It is expected that demanding for higher efficiency, better performance will push industries to adopt ASDs with faster pace than ever. The cost effective and high performance BLDC motor drive system will make big contribution for the transition.

The purpose of this paper is to design and implement a sensorless FLC to control high speed (over 10,000 rpm) BLDC motor to obtain optimal efficiency. The BLDC motor adopted in this paper requires high rpm over 10,000 rpm to yield high torque through gear reduction mechanism. The operating process has two modules in it, i.e., command module and regulating module. The command module is designed to find and issue the required PWM signal with commutation period to the BLDC motor for desired rpm. The regulating module is designed to regulate the true out commutation to match the desired commutation for desired speed in order to gain the optimum efficiency of the BLDC motor. The BLDC motor comes in with three-phase configuration and is driven by full bridge circuit which outputs three block pulses (rectangular wave) with 120° phase difference. By sensing the back-EMF voltage on the unexcited phase as the feedback signal where the other two phases are connected to the power supply, the FLC can accurately tune the PWM duty cycle to synchronize the rotors with the stator windings commutation sequence at the desired speed.

This will achieve the optimum efficiency of the BLDC motor. In order to alleviate the coding effort of FLC using microcontroller, we first compute the desired FLC outputs under many cases by hand. These data are then organized as a look-up table in the microcontroller. This will decrease the computation requirement in real-time environment. The implementation is based on Silicon's microcontroller C8051F330 to achieve excellent experimental results.

B. Brushless DC (BLDC) Motors and Sensorless Drives

Brushless dc motor [5] is one kind of permanent magnet synchronous motor, having permanent magnets on the rotor and trapezoidal shape back EMF. The BLDC motor employs a dc power supply switched to the stator phase windings of the motor by power devices, the switching sequence being determined from the rotor position. The phase current of BLDC motor, in typically rectangular shape, is synchronized with the back EMF to produce constant torque at a constant speed. The mechanical commutator of the brush dc motor is replaced by electronic switches, which supply current to the motor windings as a function of the rotor position. This kind of ac motor is called brushless dc motor, since its performance is similar to the traditional dc motor with commutators. Fig.1.2 shows the structure of a BLDC motor.

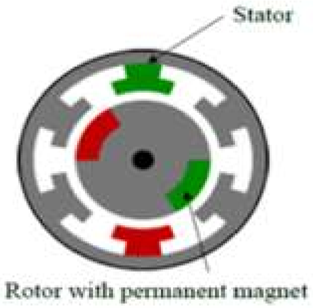
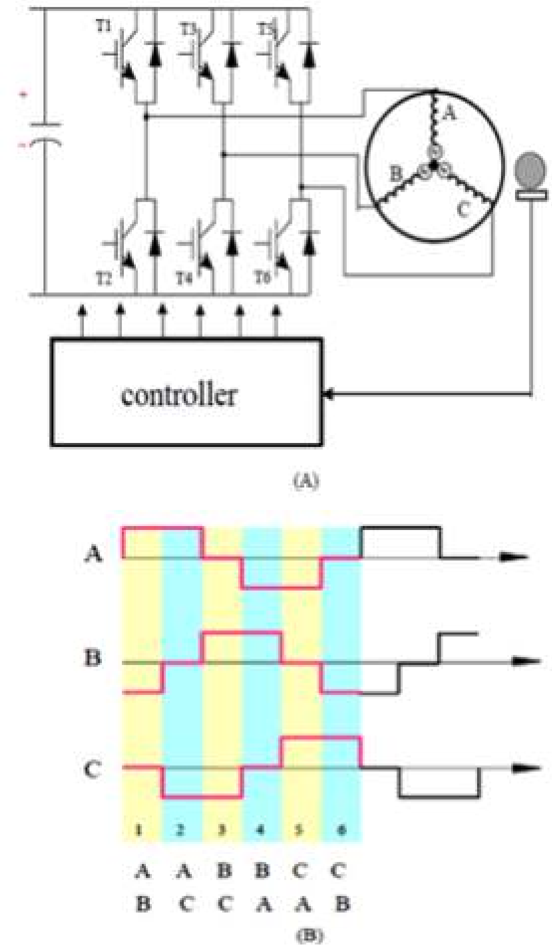


Fig.1.2. Structure of a brushless DC motor

These brushless dc motors are generally controlled using a three-phase inverter, requiring a rotor position sensor for starting and for providing the proper commutation sequence to control the inverter. These position sensors can be Hall sensors, resolvers, or absolute position sensors. A typical BLDC motor control system with position sensors is shown in Fig.1.3.



