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Design and Construction of a Sensorless Circuit for Brushless DC Motor using Third Harmonic back Electromotive Force

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ABSTRACT

In this paper the method of sensorless startup of direct current brushless motor using third harmonic back Electromotive Force (EMF) and motor startup using microcontroller for pulse width modulation, power switch control and motor output analysis is presented which renders RPM control and high speed achievement for motor. The microcontroller is used for processor and metal-oxide semiconductor field-effect transistor (MOSFETs) are used for power circuit. Besides, the motor does not have any sensors to detect rotor position. Furthermore, the microcontroller modulates pulse width, controls power circuit and analyses motor output. The innovation in this research is that the third harmonic function is used for motor control and is compared with the Back-EMF force to recognize zero crossing. Moreover, N-type MOSFETs are used in power circuit high side and low side which are useful in the current rate of MOSFETs due to their similarities. Also, the IR2101 MOSFET drive is utilized for startup which improves the firing time of MOSFETs. Besides, using tantalum capacitors and putting resistor by the gate route of MOSFETs is efficient. Finally, experimental results are given to verify the validation of the proposed method.

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NOMENCLATURE

V_{an}	Voltage between A phase and neutral Point	θ_r	
Ri_a	Multiplying the resistance in phase A flow	i_a	Phase A flow
$L\frac{di_a}{dt}$	Multiplying the self-inductance in differential flow changes in time	λ_3rd	
e_a		V_{summed}	Total voltages
E_1			

1. INTRODUCTION

Nowadays, brushless DC motors are of paramount importance due to their high efficiency and removal of copper rotor losses, low content and weight, reduction of heat losses, low noise, easy maintenance and longevity, reduction in the requirements for stimulation, operating at high speeds, removal of sparks in the brushes, elimination of all types of radio frequency interference and simple control. In return, the problem of operation's drive and their operating method without sensors can be considered as a main problem [1]. In this paper, brushless DC motors using the third harmonic back EMF methods and microcontroller processor is studied. The method of measuring the third harmonic of back EMF voltage compared with measuring the back EMF voltage have advantages such as the lack of sensitivity to phase delay as a result of using filters for measuring terminal voltages [2]. The resulting third harmonic signal maintains a constant phase relationship with the rotor flux at any motor speed and load condition [3]. Some practices show that digital filtering for back EMF noise reduction turns the waveform into the ideal form to detect zero-crossing [4]. In low speeds because of the lack of back EMF signal, estimating a

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line-to-line back-EMF in real time makes rotor position detection possible [5]. These motors are also driven using the method of integrating the back EMF voltage. However, most of these methods are either very complicated and require expensive equipment or are not of enough accuracy [6, 7]. In some papers simulations are used to practice the position of this kind of motors [8].

Speed control and rising and lowering brushless DC motors torque are challenging. These complexities together with sensor and sensorless methods to detect rotor position rise up a variety of consequences. So, speed control of the aforementioned motors and sensorless methods are regarded as a novel prospect. Among all presented methods, measuring the third harmonic back EMF to evaluate rotor position is the most suitable measure, since there exist three cycles of third harmonic in one cycle EMF which has two zero crossings. These features cause accuracy increase for motor high speeds. Therefore, in this paper, the method of measuring and comparing the third harmonic back EMF voltage using elements as microcontrollers which is always accessible but not expensive is suggested.

2. MATHEMATICAL MODEL AND THE DOMINANT RELATION OVER THE THIRD HARMONIC OF BACK EMF VOLTAGE

In this method the third harmonic of back EMF stimulation for the determination of switching time at the time of operating brushless DC motor with a guiding integral of 120 degrees is used. The method is not sensitive to pulse delay due to filters used to measure sensitive terminal voltage. The brushless DC motor's terminal voltages are as follow [9]:

$$V_{an} = Ri_a + L\frac{di_a}{dt} + e_a$$
$$V_{bn} = Ri_b + L\frac{di_b}{dt} + e_b \quad (1)$$
$$V_{cn} = Ri_c + L\frac{di_c}{dt} + e_c$$

