Australian Journal of Basic and Applied Sciences, 9(16) Special 2015, Pages: 162-171

ISSN:1991-8178

Australian Journal of Basic and Applied Sciences

Journal home page: www.ajbasweb.com

Random Pulse Width Modulation Technique for Performance Improvement of Multilevel Inverter Brushless DC Motor Drive

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ARTICLE INFO

Article history:
Received 20 January 2015
Accepted 02 April 2015
Published 20 May 2015

Keywords:
BLDC motor drive Cascaded H-bridge multilevel Inverter (CHBMLI), Pseudorandom binary sequence (PRBS).

ABSTRACT

This paper discusses a random pulse width modulation (RPWM) technique for a cascaded H-bridge multilevel inverter (CHBMLI) based Brushless DC (BLDC) motor drive. The main objectives of any RPWM technique are, spreading the harmonic power in the output voltage, scattering the acoustic switching noise spectra, reducing the torque pulsation etc. While the multilevel inverters (MLIs) are triumph in synthesizing high quality ac voltages without the need of significant filtering. By adopting RPWM technique to MLI drives, the performance of system can be improved further. The crux of the developed RPWM is in randomizing carrier wave while the conventional sinusoidal reference is utilized. The fixed frequency triangular carrier wave (C) from which the randomness is achieved by toggling between triangular wave (+C) and its inverted form (-C). The selection of two triangular carriers is determined randomly by “0” or “1” states of the pseudorandom binary sequence (PRBS) random bits. The proposed random carrier cycle inverted fixed frequency RPWM (RCCIFFRPWM) is tested for the CHBMLI feeding BLDC motor using MATLAB software and the simulated results has been presented. The results such as line voltage and current waveforms, total harmonic distortion (THD) etc. are interesting and informative.

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To Cite This Article: V.Krishnakumar, V.Kamaraj, S.Jeevananthan., Random Pulse Width Modulation Technique for Performance Improvement of Multilevel Inverter Brushless DC Motor Drive. ***Aust. J. Basic & Appl. Sci.,*** *9(16): 162-171, 2015*

INTRODUCTION

Electric drives are key part of daily lives with over billions of motors built worldwide every year. The single phase induction motor and brushed DC motor are popular usually its power rating is lower hence it is used in majority of applications. Such a motor have low efficiency and requires high maintenance. The recent industrial development shows that BLDC motor is becoming the strong challenger to induction and brushed DC motors. This is due to the merits such as higher efficiency, higher power factor, lower maintenance and higher mechanical reliability (Pillay, P., R. Krishnan, 1989). These motors are more fashionable and found its use in automotive, aircrafts, military equipment, industrial automation and medical instrumental applications. The BLDC machine requires voltage source inverter (VSI), which is called as electronic commutator. Need to generate the position dependent pulses for energizing the sequence of operation of BLDC motor. The hall sensors sense the rotor position of motor which is fed to inverter for switching pulse generation. Hence the basic operation itself demands closed loop arrangement. From the literatures, it is understood that there has been remarkable improvements evolved in application of the feedback controllers for both the BLDC motor drive’s speed and current loops (Krishnan, R. and A.J. Beutler, 1985; Krishnan, R., S. Lee, 1997). The concept of multilevel inverter [MLI] has been proposed in 1975. The features of MLI include staircase (near sinusoidal) output voltage, reduced di/dt (less torque ripple), topological modularity, little common mode voltage (CMV) etc. Recently MLI becoming the strong competitor to the conventional two level inverter. MLI have been attracting in favors of academia as well as in industries because of its application such as motor drives, active filters and power conditioning (Rodriguez, J., *et al.*, 2002). Apart from type of drive, the category of speed control method, and the merits of feedback controllers and their design, the pulse width modulation (PWM) strategy employed also play a impartment role in deciding the drive performance.

The trend in the research on MLI is developing newer circuit topologies with minimal number of

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components (Kangarlu, M.F. and E. Babaei, 2013). The basic structures being cascaded H-bridge MLI (CHBMLI), capacitor clamped (flying capacitor) MLI and diode clamped MLI. The CHBMLI structure is preferred due its closer imitation of theoretical performance in experimentation (Franquelo, L.G., 2008). The diode clamped MLI requires more number of clamping diodes and makes the balancing of dc link critical. The capacitor clamped MLI suffers due to its higher cost incurred with large numbers of clamping capacitor and also due to difficulty in packaging. The component reduced topologies pave the way for the future (Thamizharasan, S., 2014; Thamizharasan, S., *et al.*, 2012; Ramkumar, S., *et al.*, 2012). The sinusoidal PWM (SPWM) and space vector PWM (SVPWM) are known for their merits such as reduced distortion, linearity in control, adjustable spectrum etc. while the harmonics in the output voltages are clustered around the switching frequency and its multiples. A voltage-control method using constant (deterministic) frequency PWM causes discrete frequency harmonics, electromagnetic interference (EMI), and audible switching noise due to the switching frequency (Jui-Yuan Chai, *et al.*, 2008). This poor harmonic spreading ability is objectionable. A host of PWM methods known as random PWM (RPWM) methods are evolved to concern on harmonic power distribution over the spectrum.

