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BLDC TORQUE RIPPLE MINIMIZATION USING MODIFIED STAIRCASE PWM

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ABSTRACT

This paper presents a BLDC motor drive system using modified Staircase PWM (SCPWM). Based on the hall position sensor signal, the controller generates Staircase PWM to drive the BLDC motor. Because it's SCPWM instead of Sine PWM signal, minimize pulsation torque ripple is more efficiently at various speeds. The BLDC motor has the advantage of being a special electrical machine and high power applications a staircase modulation, also known as selective harmonic elimination based method, has been proposed. This method is used to reduce the switching losses to a minimum value and to improve the efficiency of the inverter. Finally, the simulation and experimental results are presented to minimize pulsation torque ripple of the BLDC drive system.

Keywords: brushless dc motor (BLDC), commutation, staircase PWM, torque ripple.

1. INTRODUCTION

Brushless DC motors (BLDC) have been widely used in domestic applications like, air conditioners, refrigerators, fans, etc. The rapid development of power electronics technology has greatly improved their efficiency, cost and design simplicity. These are the three major factors which determine the selection of a motor drive. However, in practical applications, commutation may generate considerable torque ripples [1], which usually occur due to the loss of exact phase current. Commutation torque ripples produce noise and affect the speed control characteristics of motor, especially at low speed. Therefore measures must be taken to reduce commutation torque ripples [2].

There are two types of Permanent magnet motors, the permanent magnet synchronous motor (PMSM) and the brushless DC motor (BLDC). The PMSM have sinusoidal back-EMFs and the BLDC have trapezoidal back-EMFs. Brushless DC motors (BLDC) have a simple structure with higher power density and simple control technique compared to a permanent magnet synchronous motor [3]. However, its disadvantages is pulsating torque ripple problem. For a BLDC motor, due to fixed phase induction, the amount of the commutating currents is never constant and this is the reason for the generation of pulsation torque. The pulsating torque ripple is independent of a phase current and varies with speed. This pulsating torque ripple problem arises due to the mismatch of phase current control [4].

Development of direct torque control (DTC) to a permanent-magnet, brushless DC (BLDC) drive is introduced in reference [5]. Direct torque control (DTC) was initially developed for induction machine drives [6], [7].The commutation torque ripple is minimized by combining the three-phase switching mode with a controllable during the periods when the phase currents are being commutated. Due to torque estimation DTC is capable of instantaneous torque control is very difficult to the representation of the inverter voltage space vectors.

The dc link voltage control approach is carried out by the switch selection circuit is used to reduced pulsating torque ripples of BLDC drive system. The change of dc voltage can be completed during non-commutation conduction period and switched immediately at the beginning of commutation by the switch selection circuit [8] and now it is well known fact that the commutation torque ripple can be minimized by controlling the dc-link voltage or PWM duty-ratio during the commutation period. The above method uses additional two switches to change the dc-link voltage and thus it is far from practicality.

To minimize the pulsating torque is explained many paper. The Sinusoidal PWM method [9] this makes a sinusoidal current with harmonics because of non-sinusoidal back-EMF. The torque ripple comparison between the Sinusoidal PWM method and traditional six-step control for BLDC motor the Sinusoidal PWM method is reduce ripple about 50%. Compared to other methods, this Sinusoidal PWM method doesn't have a current-sampling circuit, complex computation. However, this method can't be used where good dynamic performance is required because there is no current control loop.

Comparison among sinusoidal PWM modulation and staircase PWM modulation schemes, it can be seen that the switching losses and THD value of staircase PWM modulation is low. Meanwhile, the THD value and switching losses of sinusoidal PWM is high. In BLDC motor drive using sinusoidal PWM modulation is very difficult to convert hall signal to sinusoidal signal. In staircase PWM modulation the output modulated wave removes exact harmonics. To overcome the sinusoidal modulation schemes, staircase PWM modulation are selected.

2. COMPARISON OF SINUSOIDAL PWM AND STAIRCASE PWM METHOD

2.1 Sinusoidal PWM method

Inverters are the major power electronic conversion units in motor drive, and uninterruptible power supply applications [1]–[4].The Sinusoidal Pulse Width Modulation (SPWM) technique is widely used to regulate

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the inverter output voltage and frequency to the desired value. In this system, the power electronics switches (e.g., MOSFETs, IGBTs, etc.) are usual to the high or low state according to the combination between a high-frequency, constant-amplitude triangular carrier wave with low-frequency 50 Hz reference sine waves of adjustable amplitude and frequency [10], [11]. In the SPWM technique illustrated in Figure-1, the generated signals are positive or negative during each half cycle of the SPWM wave. Thus producing the high-power and low-frequency sinusoidal waveform Vo at the output terminals of the inverter. The amplitude of Vo (V) is calculated as follows:

$$V_o = \text{M} \times V_d \quad (1)$$

Where V_d is the dc input voltage
M is the modulation index

Increasing the switching frequency of the triangular carrier wave f_c results in a reduction of the output filter size and inverter cost [12]. The sinusoidal modulating signals are expressed in equation (1). In BLDC motor drive the hall sensor generated signal is converted into the sinusoidal form. As a result the SPWM signal in form of the harmonic sinusoidal modulation signal. It is very difficult to attain the amount of the commutating currents is flat constant and this is the reason for the generation of pulsation torque. To overcome the above problem, staircase PWM modulations are selected.

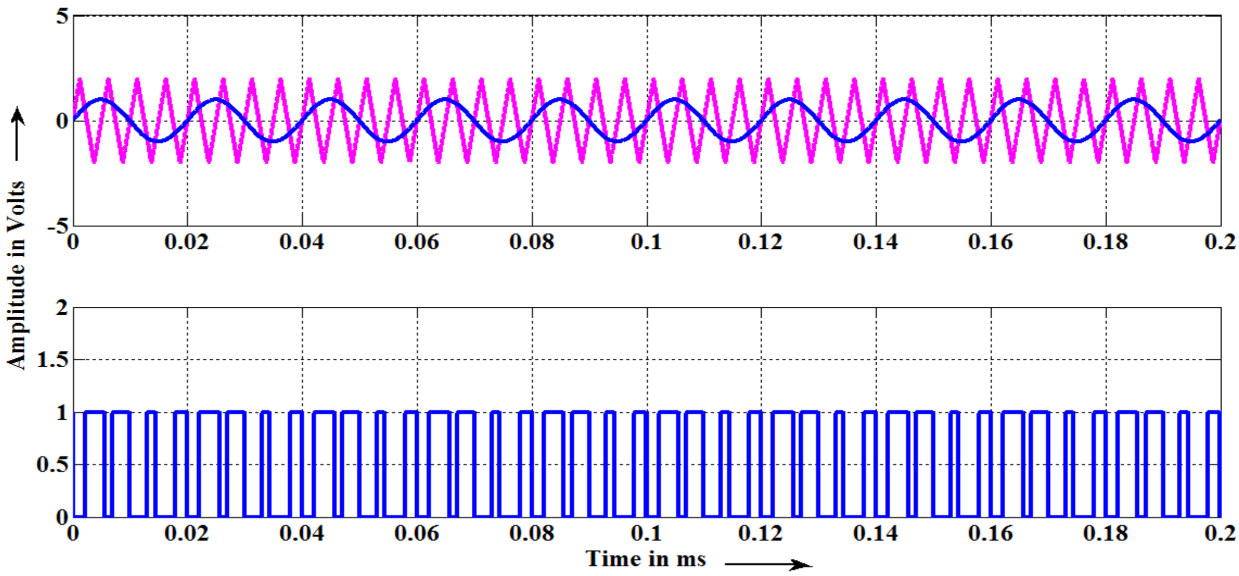

Figure-1. Sinusoidal pulse width modulation.