EMF voltages in Equation (1) could be shown by extending their Fourier series as follow:

$$e_a = E_1 \sin\theta_r + E_3 \sin 3\theta_r + E_5 \sin 5\theta_r + E_7 \sin 7\theta_{...}$$
$$e_b = E_1 \sin(\theta_r - \tfrac{2\pi}{3}) + E_3 \sin 3(\theta_r - \tfrac{2\pi}{3}) + E_5 \sin(\theta_r - \tfrac{2\pi}{3}) + E_7 \sin 7(\theta_r - \tfrac{2\pi}{3}) + \cdots \quad (2)$$
$$e_c = E_1 \sin(\theta_r - \tfrac{4\pi}{3}) + E_3 \sin 3(\theta_r - \tfrac{4\pi}{3}) + E_5 \sin(\theta_r - \tfrac{4\pi}{3}) + E_7 \sin 7(\theta_r - \tfrac{4\pi}{3}) + \cdots$$

The summation of three back EMF voltages is as follow:

$$e_a + e_b + e_c = 3E_3 \sin 3\theta_r + 3E_9 \sin 9\theta_r + 3E_{15} \sin 15\theta_r + \cdots \approx 3E_3 \sin 3\theta_r \quad (3)$$

$$V_{bn} = Ri_b + L\frac{di_b}{dt} + e_b$$

By terminal voltage summation and replacing the sum of three back EMF voltages, and with respect to Equations (2) and (3), we have:

$$V_{an} + V_{bn} + V_{cn} = \left(R + L\frac{d}{dt}\right)(i_a + i_b + i_c) + (e_a + e_b + e_c) = e_a + e_b + e_c \approx 3E_3 \sin 3\theta_r \quad (4)$$

Based on Equation (4) and assuming that the sum of currents is negligible and about zero, total voltages of terminal includes only the multiples of third harmonic back EMF voltage in phase A. The third harmonic section is dominated on higher harmonic and as a result this sum is equal to the third harmonic of back EMF voltage. Also in order to obtain the moments of switching, integral of filtered voltage signal is achieved which is the same as third harmonic of back EMF voltage component, and the third harmonic flux is obtained as follows:

$$\lambda_{3rd} = \int V_{summed}\, dt \quad (5)$$

According to Figure 1, the third harmonic flux has 30 electrical degrees phase delay comparing with the third harmonic of back EMF voltage and a phase delay of 30 degrees from back EMF voltage of phase A. So the crossing points from zero of the third harmonic flux will be based on the commutation of brushless direct current motor phases. According to Figure 1, the internal voltage of motor in phase A (e_A), third harmonic (VSUM), third harmonic flux of rotor ($\lambda r3$), rotor flux (λ_r) and the stator currents (I_A, I_B and I_C) are displayed and also commutation times are shown by point-to-point line.

To determine the back EMF of third harmonic, additional measurement circuits are required. The third harmonic procedure has a wider scope comparing with the measured terminal voltage and is practical for rotor speed from 100 to 6000 rpm.

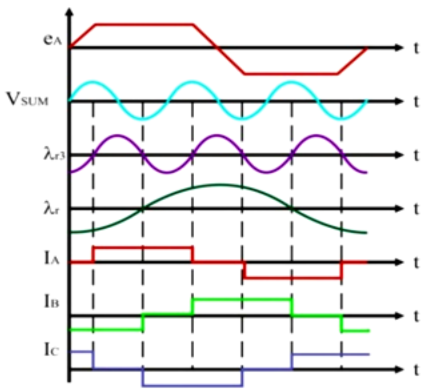

Figure 1. The internal voltage of motor in phase a, third harmonic, third harmonic flux of rotor, rotor flux and the stator currents

Meanwhile, the phase delay caused by the filtering was lower in this method and therefore the measurement error is lower, but unlike terminal voltage measuring procedure, this method may lead to significant errors at low speeds due to the extensive integration period. Also in low speeds, the third harmonic signal amplitude is small. In addition to the mentioned disadvantages, the performance of this method is not also desirable in constant power area [10, 11].

3. HOW TO MEASURE BACK EMF VOLTAGE

Since back EMF is needed to achieve the third harmonic voltage, measuring operation and practical circuits for back EMF voltage will be discussed. For a three-phase brushless DC motor, there are generally six steps that at the moment, two phases amongst the three-phases of this motor are driving the current. If the three-phases of motor are called A, B and C, respectively; in case phases A and B are driven, phase C is free which takes up 60 electrical degrees which is called a step. Phase current has the same phase as back EMF, so if the pass zero crossing of back EMF is observed, the commutation time is determined and so as stated above, the phase does not pass current and can reveal back EMF voltage. Figure 2 demonstrates the voltage's measurement conceptual circuits [10].