The random pulse width modulation (RPWM) techniques fed power electronic inverter have been creating attention towards inverter abounding drive systems (Bhim Singh, B.P. Singh, K Jain, 2003; Huazhang WANG, 2012; Andrzej, M., *et al.*, 2010). The best way to reduce the audible switching noise radiated from the BLDC motor is to increase the PWM switching frequency up to 18 kHz (ki.Seon Kim, *et al.*, 2010). By such a method, the noise problem can be solved, but it increases the switching loss of the inverter. The random PWM scheme is being investigated and these techniques include driving at a low-switching frequency. i.e., the switching frequency of RPWM scheme for dc-to-ac inverter is below 5kHZ (Young-Cheol Lim, *et al.*, 2009) and reduce the switching losses. RPWM with its clear harmonic spectrum is acquiring interest in industrial applications need to meet electromagnetic compatibility standards (Khan, H., 2012). The new RPWM scheme has been proposed which has the advantage of deterministic and non deterministic spread-spectral characteristics (Alfonso Carlosena, *et al.*, 1997). From the literature modulation technique adopted for generation of pulses by sinusoidal pulse width modulation, selective harmonics elimination, and space vector modulation strategies were given (Chiasson, J.N., *et al.*, 2003).

The innovations and contributions in PWM theory applied to VSI fed induction motor drives are appreciable. The recent investigation and innovations in the PWM methods are not encompassed in BLDC drives. In particular the features of RPWM such as the acceptable harmonic profile, mechanical vibration and acoustic noise are beneficial to BLDC drives. This paper develops a random carrier PWM (RCPWM) methods suitable for MLI based PI controlled BLDC drive system. The MATLAB based simulation study reveals the superiority of the scheme in terms of harmonic spectrum, total harmonic distortion (THD) and harmonic spread factor (HSF).

II.Bldc Drive With Rpwm:

In Fig.1 shows the closed loop speed control block diagram of MLI fed BLDC motor. The PI controller is fed by error generated from the error detector, which compares the set speed (reference) and the actual speed sensed from the motor. This finally outputs the needed duty cycle in order to achieve the required speed. The regulation of speed is done with the PI controller. The error difference between the actual speed and reference speed is calculated at every PWM cycle and is given as an input to the PI controller.

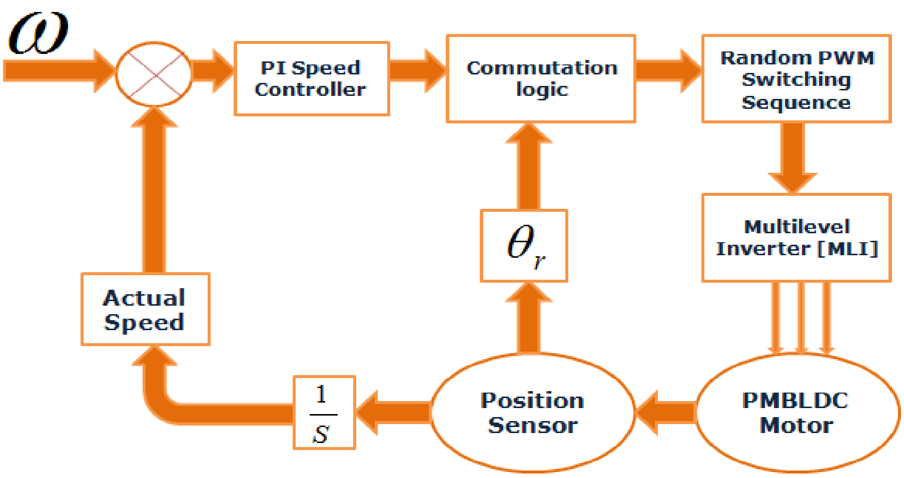

Fig. 1: Block Diagram of PMBLDC Motor Drive

III. Pseudorandom Carrier Scheme:

By appropriate tuning of duty ratio (D) of the converter switches using PWM technique, the output voltage of the inverter can be controlled. The D is the ratio of t_{on} (On-time) of the switch to the total sampling interval ($t_{on}+t_{off}=T$).

$$D = \frac{t_{on}}{T} \quad (1)$$

The D does not depend on the location/pulse position and on the switching frequency. By randomly varying either the switching frequency or pulse position, the harmonic profile of the output voltage can be modified to a better fashion without disturbing the fundamental component and the distortion level. The required change in the harmonic spectrum is distributing the harmonics throughout the frequency range rather than clustering around a specific frequency. The direct way of achieving the randomized carrier frequency is through randomly varying the slope of the PWM carrier triangular wave. In order to realize the randomized switching frequency modulation, a PWM triangular carrier generation circuit with randomized frequency is needed.