(A)

(B)

Fig. 1.3 (a) Typical brushless dc motor control system; (b) Typical three phase current waveforms in the BLDC motor.

Those sensors will increase the cost and the size of the motor, and a special mechanical arrangement needs to be made for mounting the sensors. These sensors, particularly Hall sensors, are temperature sensitive, limiting the operation of the motor to below about 75oC [6]. On the other hand, they could reduce the system reliability because of the components and wiring. In some applications, it even may not be possible to mount any position sensor on the motor. Therefore, sensorless control of BLDC motor has been receiving great interest in recent years.

II. DIRECT BACK EMF DETECTION FOR SENSORLESS BLDC DRIVES

In this section, a brief review of the conventional back EMF detection will be given first. Then, the proposed novel back EMF detection will be described. Experiment results demonstrate the advantages of the novel back EMF sensing scheme and the sensorless system. Specially, a low cost mixed-signal microcontroller that is the first commercial one dedicated for sensorless BLDC drives is developed, integrating the detection circuit and motor control peripherals with the standard microcontroller core.

A. Conventional Back EMF Detection Schemes

For three-phase BLDC motor, typically, it is driven with six-step 120 degree conducting mode. At one time instant, only two out of three phases are conducting current. For example, when phase A and phase B conduct current, phase C is floating. This conducting interval lasts 60 electrical degrees, which is called one step. A transition from one step to another different step is called commutation. So totally, there are 6 steps in one cycle. As shown in Fig.1.3 in previous section, the first step is AB, then to AC, to BC, to BA, to CA, to CB and then just repeats this pattern. Usually, the current is commutated in such way that the current is in phase with the phase back EMF to get the optimal control and maximum torque/ampere. The commutation time is determined by the rotor position. Since the shape of back EMF indicates the rotor position, it is possible to determine the commutation timing if the back EMF is known. In Fig.2.1, the phase current is in phase with the phase back EMF. If the zero crossing of the phase back EMF can be measured, we will know when to commutate the current.

As mentioned before, at one time instant, since only two phases are conducting current, the third winding is open. This opens a window to detect the back EMF in the floating winding. The concept detection scheme [5,6,7] is shown in Fig.2.2. The terminal voltage of the floating winding is measured. This scheme needs the motor neutral point voltage to get the zero crossing of the back EMF, since the back EMF voltage is referred to the motor neutral point. The terminal voltage is compared to the neutral point, then the zero crossing of the back EMF can be obtained. In most cases, the motor neutral point is not available. In practice, the most commonly used method is to build a virtual neutral point that will, in theory, be at the same potential as the center of a Y wound motor and then to sense the difference between the virtual neutral and the voltage at the floating terminal. The virtual neutral point is built by resistors, which is shown in Fig 2.2 (B). This scheme is quite simple. It has been used for a long time since the invention [6]. However, this scheme has its drawbacks.

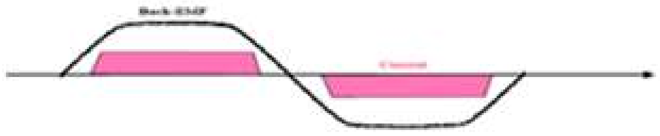


Fig. 2.1. The phase current is in phase with the back EMF in brushless dc motor.

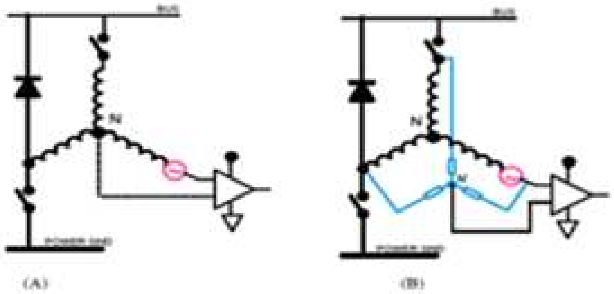


Fig. 2.2. (a) Back EMF zero crossing detection scheme with the motor neutral point available; (b) back EMF zero crossing detection scheme with the virtual neutral point.