The main problem with these methods is the potential difference which quickly goes up and down and carries high frequency noises. For example, in case of having a 200 volts motor, the potential difference between the neutral points can vary from 0 to 200 volts. However, in practice voltages which are less than 5 volts are suitable for comparison purposes, therefore voltage divider and low pass filter could be effective to reduce the resulting potential difference and reduce high-frequency noise. Figure 3 shows our proposed model [12].

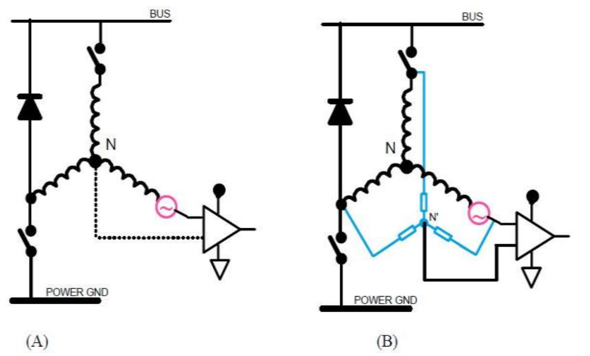

Figure 2. Conceptual circuits for measuring back EMF voltage

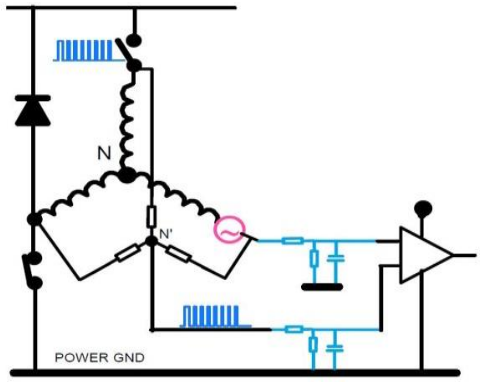

Figure 3. Practical procedure for measuring EMF voltage using virtual neutral point

According to Figure 4 which is the equivalent circuit of Figure 3, when upper switch of phase A is turned on, current is applied to windings A and B through switch, and when the upper switch of phase A is turned off, current is discharged through the diode which is parallel with lower key of phase a. In the meantime, C-terminal voltage is measured while the current does not exist in this phase [12].

According to Figure 4, it can be seen that $v_c = e_c + v_n$ where, v_c is C terminal's free voltage, e_c is back EMF voltage and v_n is neutral point voltage or the middle of motor windings [12].

Based on phase A, if the diode voltage drop is not considered, we have:

$$v_n = 0 - ir - L\frac{di}{dt} - e_a \quad (6)$$

Based on phase B, if the Key voltage drop is not considered, we have:

$$v_n = ri + L\frac{di}{dt} - e_b \quad (7)$$

After summing Equations (6) and (7), we have:

$$v_n = -\frac{e_a + e_b}{2} \quad (8)$$

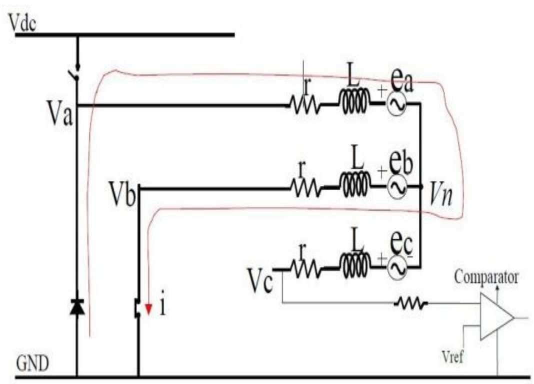

Figure 4. Equivalent electrical circuit of Figure 4

Considering a balanced three phase system and if the third harmonic is ignored, we have:

$$e_a + e_b + e_c = 0 \quad (9)$$

And if the third harmonic is considered, we have:

$$e_a + e_b + e_c = e_3 \quad (10)$$

Where, e_3 is the third harmonic. First the circuit without considering the third harmonic is analyzed.
Based on equations (8) and (9), we have:

$$v_n = \frac{e_c}{2} \quad (11)$$

So, C terminal voltage is as follows:

$$v_c = e_c + v_n = \frac{3}{2}e_c \quad (12)$$

From Equation (12) it can be concluded that during the time where there is no pulse width modulation; that is the time for directing freewheeling diode, free phase terminal voltage has direct access to the back EMF voltage and in this case switching noise is not added. It's also worth noting that the terminal voltage is not related to the neutral point, so it is not necessary to know the middle point voltage of motor. Also as long as EMF is extracted from the motor terminal, the crossing time from zero is precisely determined [13].