2.2 Maximum torque per Ampere (MTPA)

When the motor works at the mode of maximum torque per ampere (MTPA), the copper losses are the smallest value. It can be attained by changing the input voltage of the BLDC motor drive. Generally, BLDC motor permanent magnet is surface mounted and there is no reluctant torque in the developed torque. Thus, the MTPA can be achieved by $i^r d_s$=0. Considering the DC value of the BLDC motor model, the steadystate voltage equation can be written as [9]:

$$U^r d_s = -\omega_r L_s i^r q_s \quad (2)$$

$$U^r q_s = r_s i^r q_s + \omega_r \text{K} \quad (3)$$

The optimal angle of the input voltage and back-EMF vector is

$$\delta = \tan^{-1}\left(\frac{U^r d_s}{U^r q_s}\right)$$

$$\delta = \tan^{-1}\left(\frac{\omega_r L_s i^r q_s}{r_s i^r q_s + \omega_r \text{K}}\right) \quad (4)$$

where θ is the angle between the voltage and back-EMF vector. Figure-2 shows the steady state voltage relation. In Maximum Torque per Ampere (MTPA) control, the terminal voltage

$$V_a = \frac{-V_{dc}}{2} \text{MI Sin}(\theta_r + \delta) \quad (5)$$

$$V_b = \frac{-V_{dc}}{2} \text{MI Sin}(\theta_r - \alpha + \delta) \quad (6)$$

$$V_c = \frac{-V_{dc}}{2} \text{MI Sin}(\theta_r + \alpha + \delta) \quad (7)$$

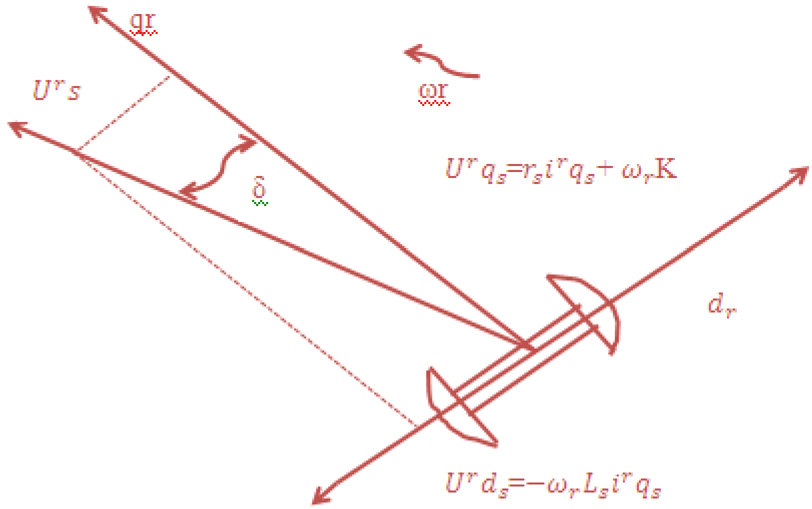

Figure-2. Steady state voltage relation in Maximum Torque per Ampere (MTPA).

Where V_{dc} is the DC link voltage and MI is the modulation index (MI is defined as the peak phase voltage divided by half of the DC link voltage). In this MTPA method varying the input voltage of the BLDC drive. Due to the reason dc link voltage control approach is carried out. In this method that the commutation torque ripple can be minimized by controlling the dc-link voltage or PWM duty-ratio during the commutation period. The other method is the switch selection circuit is used to reduce pulsating torque ripples of BLDC drive system. The change of dc voltage can be completed during non-commutation conduction period and switched immediately at the beginning of commutation by the switch selection circuit. The above method uses additional two switches to change the dc-link voltage and thus it is difficult for practicality and more switching losses is occurred. To overcome the above problem, staircase PWM modulations are selected.

2.3 Staircase PWM method

In staircase PWM Modulation the modulated output wave eliminates specific harmonics. An optimized staircase PWM modulation technique is the fundamental voltage component V_1 is proportional to the staircase modulation amplitude M. The value of fundamental voltage V_1 is greater than 90% of the corresponding value for the non-modulated waveform are achieved for M=1. In order to obtain the desired value of output voltage, the modulation frequency ratio m_f, step size, length and the total number of steps in staircase wave are selected. If the total number of pulses is less than 15 per each half cycle this is optimized PWM method. This method is used to reduce the switching losses to a minimum value and improving the efficiency of the inverter. The switching angles are calculated to eliminate specific harmonics at the output voltage. Figure-3 shows the staircase PWM modulation waveform.

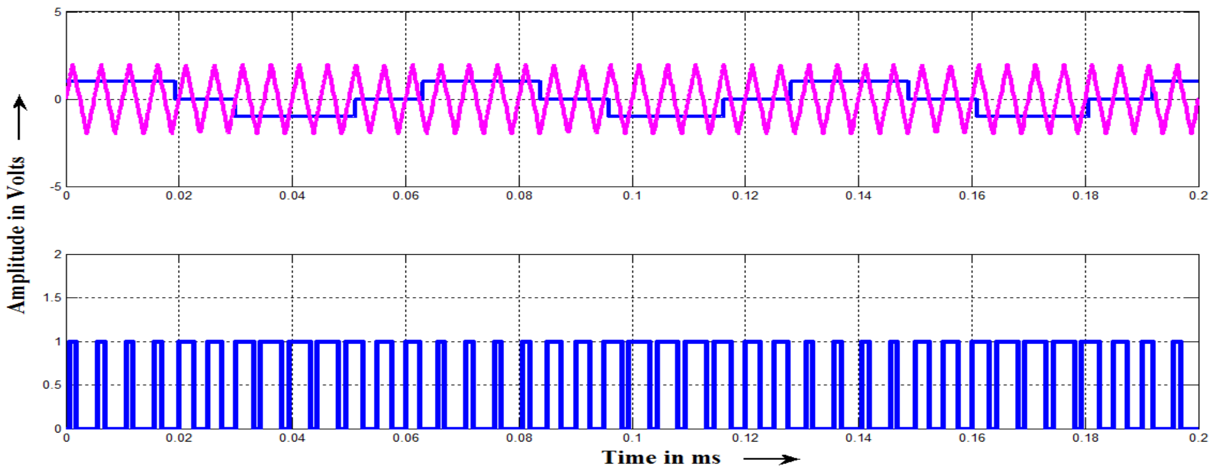

Figure-3. Staircase pulse width modulation.

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3. STAIRCASE PWM MODULATION

3.1 Convertion of hall signals into staircase PWM signals

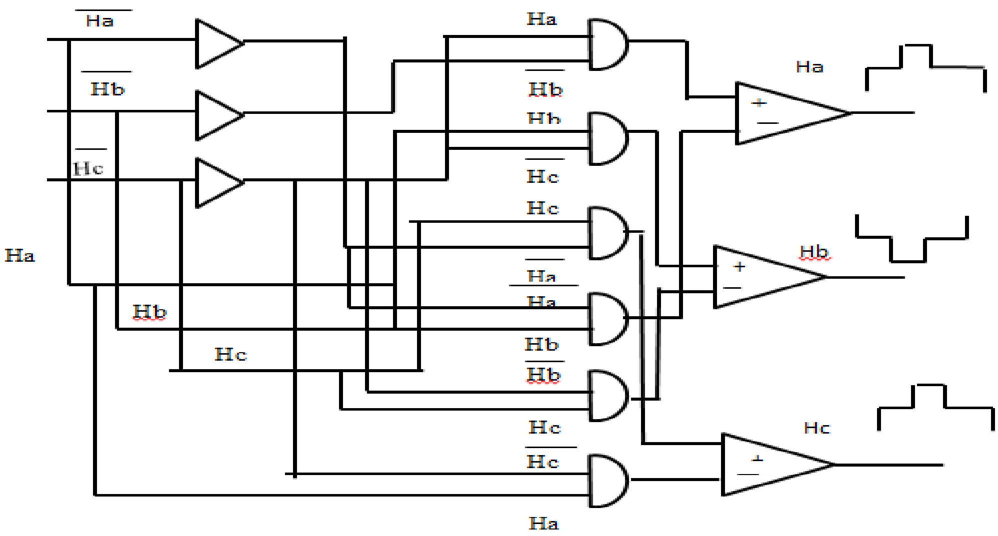

Figure-4. Framework of Hall signals into staircase PWM signa.

The control loops are synchronises the inverter gates signals with the hall sensor signals. The inverter gates signals are made by decoding the Hall effect signals of the motor. The decoding hall signals separate the inverted ($\overline{Ha}, \overline{Hb}, \overline{Hc},$) and non-inverted (Ha, Hb, Hc.) form. The three inverted and their corresponding non-inverted signals are directly given to the input of the AND gate. The comparator are compares the output of the AND gate. The hall signals voltage (V>0) it produce inverted voltage (Ha, Hb, Hc) and if the voltage (V<0) it produce non-inverted voltage ($\overline{Ha}, \overline{Hb}, \overline{Hc},$). Finally, the combination of AND and comparator compares positive and negative voltages which produces staircase signals. Figure 5 and 6 shows the simulation and hardware results of hall signals.