III. PROPOSED POSITION SENSORLESS CONTROL OF PMBLDC MOTOR

Based on the discussion presented above, a scheme is proposed for sensor-less control of PMBLDC motor shown in Fig. 3.1, for aligning its rotor at a known position. This is accomplished by applying high frequency pulses to the upper switches of phases A and C along with lower switch of phase B of voltage source inverter [27]. The applied frequency should be chosen such that the motor does not draw excessive current and the rotor should be stabilized at a known position. Fig. 3.2 shows the proposed scheme starting of PMBLDCM from known position, which uses a predetermined switching sequence (commutation pulse generator) so patterned that the motor speed up Gradually while overcoming the inertia and the load on the motor shaft. These pulses are multiplied by PWM pulses (HF pulse generator) so that the current drawn by the motor does not become dangerously high.

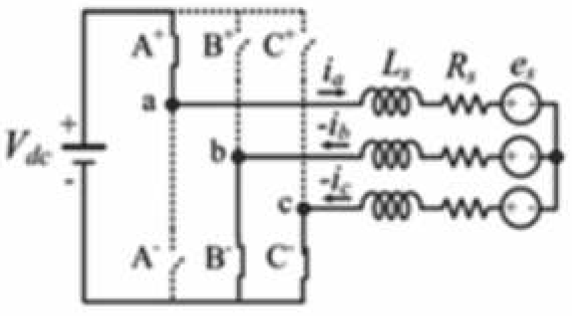


Fig. 3.1. The Proposed Scheme to align the rotor at known position

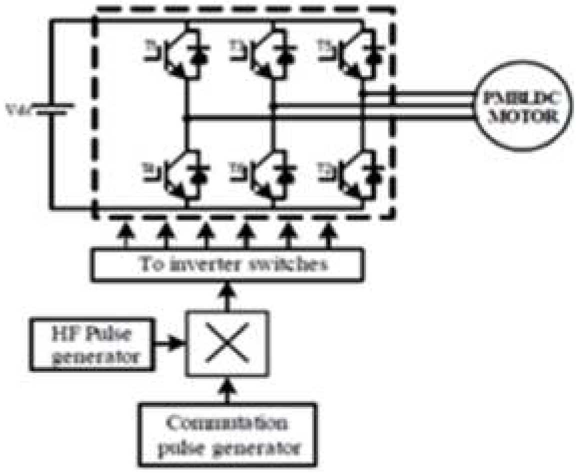


Fig. 3.2. Schematic diagram for starting of PMBLDC known Position

After achieving certain speed where enough back EMF is available the control is shifted to back-EMF based sensor-less control [6, 9]. In this method, the controller generates switching sequences for the VSI after detecting zero crossing of back-EMF and provides a 30 electrical degree phase shift so that the current waveforms of the PMBLDCM coincides the flat portion of the back-EMF waveforms and generates a constant torque at the motor shaft. Speed of the PMBLDCM is controlled by a current control loop using current multiplier approach.

IV. IMPLEMENTATION OF SENSORLESS RUNNING OF PMBLDC MOTOR USING PROPOSED SCHEME

The complete control scheme is modeled and simulated in MATLAB-SIMULINK environment to demonstrate the position sensor-less control of a PMBLD CM drive having following data. Rated power = 691.15 wat tts; Rated speed = 3000 rpm; Rated torque = 2.2 Nm; Number o of poles = 4; Stator resistance = 2.78 Ω/phase; Stator inductance = 7.7050 mH/phase; Torque constant = 0.74 Nm/A; Inertia = 0.00014 Kg.m2.

The results shown in Fig. 4.1 demonstrate successful alignment of the rotor at a known position from where the motor is started successfully and runs up to the threshold speed and thereafter shifted to the back-EMF control method for position sensor-less operation at 0.25 sec. Fig. 4.2 shows the variation of speed under position sensor-less running mode at constant torque on motor shaft. The stator current remains within limits of its rated value with successful acceleration of the motor.