In the proposed RCPWM scheme the pseudorandom triangular carrier is gained by using a fixed frequency triangular carrier (C) and its inverted version (180 phase shifted, Ć). That is two triangular carriers each of them having same fixed frequency, but in phase opposition. The random selection between these two triangular carriers is decided by “low” or “high” states of the pseudorandom binary sequence (PRBS) random bits (Young-Cheol Lim, *et al*., 2009) as listed in Table I. A multiplexer with two input and one output, which generates the resultant carrier with pseudorandom frequency, is used.

Table I: Truth Table Of The Multiplexer

PRBS states	Output ‘R’
0	Ć
1	C

Fig.2 shows the random carrier generation principle of the proposed method. As shown in Fig. 2, the triangular carriers with fixed frequency “*C*” and the triangular carriers with fixed frequency with reverse phase “Ć” are input to the “2 × 1”multiplexer. Then “*C*” and “$\overline{C}$” are randomly selected by the output PRBS bits “0” or“1” of the random bits generator (Jui-Yuan Chai, *et al*., 2008; ki.Seon Kim, *et al*., 2010). Choice between “*C*” and “Ć” is dependent on the output “P” of the PRBS random bits generator. In case that the “P” is “1” then “R” is selected as “*C*,” and if “P” is “0” then “R” is selected as “Ć”. The PRBS bits generator consists of a linear feedback shift register (serial input parallel output shift register and an EXCLUSIVE-OR gate) as shown in the figure. It generates the lead-lag random bit trains. A shift register with n-bits is clocked at fixed frequency f_{clock}. The EX-OR gate generates the serial input signal from EX-OR combination of feedback bits of the shift register. A set of states is generated and repeated after K-clock pulses. The maximum number of conceivable states of an n-bits register is $K=2^n-1$. Table I shows the truth table of the multiplexer illustrating the relation between PRBS states and output “R,” which is dependent only on “*C*” and “Ć”. Fig. 3 shows the detail waveforms of the proposed method.

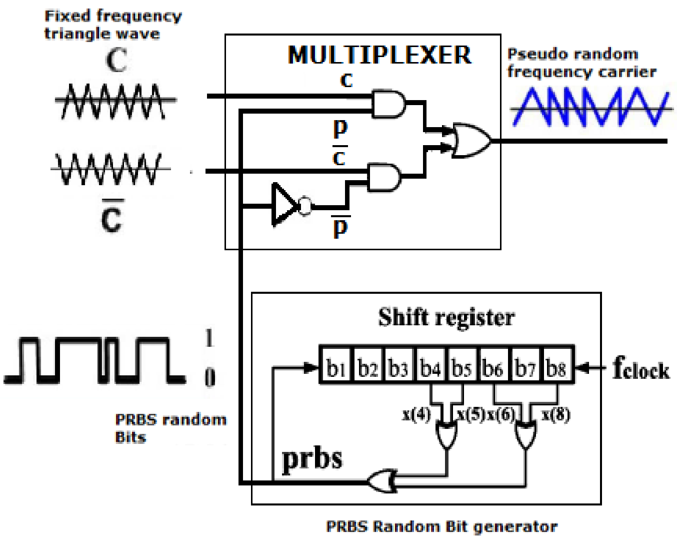

Fig. 2: Basic principle of proposed scheme.