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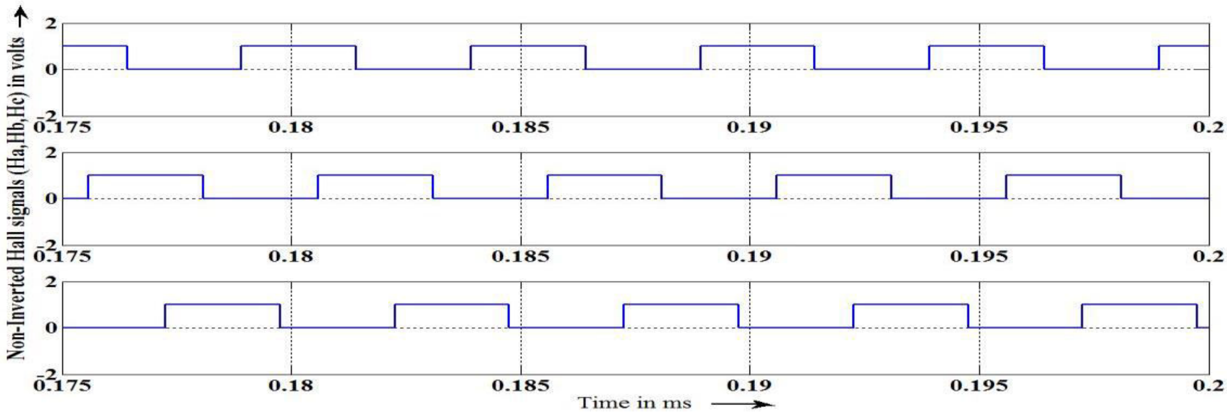
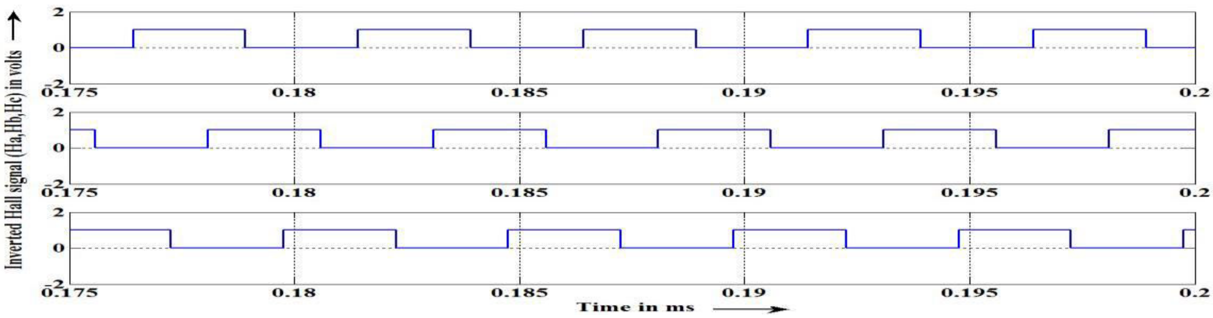


(a)



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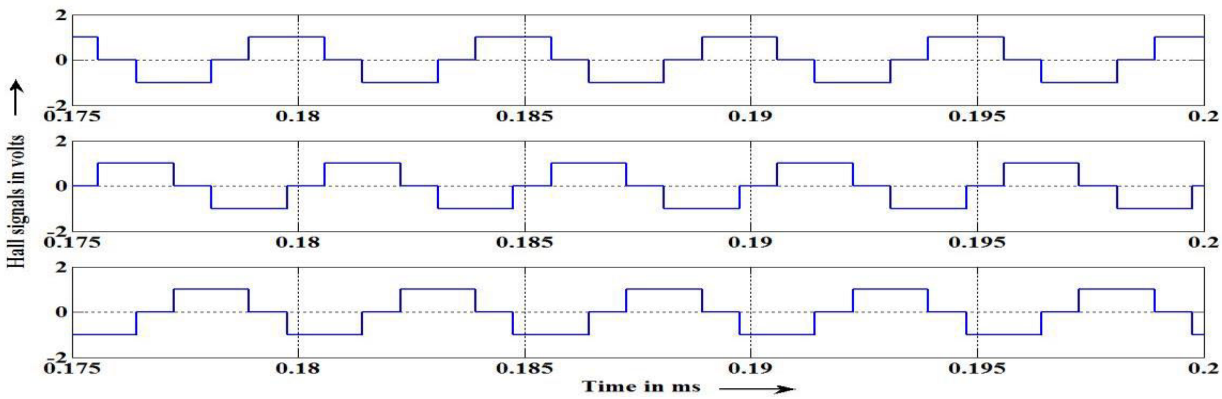

(c)

Figure-5. Simulation result for Hall signal, (a) Measured Non Inverted Hall signal, (b) Inverted Hall signal. (c) Measured combined Hall signal output.

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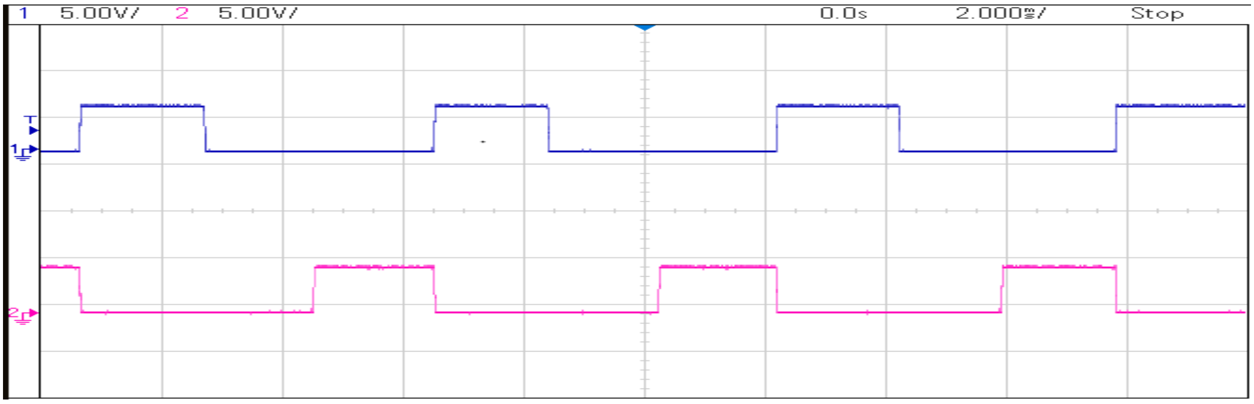
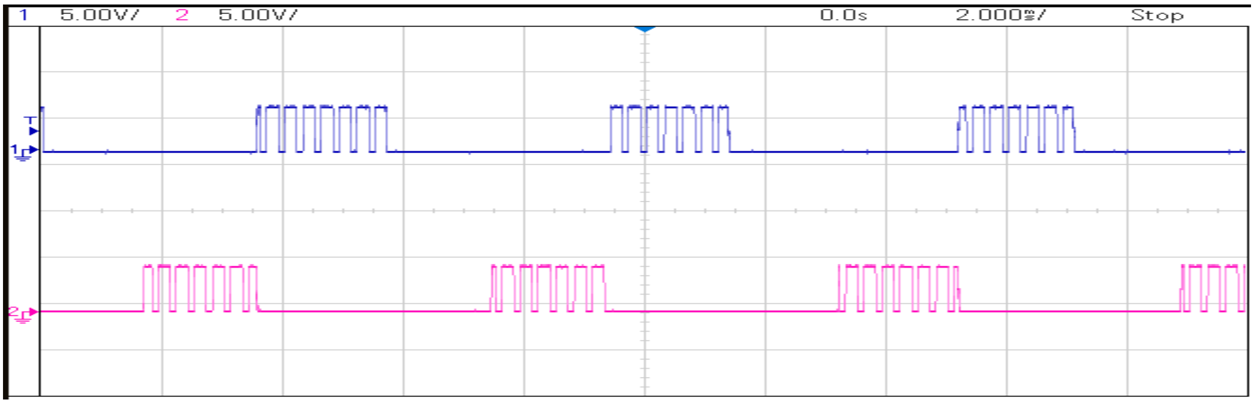


(a)



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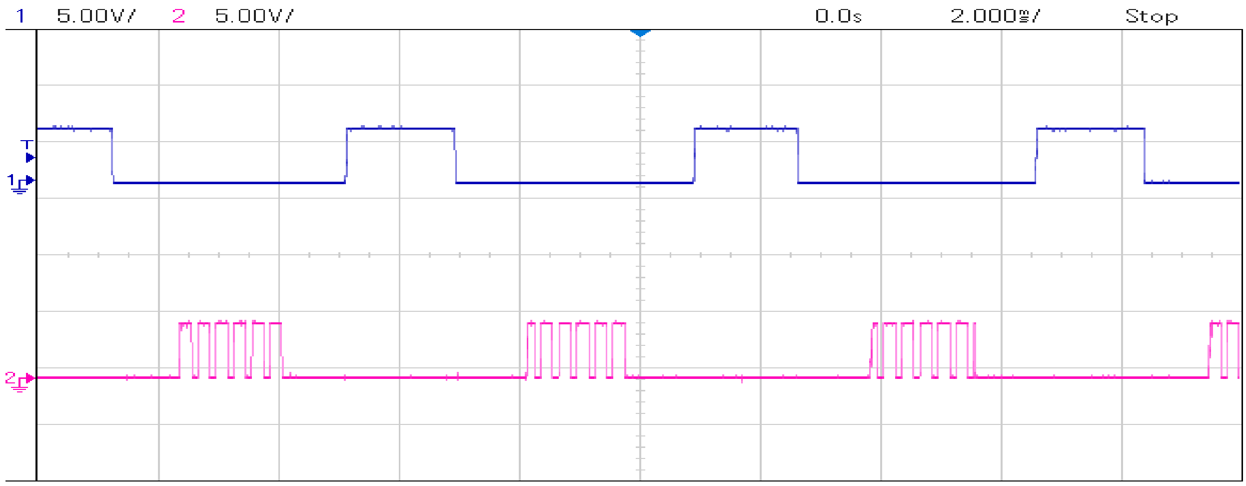

(c)

Figure-6. Hardware result for Hall signal, (a) Measured Inverter and Non Inverted Hall signal Ha,(b) Measured Inverter and Non Inverted Hall signal Hb, (c) Measured Inverter and Non Inverted Hall signal Hc.