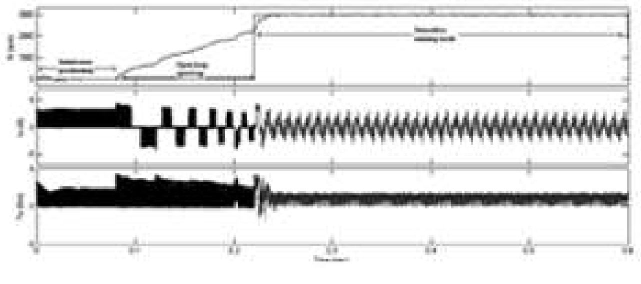


Fig. 4.1. Starting with 50% torque and rated speed (3000 rpm)

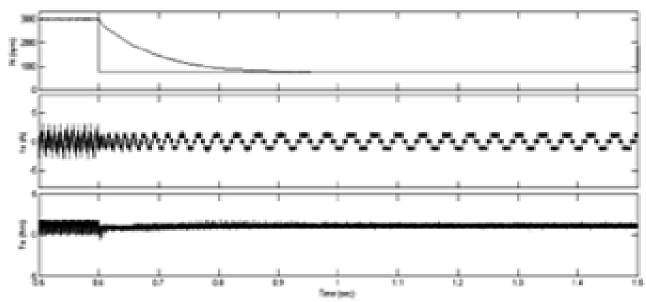


Fig. 4.2. (a) Speed variation from speed 3000 rpm to 750 rpm

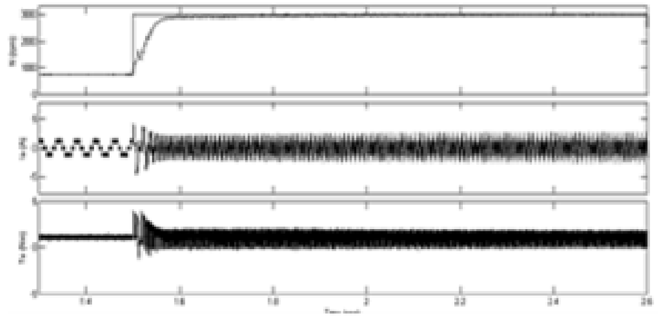


Fig. 4.2. (b) Speed variation from 750 rpm to rated speed 3000 rpm

V. PROPOSED FUZZY LOGIC CONTROLLER (FLC) FOR SENSORLESS BLDCMOTOR

Fig. 5.1 shows a FLC for sensorless BLDC motor control. The fuzzy partition of input space (BEMF) and output space (PCA) will be partitioned into five-term set in this paper. Fig. 5.2 shows the architecture of a FLC for sensor less BLDC motor. BEMF is the input of FLC for sensor less BLCD motor where PCA is the output.

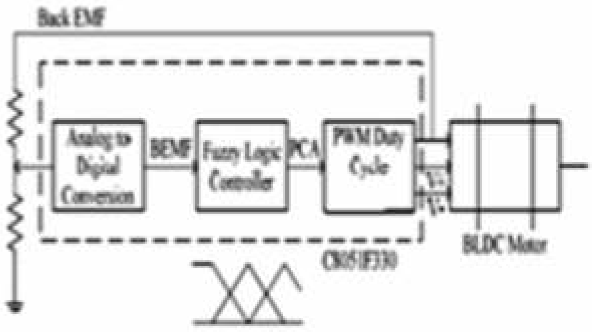


Fig. 5.2. The architecture of a FLC for sensor less BLDC motor

The five-term set for input space (BEMF) is as {Very Small, Small, Medium, Large, Very Large}. The five-term set for output space (PCA) is as {PCA-4, PCA-2, PCA, PCA+2, PCA+4}. Because of the five-term set on input space, there are five fuzzy rules defined as following lists:

Rule 1: if x is A1, then y is B5.
Rule 2: if x is A2, then y is B4.
Rule 3: if x is A3, then y is B3.
Rule 4: if x is A4, then y is B2.
Rule 5: if x is A5, then y is B1.