In case the third harmonic effect is considered, based on Equations (8) and (9), we have:

$$v_n = \frac{e_c}{2} - \frac{e_3}{2} \quad (13)$$

So, for C terminal output voltage, we have:

$$v_c = e_c + v_n = \frac{3}{2}e_c - \frac{e_3}{2} \quad (14)$$

So the terminal voltage carries the third harmonic. Although crossing from zero of main wave and third harmonic are the same, third harmonic is not effective on crossing from zero crossing of the main wave [15].

4. THE DESIGNED CIRCUIT

4. 1. Microcontroller Feeder Circuit The circuit is powered by a 12-volt switching transformer, so this part of circuit is used as the microcontroller power and makes 5volt voltage from 12-volt input voltage (Figure 5). C18 capacitor acts as a 12V input filter. Also, J1 is the input terminal of circuit which is connected to 12V feeder. D16 diode protects the circuit, if opposite input (positive instead of negative or vice versa) is applied. C4 capacitor is used to prevent the input voltage ripple and C5 capacitor act as an input noise gate filter.

U4 IC Regulator is used to convert the 12-volt input to 5volt input. C6 capacitor is applied as the output filter and C7 capacitor is the output noise gate filter. R13 resistance directs current to the main supply which is connected to D17 LED showing that circuit power is connected. Also in case the output voltage is more than 5 volts, D18 Zener diode is connected to the output for protection purposes.

4. 2. Power Circuit Figure 6 shows the power circuit which is used in one phase. 12 V voltages are applied to drain of Q1 MOSFET. R1 resistor causes waveform bow with a slight delay applied to voltage. So MOSFET is turned on later and on the other hand during turn off, D1 diode causes the MOSFET to turn off sooner. In fact, these two elements are used for protection. R3 resistor ensures that in case there is no MOSFET gate voltage, MOSFET does not turn on and in this case, it is Pulled Down. In order to turn Q1 MOSFET on, the gate voltage must be 5 volts more than that of the source. In this circuit the source of the upper MOSFET is not connected to ground, and Q1 and Q2 can never be turned on simultaneously, so IR2101 module is used to fix the problem. In case the lower MOSFET is turned on which means that is connected to the ground, C1 capacitor is charged through VS1. When Q2 is turned off and so it is desired to turn Q1 on, the voltage of C1 capacitor turns Q1 on. D2 Diode is a fast diode and is able to quickly charge C1 capacitor. Figure 6 shows the structure of the power circuit.

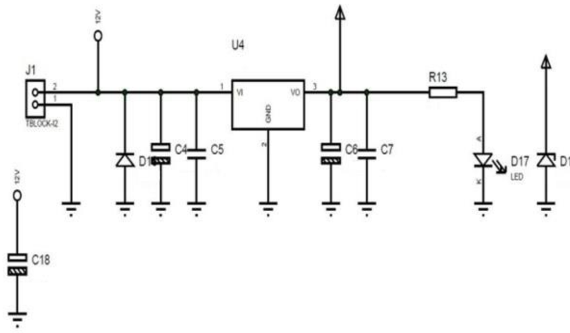

Figure 5. Microcontroller feeder circuit

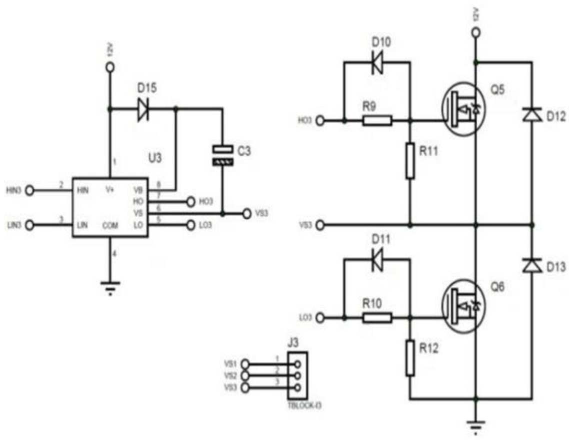

Figure 6. MOSFET power circuit, MOSFET driver circuit and output socket

4. 3. Circuit to Increase and Reduce Motor Speed According to Figure 7, four circuits are used to increase and reduce the motor speed and to reset the microcontroller. From left to right, the motor speed decreasing circuit, the motor speed increasing circuit and the microcontroller reset circuits are shown. The aforementioned circuits are connected to the microcontroller bases and operate by the software.