3.2 Staircase PWM signals

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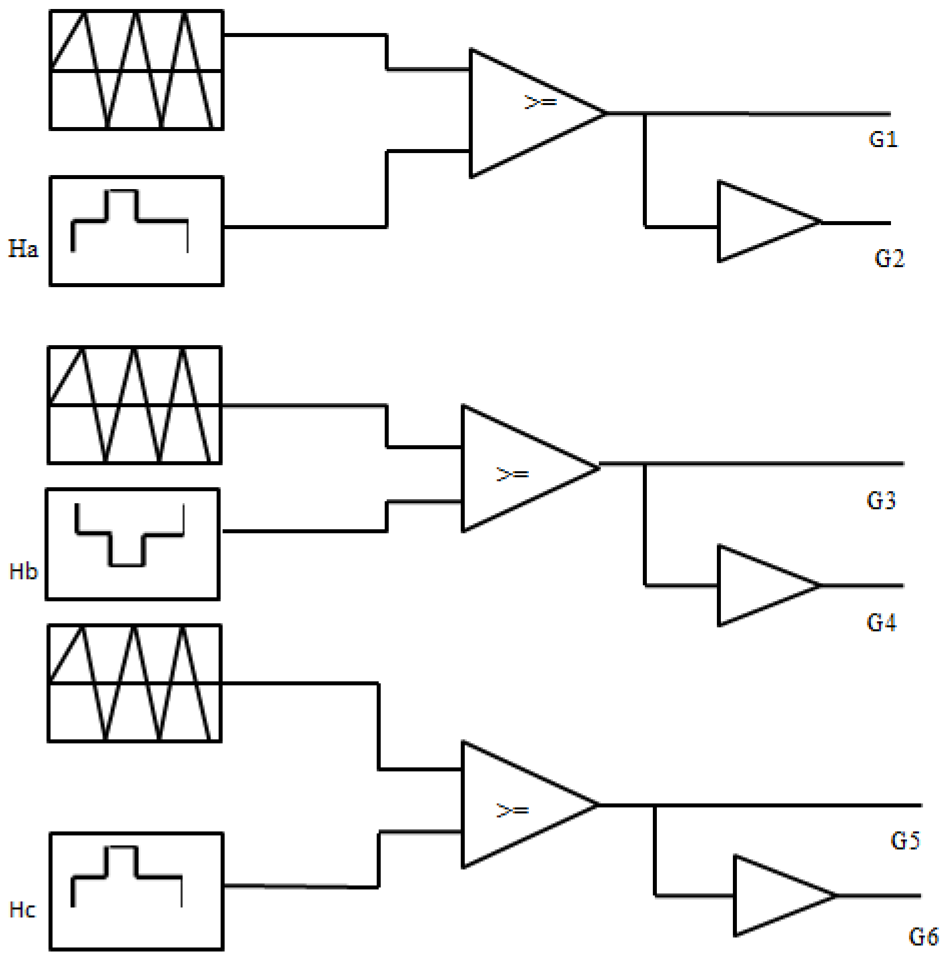

Figure-7. Framework of staircase PWM signals generator.

In Modified Staircase PWM Modulation technique, by varying the width of each pulse in proportion to the amplitude of the reference staircase wave and eliminates specific harmonics, the width of all the pulses are different. This type of modulation is known as Staircase PWM Modulation. By comparing staircase reference signal with a triangular carrier wave of frequency, fc, the gating signal is generated. The number of pulses per full cycle is depends upon the carrier frequency. Three different combination of pulse gating signal is generated. (i) Staircase signal varying constant maximum value in positive half cycle, it can be generate high frequency pulses. (ii) Staircase signal varying constant minimum value in negative half cycle, it can be generate low frequency pulses. (iii) staircasesignal varying minimum to maximum value and maximum to minimum value vise-versa, it can be generate intermediate frequency of maximum value in positive half cycle and minimum value in negative half cycle.

Figure-7 shows the diagram of staircase modulation method for BLDC drive, G1, G2 ,...,G6 sequentially indicate the switching functions of the six in 3-phases, high level means that the corresponding switches in the active state, while zero level indicates that the switches is does not contribute voltage to the arm. The switching signals of the upper and lower arms are complementary correspondingly. The phase voltage Va, Vb, Vc in Figure-2 can be expressed by Fourier series as follows:

$$Va=\sum_{m=0}^{\alpha}(a\,m\cos(m\omega t)+\ b\,m\sin(m\omega t)) \quad (8)$$

where m denotes the order of harmonics, ω is the radian fundamental frequency, and both a m and b m are Fourier coefficients. Since the phase voltage Va is an odd function and it is symmetrical in each quarter of a fundamental cycle, (3) can be rewritten to as follows:

$$Va=\sum_{m=0}^{\alpha}\ b\,m\sin(m\omega t). \quad (9)$$

Then, a detailed expression of the phase voltage Va is given as follows:

$$Va(\omega t)=\sum_{i=0}^{n}\frac{4Vdc}{m\pi}(\cos(m\theta 1\ )\pm\cos(m\theta 2)\pm\cos(m\theta\ 3\ )\pm\cdots \pm\cos(m\theta\ s\ ))\sin(m\omega t) \quad (10)$$

where V dc is the theoretical value of the input voltage, andthe symbols of trigonometric functions cosine are decided by the corresponding edge type of the switching

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angle θs, that is positive sign for rising edge while negative sign for falling edge. In addition, all the switching angles should satisfy

$$0 \leq \theta 1 \leq \theta 2 \leq \ldots\ldots \leq \theta s \leq \frac{\pi}{2} \quad (11)$$

In a three-phase system, m is set to be odd and could not be divided exactly by 3, all the harmonics not higher than 3s - 2 (s is odd) or 3s - 1 (s is even) can be eliminated [21]. In this paper, both the simulation and experiments are designed for a three-phase, three-level inverter where, n = 2. So the event, third and fifth harmonics can be eliminated. V1 is defined as the fundamental amplitude of the preferred output phase voltage Va. and M is the modulation index of the inverter, then the relation between M and V1 is written as follows:

$$M=\frac{V1}{Vdc.\frac{\pi}{2}}=\frac{2V1}{Vdc} \quad (12)$$

Switching angles equations can be found from (10) and (12)

$$\cos(\theta 1\ ) + \cos(\theta 2\ )=\frac{\pi\ M}{2} \quad (13)$$

$$\cos(5(\theta 1)\ ) + \cos(5(\theta 2)\ ) = 0 \quad (14)$$

The equations in (13) and (14) can be represented bycolumn vector. Where θ is the vector of the switching angles.

4. SIMULATION AND EXPERIMENTAL RESULTS

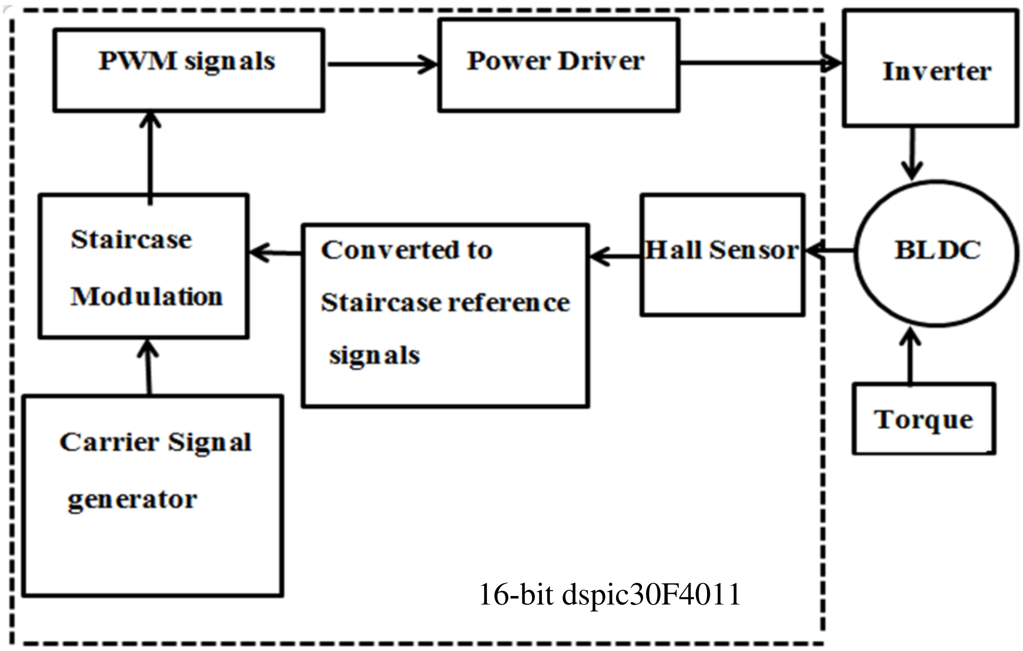

Figure-8. Framework of the experimental system.