where x represents BEMF, y represent PCA, {A1, A2, A3, A4, A5}= {Very Small, Small, Medium, Large, Very Large} individually, and {B1, B2, B3, B4, B5}= {PCA-4, PCA-2, PCA, PCA+2, PCA+4} individually. Triangular membership functions for input parameters and output parameters are listed as follows. Input:

$$\mu_{A1} = \begin{cases} 10, & x \le -50 \\ 10-(x+50)/3, & -50 < x < -20 \end{cases}$$

$$\mu_{A2} = \begin{cases} (x+50)/3, & -50 < x \le -20 \\ -x/2, & -20 < x < 0 \end{cases}$$

$$\mu_{A3} = \begin{cases} (x+20)/2, & -20 < x \le 0 \\ 10-x/4, & 0 < x < 40 \end{cases}$$

$$\mu_{A4} = \begin{cases} x/4, & 0 < x \le 40 \\ 10-(x-40)/3, & 40 < x < 70 \end{cases}$$

$$\mu_{A5} = \begin{cases} (x-40)/3, & 40 < x < 70 \\ 10, & 70 \le x \end{cases}$$

Output:

$$\mu_{B1} = \begin{cases} 10, & y \le PCA-4 \\ 5PCA-5y-10, & PCA-4 < y < PCA-2 \end{cases}$$

$$\mu_{B2} = \begin{cases} 5y-5PCA+20, & PCA-4 < y \le PCA-2 \\ 5PCA-5y, & PCA-2 < y < PCA \end{cases}$$

$$\mu_{B3} = \begin{cases} 5y-5PCA+10, & PCA-2 < y \le PCA \\ 5PCA-5y+10, & PCA < y < PCA+2 \end{cases}$$

$$\mu_{B4} = \begin{cases} 5y-5PCA, & PCA < y \le PCA+2 \\ 5PCA-5y+20, & PCA+2 < y < PCA+4 \end{cases}$$

$$\mu_{B5} = \begin{cases} 5y-5PCA-10, & PCA+2 < y < PCA+4 \\ 10, & PCA+4 \le y \end{cases}$$

where x is the ADC value which is the back-EMF voltage detected on the unexcited phase at the desired rotational speed. Fig. 5.3 shows the membership functions for input parameters, {Very Small, Small, Medium, Large, Very Large}. Fig. 5.4 shows the membership functions for output parameters, {PCA-4, PCA-2, PCA, PCA+2, PCA+4}.

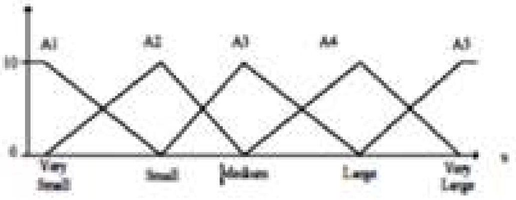


Fig. 5.3. Fuzzy partitions for input parameter

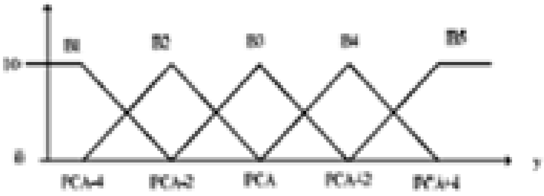


Fig. 5.4. Fuzzy partitions for output parameter

Equation (1) is the COA defuzzification implication which generates the center of gravity of all possible distribution of a control action.

$$Z_{COA} = \frac{\sum_{j=1}^{n} \mu_c(z_j) z_j}{\sum_{j=1}^{n} \mu_c(z_j)} \qquad (1)$$

Since the microcontroller C8051F330 adopted in this paper has only limited integer computing power, it is therefore not suitable for implementing the real-time FLC. In order to reduce the computational load of real-time FLC for the microcontroller C8051F330, the input triangular membership functions have to be changed into block pulse membership function (BPMFs) to cover nearly all cases. BPMF's for input parameters are listed as follows.

Input:

$$\mu_{A1} = \begin{cases} 10, & x \le -35 \\ 0, & otherwise \end{cases} \qquad \mu_{A2} = \begin{cases} 10, & -35 < x \le -10 \\ 0, & otherwise \end{cases}$$

$$\mu_{A3} = \begin{cases} 10, & -10 < x \le 20 \\ 0, & otherwise \end{cases} \qquad \mu_{A4} = \begin{cases} 10, & 20 < x \le 55 \\ 0, & otherwise \end{cases}$$

$$\mu_{A5} = \begin{cases} 10, & 55 < x \\ 0, & otherwise \end{cases}$$

There are two major modules for the intelligent control of the sensorless BLDC motor, i.e., command module and regulating module as shown in Fig. 9. The command module is designed to find and issue the necessary PWM signal with frequency to control circuit of BLDC motor for desired rotational speed. The regulating module is designed to regulate the true output commutation to match the desired commutation for desired speed. Fig. 10 displays a photograph of the experimental equipment.