4. 4. The Circuit to Sample Motor Output Figure 8 shows the circuits to sample motor output. The circuits in the first row are voltage divider circuits which sample back EMF output of the motor using a low-pass filter capacitor and pass it to the second-row circuit of Figure 8 which adds motor's output. The result is connected to ADC1, ADC2 and ADC3 inputs to be compared. Also, the summation of outputs is transferred to the microcontroller which is compared with the instantaneous values of back EMF. As stated in Equation (10), the instantaneous summation of outputs is the same as the third harmonic. This means that this part of the circuit is used to compare back EMF duty free phase with the third harmonic back EMF. In order to detect rotor position, the microcontroller applies voltage to two phases and the third phase voltage is compared with the instantaneous summation of all phases. As soon as the phase voltage becomes less than the phase's instantaneous summation, the zero crossing is occurred and the phases order should change for switching.

4. 5. Microcontroller One of the most important parts of startup motor drive is composed of microcontroller which controls power switches using pulse width modulation, samples back EMF generated in motor output terminals and detects third harmonic of back EMF. In this regard, ATMEGA1284P-PU is used as a microcontroller having 128 KB memory, six basic pulse width modulations, significantly low microcontroller noise comparing with other microcontrollers, up to eight analog to digital inputs and up to 20 MHz speed. Figure 9 shows the microcontroller circuit with 20 MHz X1 crystal connected to C9 and C10 capacitors as splitter. Furthermore, J2 socket is used for microcontroller programming.

4. 6. The Proposed Circuit Output Image of the circuit proposed is given in Figure 10. This drive is able to launch, detect position and control the motor speed and in case the rotor shaft is locked, the motor stops automatically and then starts up.