An experimental arrangement based on a 16-bit dspic30F4011 Digital Signal Controller with a 30-MHz oscillator is implemented, with all codes written in the “C language.” The system includes the BLDC motor, hall sensor, controller and Power Module can be assembled in the motor. In this experiment, the selected is the staircase PWM modulation, a 150V three-phase inverter. The controller is the 16-bit dspic30F4011 Digital Signal Controller, a PWM controller formotor control. The hall sensor is placed on the bottom side of the motor setup to detect the direction of the magnetic field. The hall sensor signal is given to the signal conditioner circuit with the help of the pull up resister. The signal conditioner output is fed to the 16-bit dspic30F4011 Digital Signal Controller. The staircase signal modulation process is done by the help of 16-bit dspic30F4011 Digital Signal Controller. Finally, the PWM controller signal is given to the inverter gates for motor control.

Figure-9 shows the simulation and hardware output of the inverter current waveform. Stator current of phase a, phase b, and phase c respectively. Figure-6 shows the stable working waveforms are the PWM in phase a, PWM in phase b and PWM in phase c, respectively. The current spike is limited and this shows the motor operation is stable. The phase current, and torque are compared between the six-step method and the staircase modulation control method. The figures that the phase current is more ideal and the torque has less commutation ripple under the control of the recommended method. Figure 10(a) and 10(b) shows the simulation and hardware output of the inverter line voltage Vab. To verify the feasibility of the proposed strategy, simulations and experiments are carried out.

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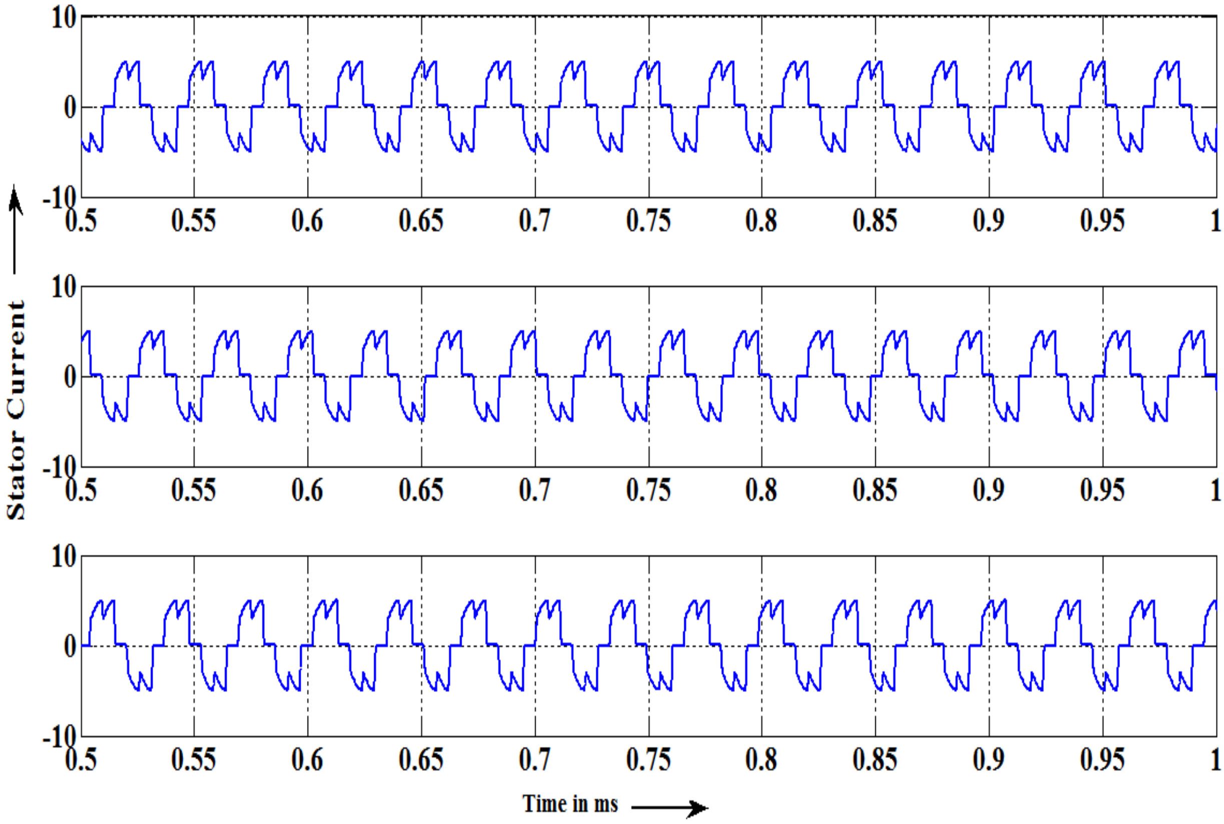
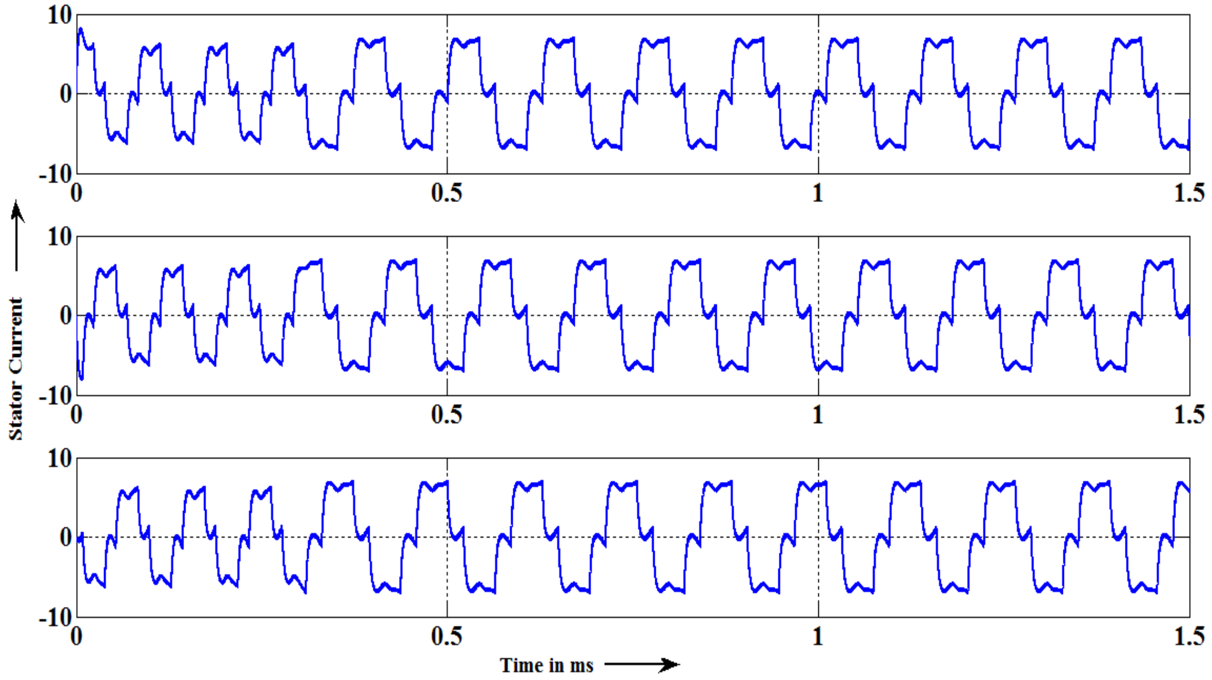


(a)



(b)

Figure-9. (a) Shows the simulated phase current I(a), I(b) and I(c) results for the traditional six-step control method and Figure- 9.(b) Modified Staircase PWM method.