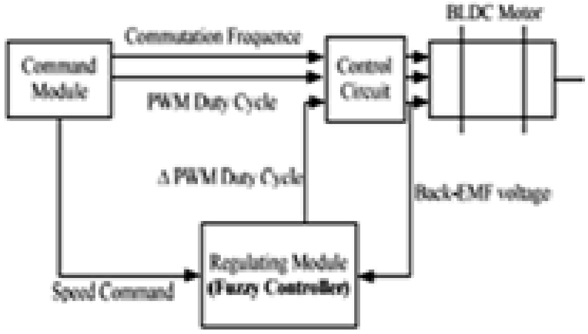


Fig. 5.5. Intelligent closed-loop control of BLDC

Fig. 5.7 shows the unfiltered and filtered a-phase terminal voltages and gating signals of the a-phase switching devices at ωr= 6000 rpm. Although the filtered terminal voltage lags the nonfiltered terminal voltage, A+ and A− both are nearly in phase with the actual terminal voltage.

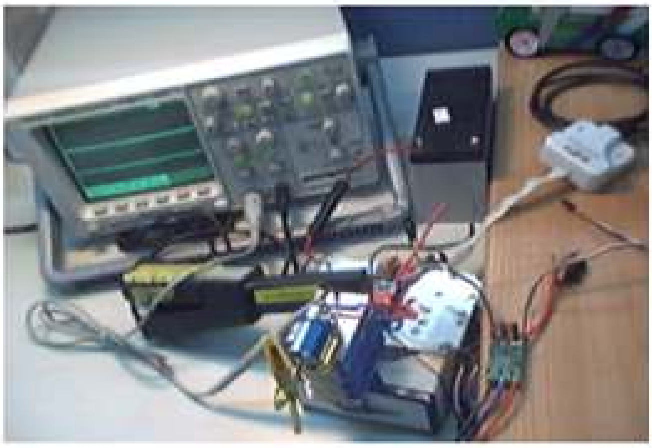


Fig. 5.6. Experimental equipment for fuzzy logic controller of sensorless BLDC motor control

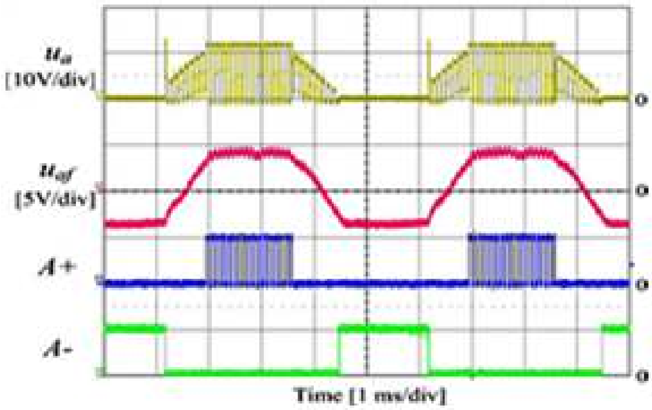


Fig. 5.7. A-phase terminal voltages and gating signals at ωr= 6000 rpm.

Fig. 5.8 shows the unfiltered and filtered a-phase terminal voltages and stator current at heavy load when the rotor speed is 6000 rpm. The stator current is increased and the conducting period of the freewheeling diode is extended a little bit.