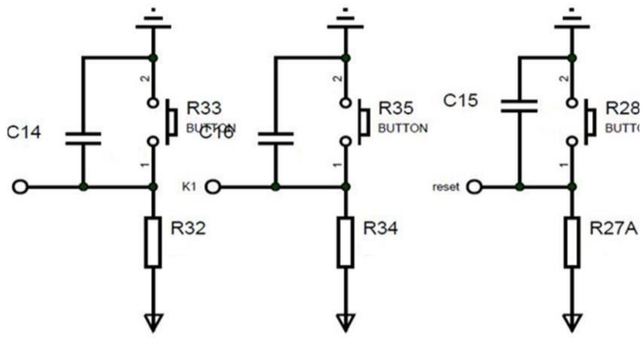

Figure 7. Circuits to increase and decrease motor speed

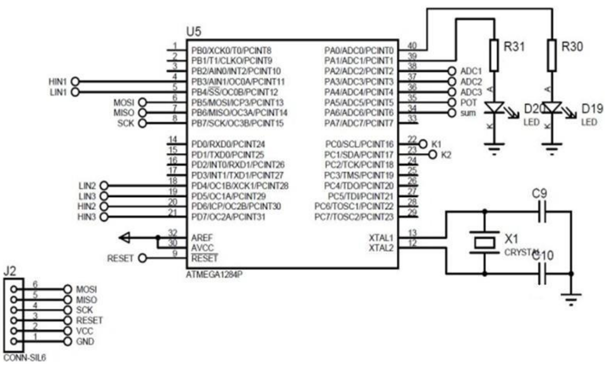

Figure 9. Schematic of the microcontroller and the bases used

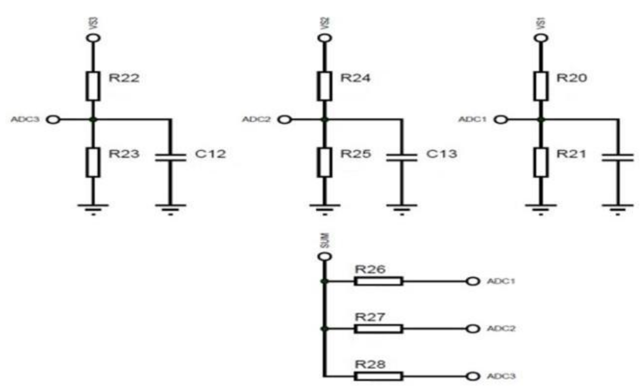

Figure 8. The circuit to sample motor output

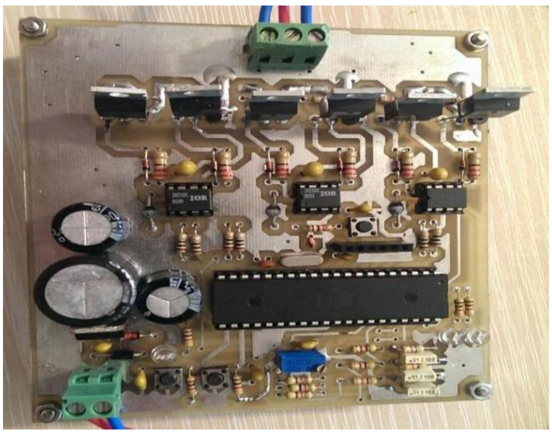

Figure 10. The image of circuit made

Figure 11 demonstrates the fundamental and the third harmonic of back EMF waveforms. As shown in Figure 11, the third harmonic has a higher frequency (three times more) than the fundamental waveform which highlights the benefit of using third harmonic.

The ripples occurred in Figure 11 are due to switching. Figures 12 and 13 also represent the minimum and maximum drive switching frequencies which are 125.6 and 943.4 Hertz, respectively. It is obvious that increasing switching frequency renders motor speed increase. As shown in figures, increasing pulse width modulation frequency, increases the motor speed.