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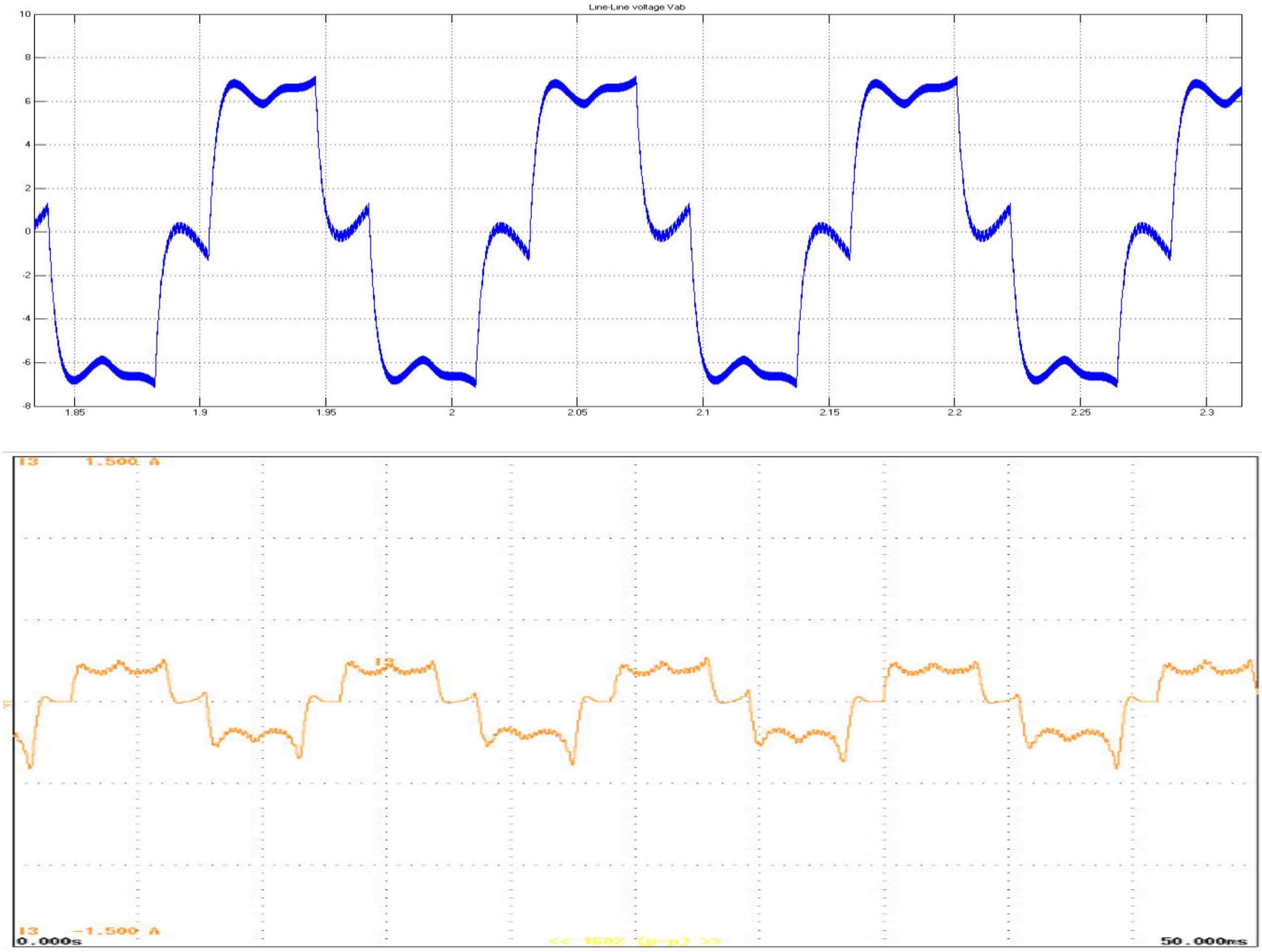

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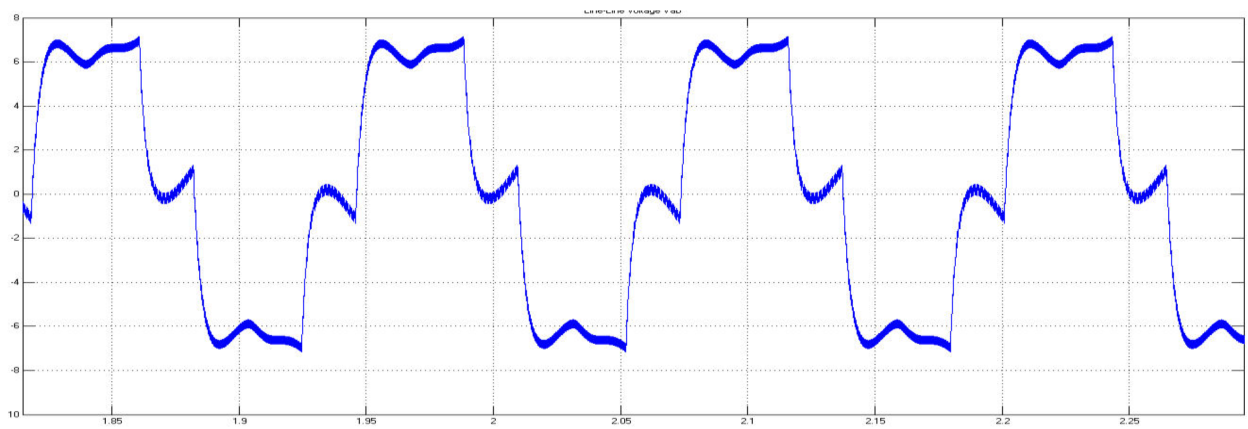

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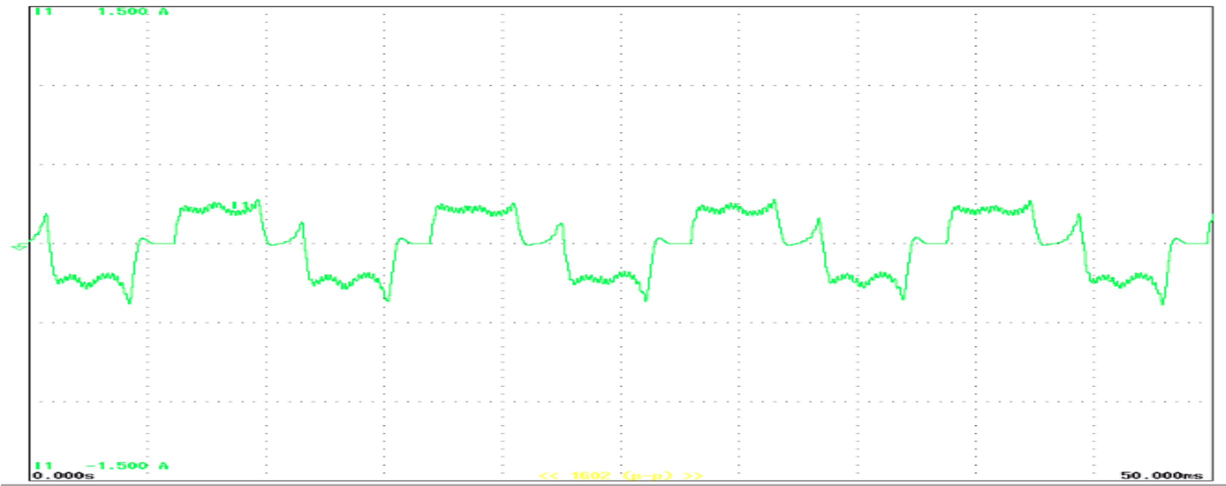