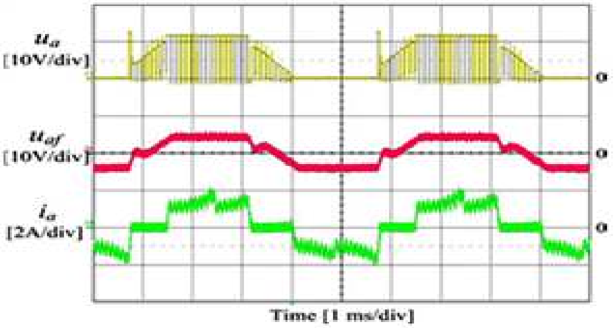
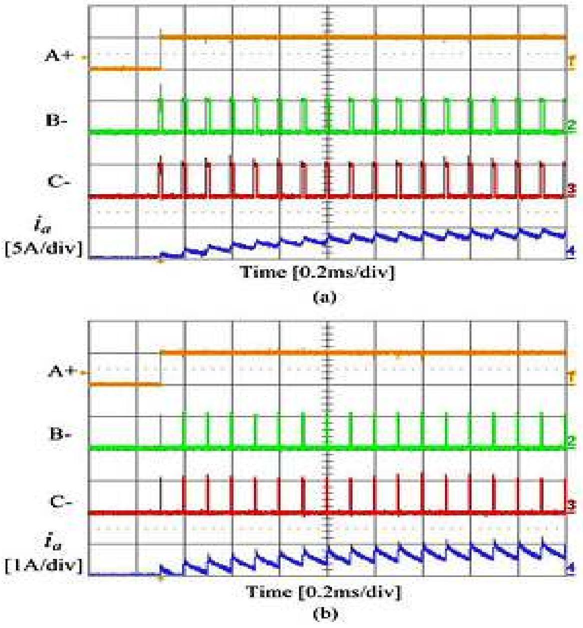


Fig. 5.8. Terminal voltages and stator current at heavy load when the rotor speed is 6000 rpm.

The response of the a-phase stator current while aligning the rotor position is shown in Fig. 5.9. The switching device A+ is always conducted and both switches B− and C− are modulated by 7% and 15% duty cycles, respectively. The average values of stator current are about 0.8 and 4 A when the duty cycle is 7% and 15%, respectively.



(a)

(b)

Fig. 5.9. PWM signals and stator current response under aligning rotor position. (a) At 7% duty cycle. (b) At 15% duty cycle.

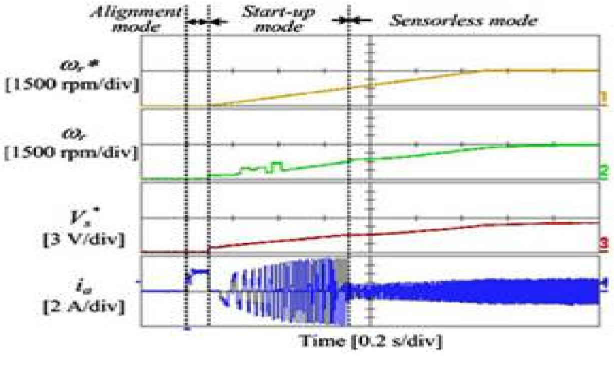


Fig. 5.10. Transient responses from the start-up mode to the sensorless mode.

Fig. 5.10 shows the experimental results for responses of the reference and rotor speeds, reference voltage, and a-phase current in order to verify the start-up technique. At first, the rotor is aligned to the initial position for a time interval of 80 ms by adjusting the duty cycle to 15%. After then, the motor is accelerated to 3000 rpm by the proposed start-up method. Subsequently, a sensorless control scheme for the BLDC motor is applied for speeding up the motor to 6000 rpm. The start-up time is about 1.2 s, which is acceptable for vehicle fuel pump application.

VI. CONCLUSION

The intelligent control for sensorless BLDC motor has been designed and implemented successfully in this paper by using the Silicon's microcontroller C8051F330. The control law in this paper is to hold the zero-crossing point of back-EMF signal at the desired position even there exists a external disturbance. a high frequency pulse injection method is proposed for quick alignment of the rotor to a known position and then speed it up in open loop till its back- EMF becomes detectable. Thereafter it is shifted to back-EMF detection method. The whole control strategy contains two modules, i.e., command and regulating modules. The command module will find proper commutation sequence period and PWM duty cycle for BLDC motor to rotate at the desired speed. The regulating module is designed to regulate BLDC motor speed when there is an external disturbance, such as loading effect. The regulating module is designed by FLC to yield excellent results. In comparison with a none regulation module or a regulating module with P controller, the results indicate FLC have yielded a better result.

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