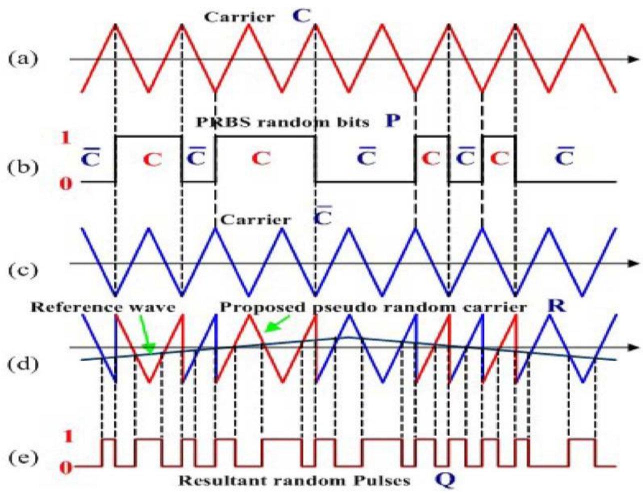

Fig. 3: Generation of the pseudorandom carrier and PWM pulses

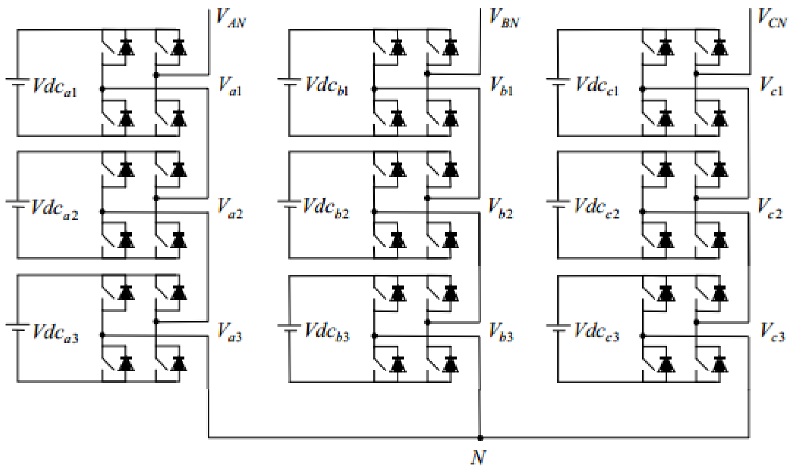

Fig. 4: Three phase multilevel inverter for seven level voltages

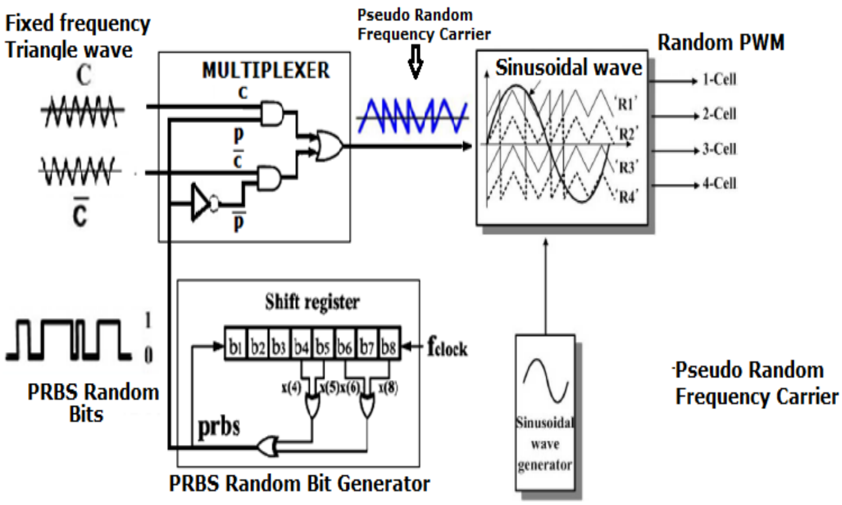

Fig. 5: RPWM for multilevel inverter

Fig.4. shows the three phase CHBMLI. Fig.5. shows the resultant RPWM scheme for CHBMLI. To apply it to a multilevel inverter, the resultant carrier “R” is arranged for phase disposition, as shown in the right side of Fig. 5. The PWM pulses of each HBML inverters can be obtained by comparison of a reference with the phase-disposition arrangement of pseudorandom carriers.

For evaluating the random PWM schemes, a simple quality marker would be useful. For this purpose, Harmonic Spread Factor(HSF) is used. It is defined as

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$$HSF = \sqrt{\frac{1}{N}\sum_{j>1}^{N}(H_j - H_0)^2} \quad (2)$$

$$H_0 = \frac{1}{N}\sum_{j>1}^{N}(H_j) \quad (3)$$

Where H_j is the amplitude of j^{th} harmonics, N is the order of harmonics and H_0 is the average value of all N harmonics. The HSF quantifies the spread spectra effect of random PWM schemes, and it should be small.

IV. Simulation Study:

The proposed RCPWM is schematized in MATLAB-Simulink R2012a for the BLDC motor specification listed in the Appendix. The developed Simulink model of the MLI BLDC drive is indicated in Fig.6 while the implementation tactics of RCPWM is tinted in Fig.7. The simulation is performed for both SPWM and RPWM at different modulation depths (Ma) and for the load torque varying from 5 N-m to 25 N-m. The ordinary differential equation solver Ode 23tb(stiff/TR-BDF2) is chosen with the initial step size (auto rated), The carrier frequency is taken as 3kHz for SPWM while in RCPWM it is 3kHz and its inverted form. The length of the LFSR is 8-bit. For harmonics analysis powergui with discrete/continuous is used.