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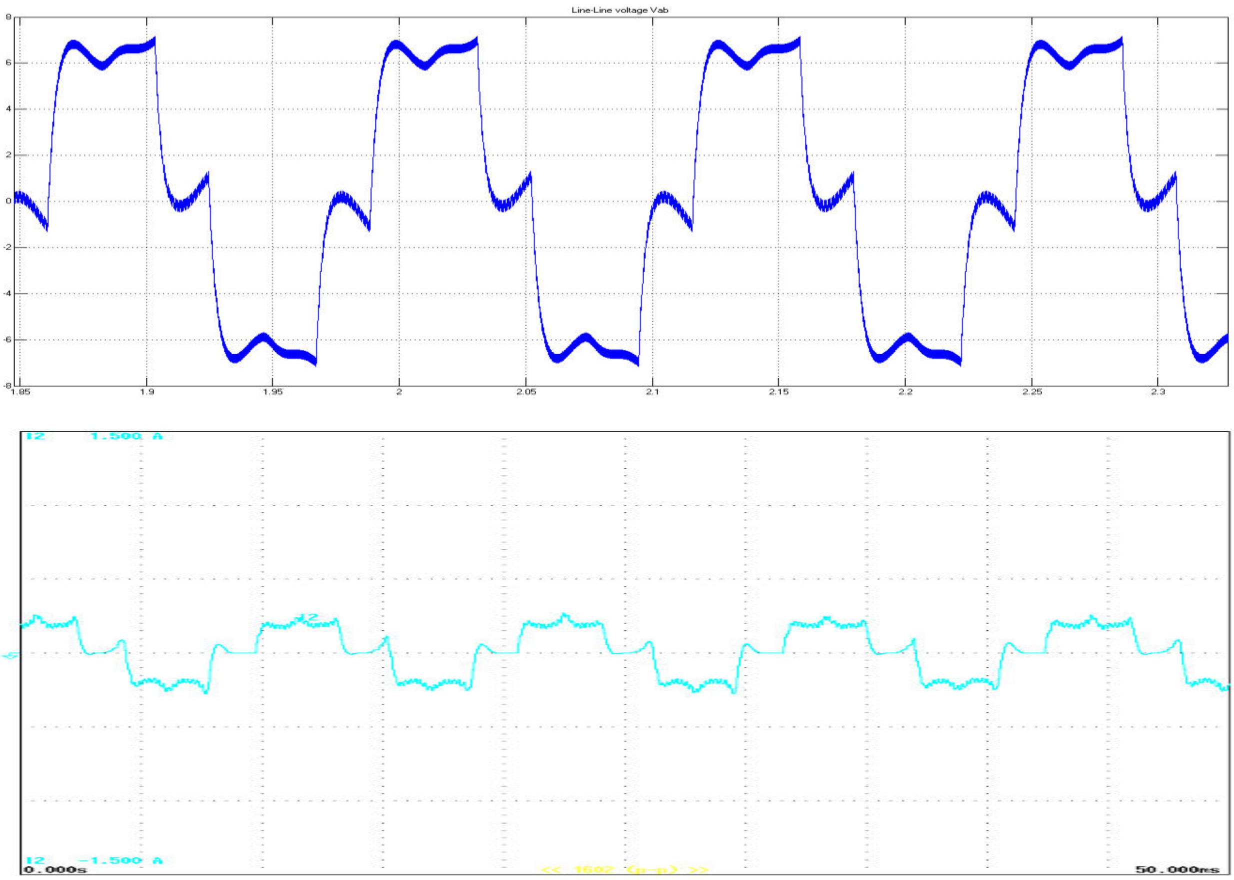

(c)

Figure-10. Shows the hardware results for phase current Ia, Ib and Icfor the Modified Staircase PWM method. (a) Comparison of Hardware and simulation result for phase current Ia. (b) Comparison of Hardware and simulation result for phase current Ib. (c) Comparison of Hardware and simulation result for phase current Ic.

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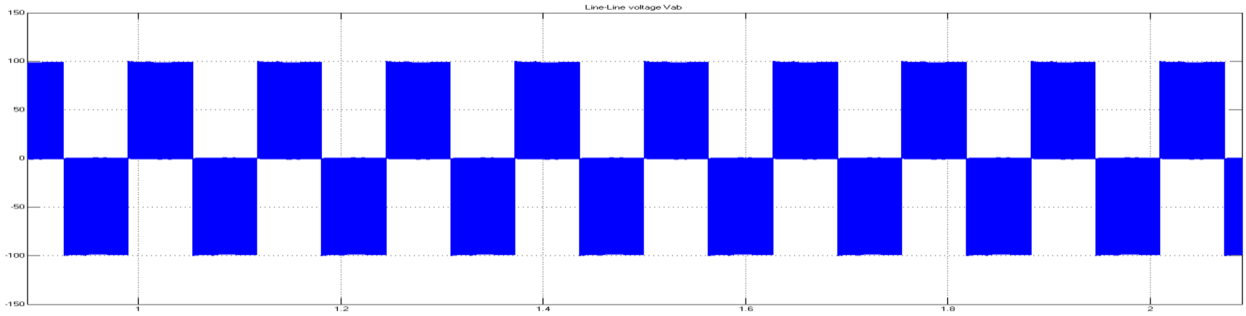

Figure-11. (a) Simulated waveform of Inverter line voltage Vab.

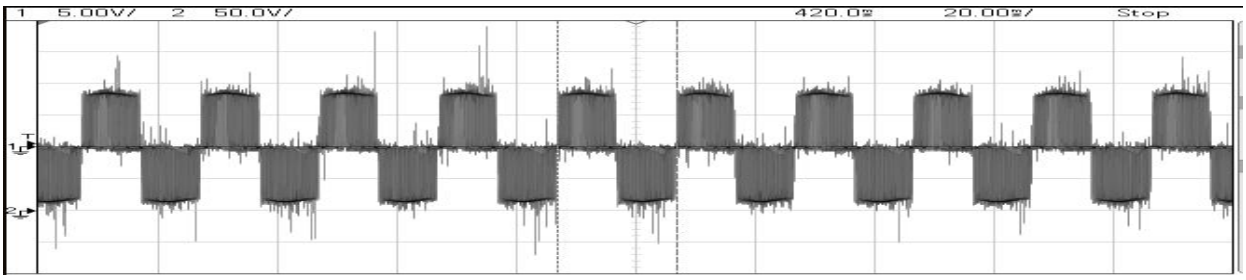

Figure-11. (b) Hardware waveform of Inverter line voltage Vab.

The simulated phase currents of the BLDC Motor drive system with the traditional six-step control method and Modified Staircase PWM method at 1000 rpm are compared in Figure 8(a) and (b) under the same operating condition. The spikes of currents occurringat the end of commutation get smooth, and the current is muchcloser to a rectangle. Figures 11 and 12 show the simulated torque variation with traditional six-step control method and Modified Staircase PWM method at 1000rpm. It can be seen that under the suitable modified staircase PWM method of the inverter during commutation, torque pulsation is significantly reduced. The effect of torque ripple suppression is more obvious at variousspeeds.

The torque pulsations produce noise and vibration in the BLDC drive system. So elimination of noise and vibration is a main considerable problem in BLDC Motor. Two techniques are mostly used to minimize the torque ripple pulsations. To improve the motor designing factor and power electronics control schemes. Torque ripple is defined as the increases and decreases in periodic output torque. The formula for finding the torque ripple is defined as the ratio of the percentage of difference between the maximum torque (T max) and the minimum torque (T min) compared to the average torque (T avg). It can be calculated that torque ripple decreases from about 45.1% to 20.2% at 1000 rpm. A BLDC motor with a nameplate data shown in Table-1 is dealt.

Percentage torque ripple can be calculated by the following formula,

$$\frac{(Tmax-Tmin)}{Tavg} \times 100 \quad (7)$$

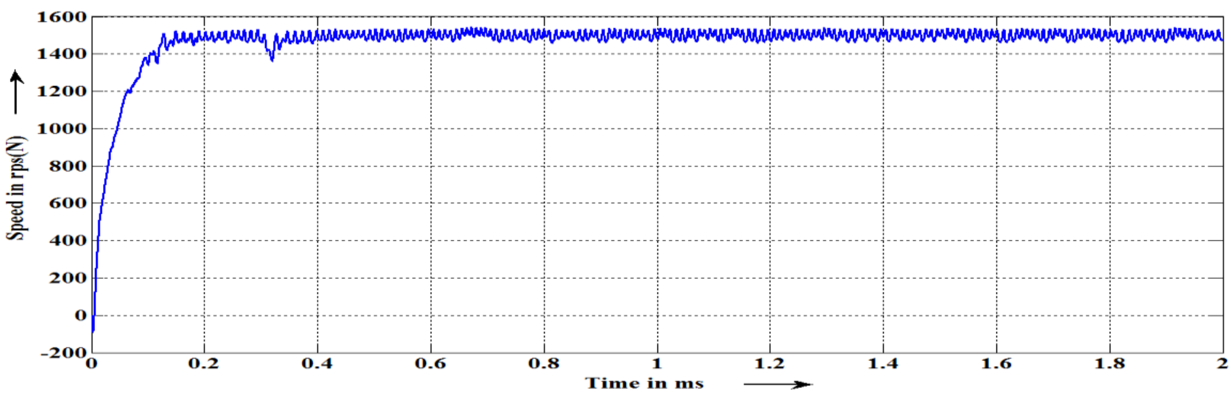

Figure-12. (a) Measured speed with a traditional six-step control method.

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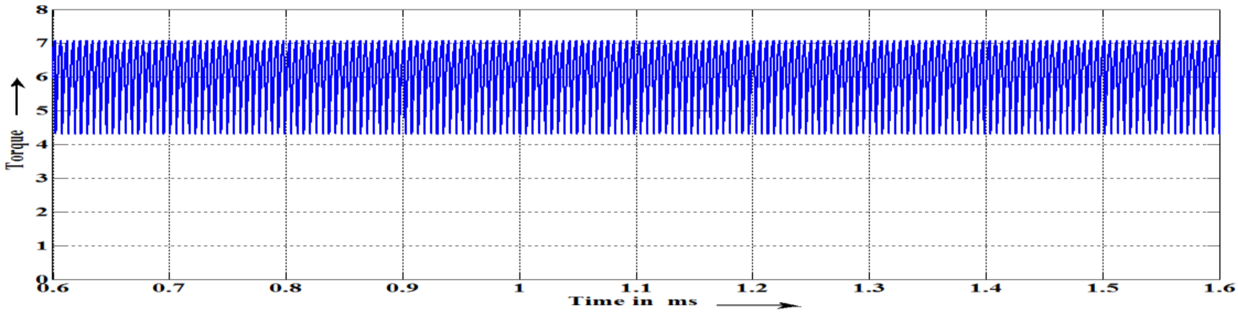

Figure-12. (b) Measured torque with a traditional six-step control method.