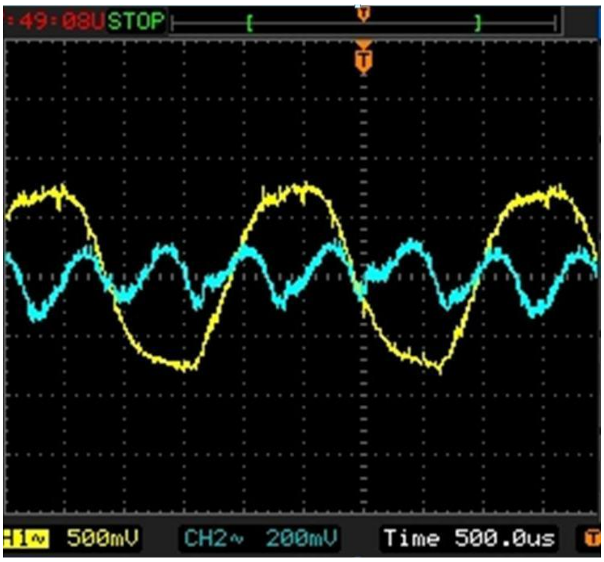

Figure 11. Fundamental wave and third harmonic back EMF of motor

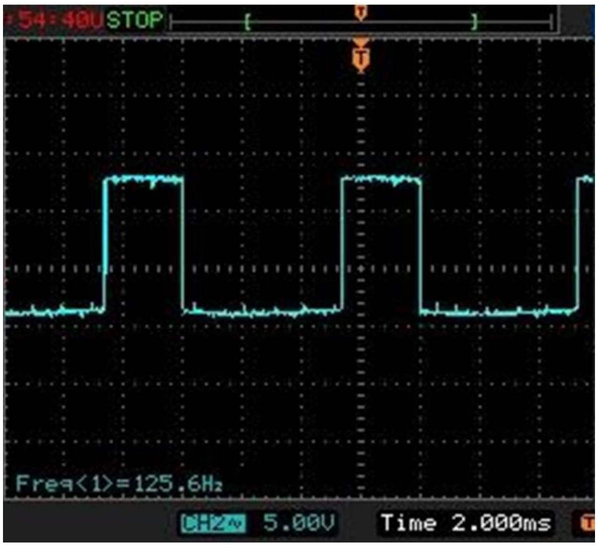

Figure 12. Switching waveform at the lowest frequency

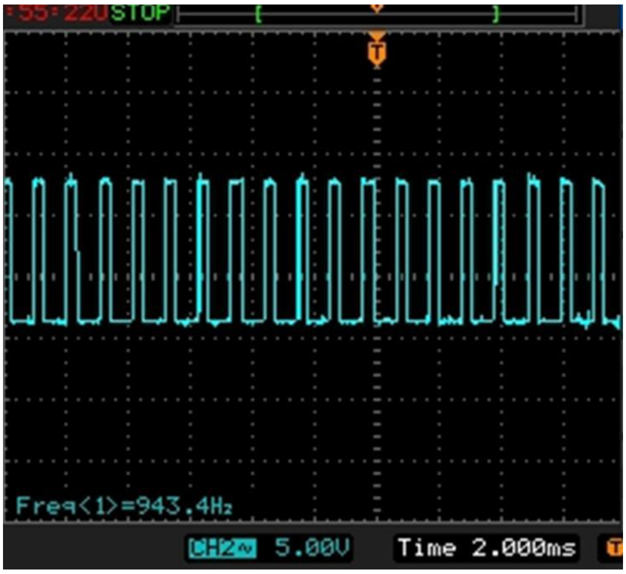

Figure 13. Switching waveform at the highest frequency

With this method, this motor can be easily used in a wide speed range and has a small torque ripple which shows the effectiveness of this method.

5. CONCLUSION

Practical methods are mostly based on observing the zero crossing of the third harmonic. This paper focuses on comparison of the third harmonic with main wave form to predict zero crossing for improved timing. In this paper, third Harmonic Back EMF method is chosen to operate brushless DC motors. So, the use of third harmonic back EMF and comparison with back EMF free phase is a precise and simple method where zero crossing points are well marked and motor performs well within a wide speed range. Also in the power circuit, a combination of MOSFETs types (p and n) is not used and since they are all n-type and similar, their flow rates are the same and better than p-type which end in circuit performance improvement. IR2101 drive is utilized for MOSFET setup and the time MOSFETs are on and off is controllable and precise. Tantalum capacitors are also used and their low leakage current, high capacity, better frequency responses comparing with electrolytic types and less charge and discharge time renders optimal performance achievement. Also, fast diodes are effective in this regard. Furthermore, Ferrite Bits are used at the source of the lower MOSFET to minimize the circuit noise. The high-speed program, using the third harmonic instead of the reference voltage or ground for zero crossing detection are other advantages of the proposed circuit which help achieving a wider range of motor speed.

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چکیده

در این مقاله روش راه‌اندازی بدون حسگر موتور جریان مستقیم بدون جاروبک با استفاده از هارمونیک سوم ولتاژ ضدمحرکه و راه‌اندازی موتور با استفاده از میکروکنترلر که وظیفه مدولاسیون پهنای پالس، کنترل کلیدهای قدرت و تحلیل شکل موج خروجی موتور را بر عهده دارد، بررسی شده است که قابلیت کنترل دور و دست‌یابی به سرعت‌های بالا را برای موتور مورد استفاده فراهم نموده است. در مدار طراحی شده از میکروکنترلر به‌عنوان پردازنده و از ماسفت به‌عنوان مدار قدرت استفاده شده است و همچنین موتور مورد استفاده فاقد حسگر بوده و میکروکنترلر وظیفه مدولاسیون پهنای پالس، کنترل کلیدهای قدرت و تحلیل شکل موج خروجی موتور را بر عهده دارد. نوآوری این پژوهش روش استفاده از هارمونیک سوم و مقایسه آن با ولتاژ ضد محرکه فازها برای تشخیص گذر از صفر و همچنین استفاده از ماسفت‌های نوع n در کلیدهای بالایی و پایینی مدار قدرت می‌باشد که مشابه بودن آن‌ها در میزان جریان‌دهی ماسفت‌ها مفید واقع شده است. علاوه بر این، برای راه‌اندازی ماسفت‌ها از درایو IR2101 استفاده شده که باعث بهینه شدن زمان روشن و خاموش بودن ماسفت‌ها می‌شود، البته استفاده از خازن‌های تانتالیوم و همچنین آرایش مقاومت سر راه گیت ماسفت نیز به بهتر شدن این مسئله کمک می‌نماید. در نهایت نتایج آزمایشگاهی جهت تصدیق عملکرد روش پیشنهادی ارائه می‌شوند.

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