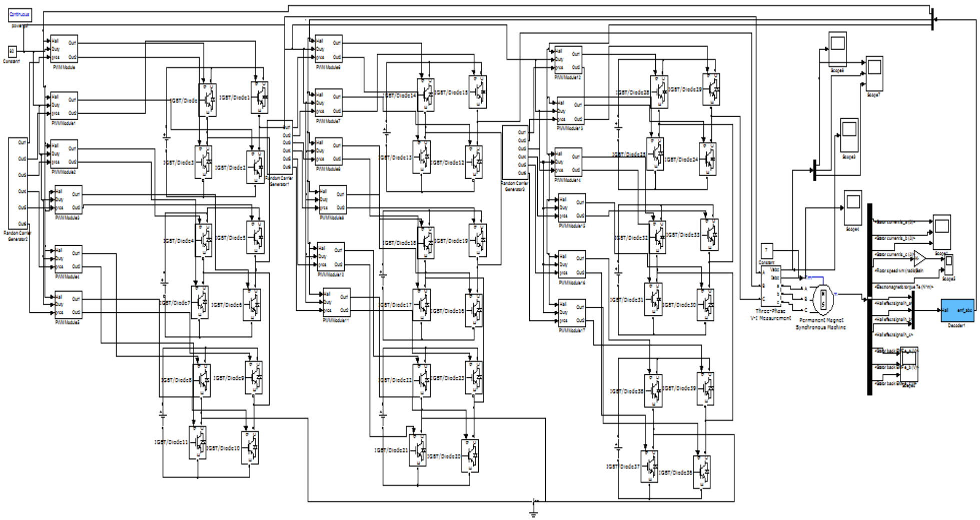

Fig. 6: Simulink schematic of MLI-BLDC motor drive

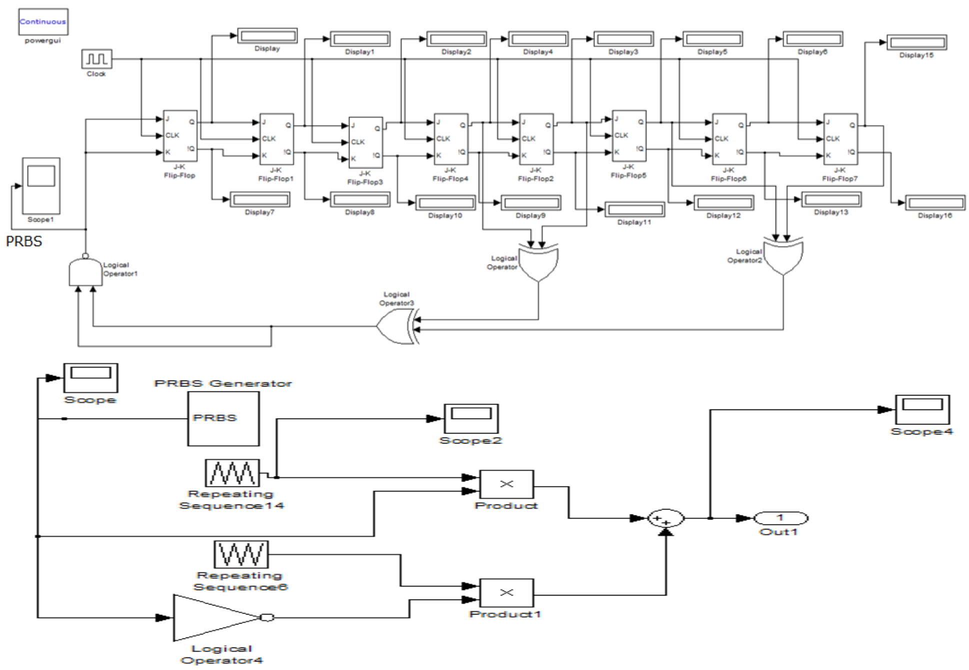

Fig. 7: Implementation of developed RCPWM in Simulink tool

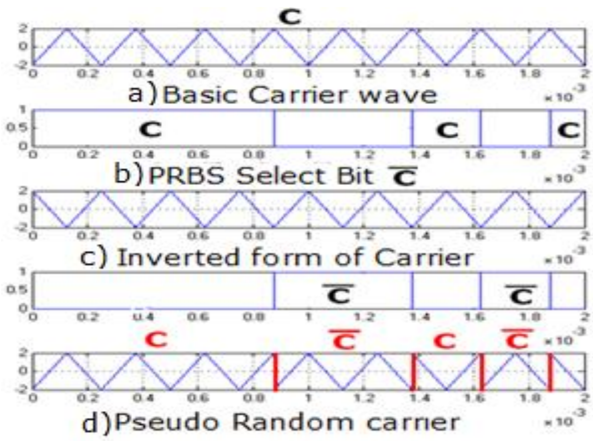

Fig. 8: Simulated detail results of the proposed scheme. ("*C*" = 3 kHz, shift Register bits = 8 bits).

Fig.8. shows the simulation results of a) basic carrier triangle wave and its c) inverted form of carrier and corresponding b) PRBS bit selection d) Pseudo random carrier generation.

Fig 10, 11, 12 shows the simulation results of stator current, back emf, electromagnetic torque and rotor speed for an open loop control of a BLDC motor.