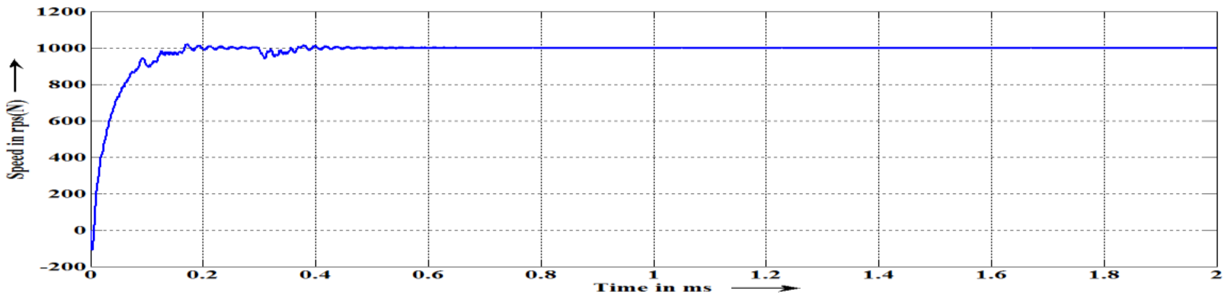

Figure-13. (a) Measured speed with a Modified Staircase PWM method.

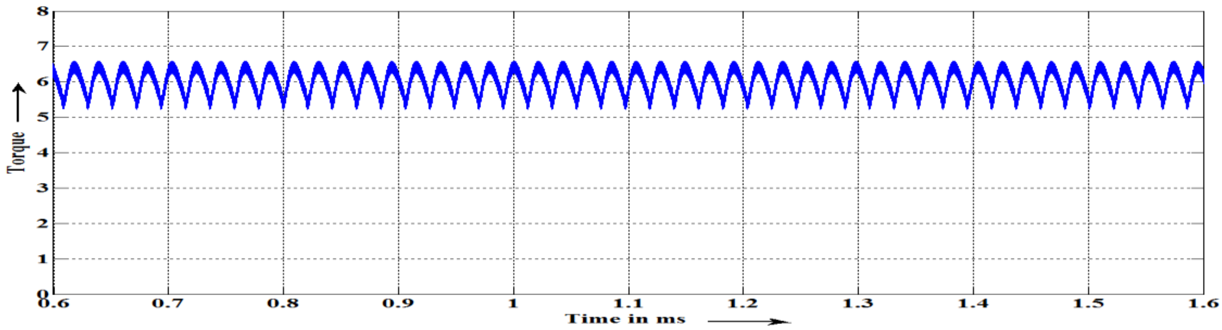

Figure-13. (b) Measured torque with a Modified Staircase PWM method.

Table-1.

Parameters	Values
Rated Voltage ,V_{DC}	(24-120)
Rated Power	160 W
Rated Speed	1500 rpm
Rated Torque	1.5 Nm
Peak Torque	2 Nm
PWM Switching Frequency (kHz)	20 kHz

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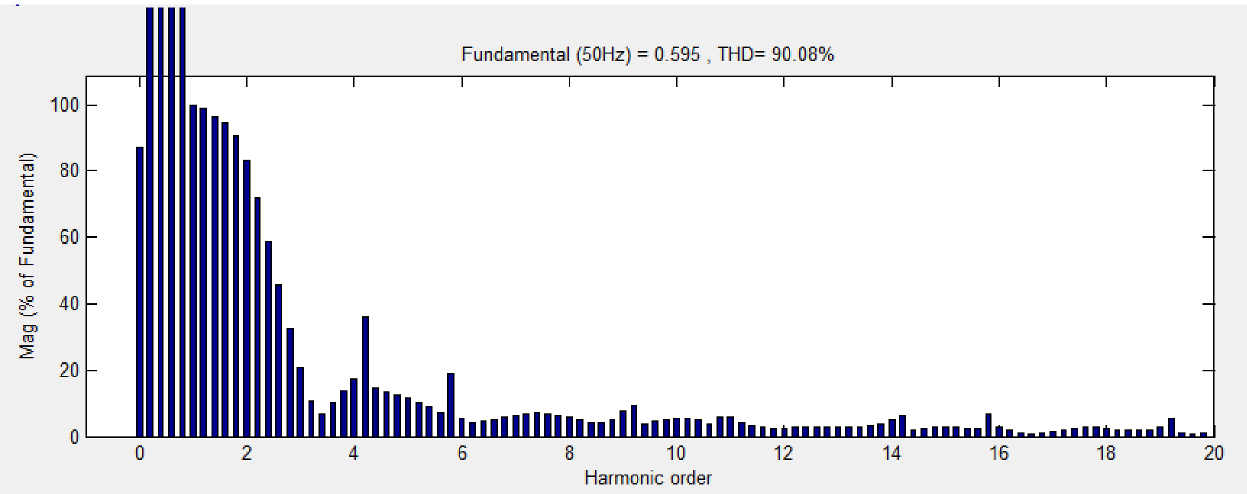

Figure-14. (a) Harmonic spectrum of traditional six-step control method -fed BLDC drive at rated torque of 1 Nm.

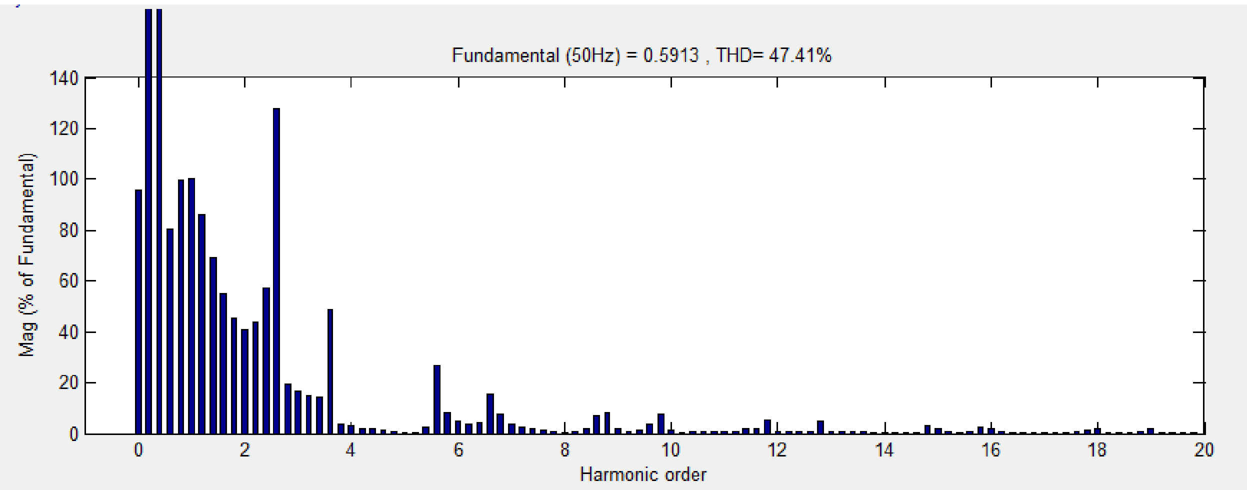

Figure-14. (b) Harmonic spectrum ofModified Staircase PWM method control method -fed BLDC drive at rated torque of 1 Nm.

Figure 14(a) and 14(b) shows the THD performance of the three-level inverter-fed BLDC drive at traditional six-step control and staircase PWM modulation control method. The simulation results show that even THD value can reduce 52 % is well within the limit, and it is seen that the drive is capable of operating even at low speed range and precision speed range. In Figures 11 and 12, speed response and torque are compared between the conventional six-step method and modified staircase PWM control strategy. The load torque varies from 0 to 2 N·m at 1500 r/min, in six-step method and from 0 to 1 N. m at 1000 r/min in modified staircase PWM control method . It can be seen in the figures that the phase current is near to ideal and that the torque has less variation under the control of the proposed staircase PWM control method.

5. CONCLUSIONS

The ripple pulsating torque in the motor developed torque when the BLDC motor is driven by Staircase PWM modulation. In the simulation and hardware results , compared to the traditional six-step control, this method can reduce ripple pulsating torque about 44.7%.The regulation of speed so that torque can respond directly during transient commutation and robustness can be improved. The simulation and hardware result shows this method can be used when the precision speed range.

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