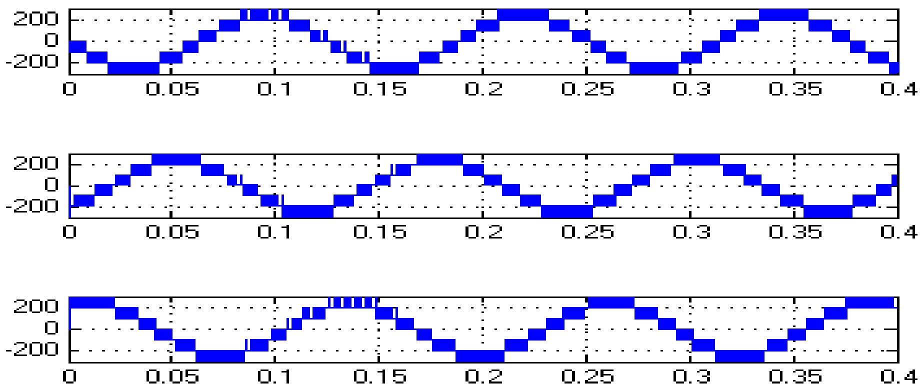

Fig. 9: Output voltage waveform of three phase 7 level CHBMLI-open loop

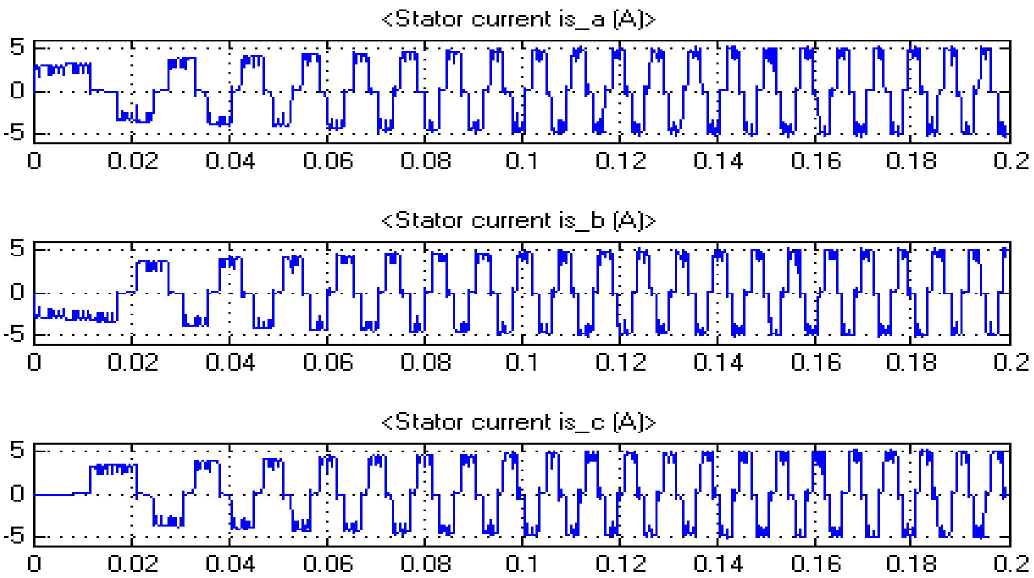

Fig. 10: Stator current waveforms-open loop

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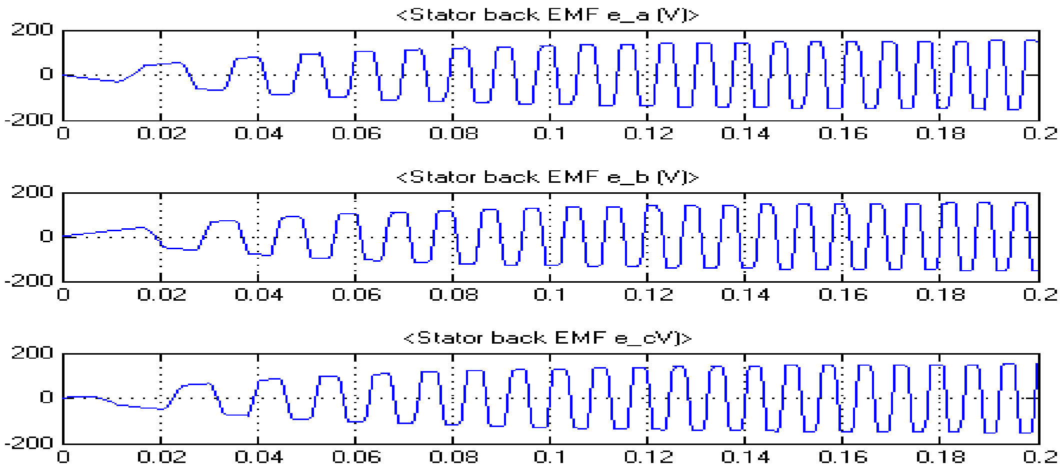

Fig. 11: Back EMF waveforms-open loop

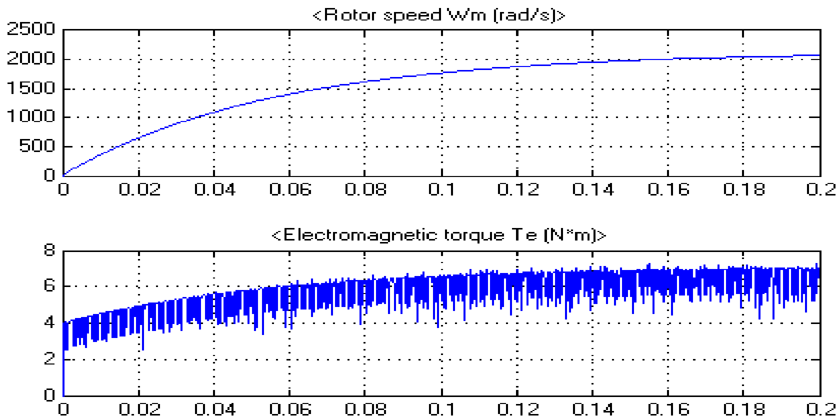

Fig. 12: Rotor speed and an electromagnetic torque responses-open loop

Fig 13, 14, 15 shows the experimental result of stator current, back emf, electromagnetic torque and rotor speed for a closed loop control of a BLDC motor.

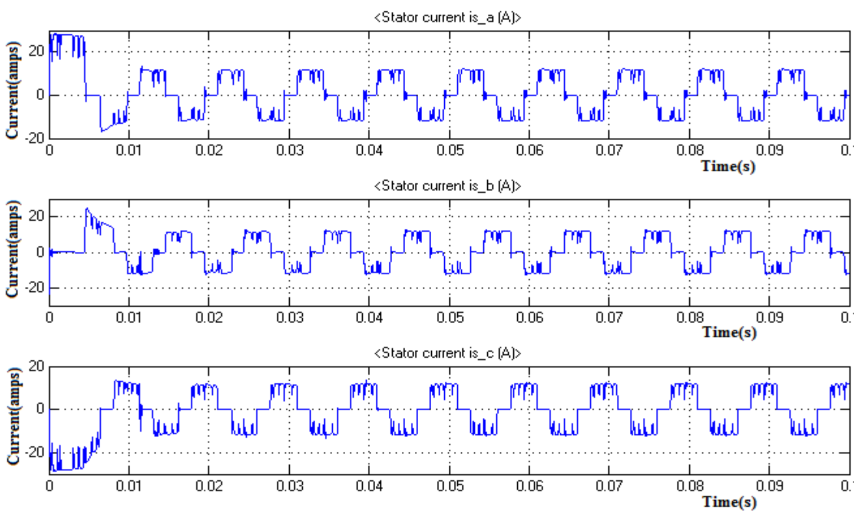

Fig. 13: Stator current waveform for a closed loop control of a multilevel inverter fed BLDC motor

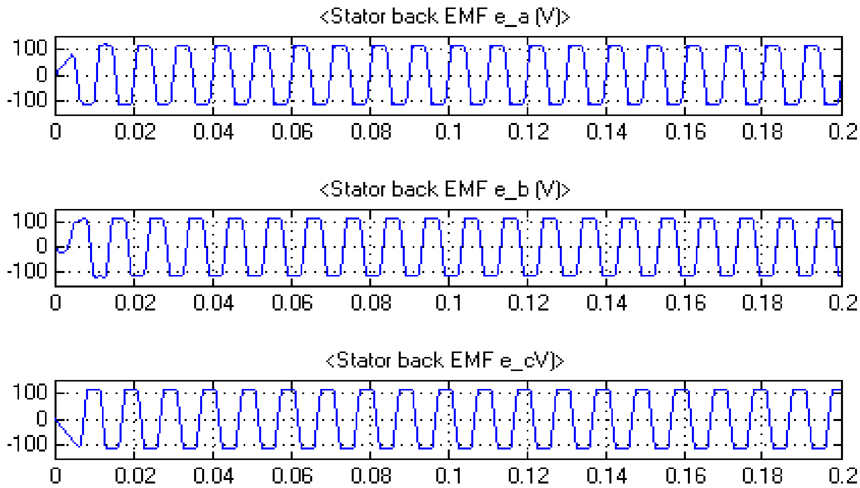

Fig. 14: Stator Back EMF waveform for a closed loop control of a multilevel fed BLDC motor

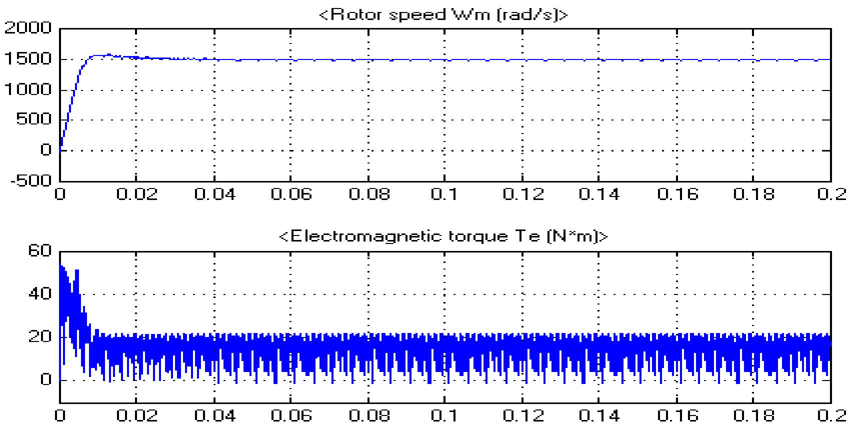

Fig. 15: Rotor speed and an electromagnetic torque for a multilevel inverter fed BLDC motor.

Due to the random pulse width modulation technique the total harmonic distortion get reduced. Figure-16 shows the current harmonic waveform for a multilevel inverter fed BLDC motor applied with the randomized gate pulse. It is proved from the figure that the total harmonic distortion of a randomized gate pulse is less compared to the conventional gate pulse.

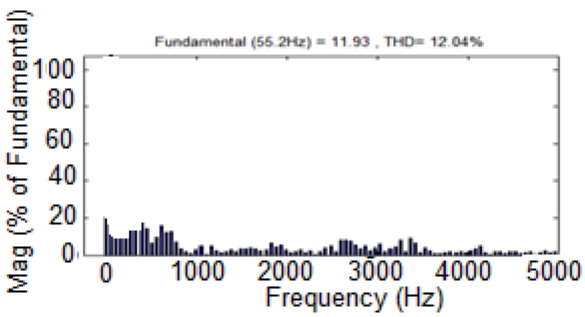

Fig. 16: Stator current (I_a) harmonic for a randomized gate pulse.

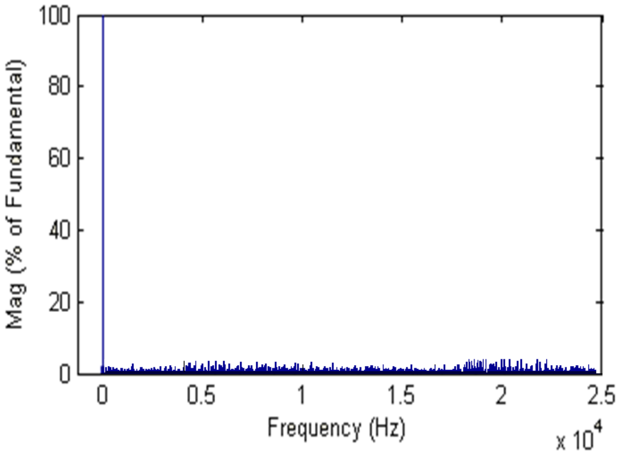

Fig. 17: Harmonic spectrum of output voltage – RCPWM

Table 2: Values of THD analysis given for different Modulation Index

Ma	V_1 (V)		THD (%)		HSF	
	SPWM	RCPWM	SPWM	RCPWM	SPWM	RCPWM
0.4	20.23	24.85	206.13	198.21	8.248	6.6710
0.6	28.46	32.68	178.66	170.32	6.556	5.6054
0.8	41.79	46.19	149.81	141.30	5. 880	5.0572
1.0	48.17	52.53	114.96	107.5	4.952	3.7386
1.2	49.54	53.84	108.31	100.42	4.142	3.5091

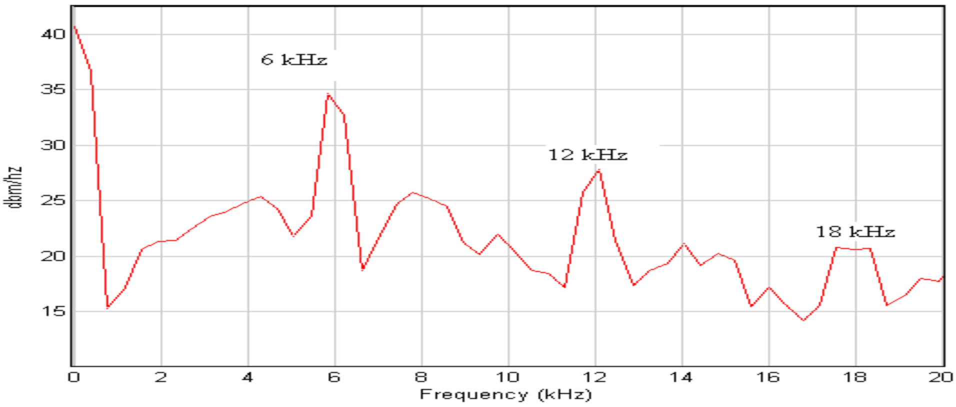

Fig. 18: Power spectral density for Ma= 0.8

Conclusion:

In this paper, a pseudorandom frequency carrier based RPWM scheme has been proposed as a new approach applicable to BLDC motor drive. The proposed scheme produces the pseudo triangular carrier waveform with the random frequency through the random symphony of the two triangular carriers, each of the same fixed frequency but of opposite phase. The resultant pseudo triangular carrier waveform is compared with the sinusoidal waveform to produce the randomized gate pulse. The randomized gate pulse is used to drive the IGBT power switches of the MLI drive. The resulting harmonic spectra are found to have spreading the harmonic power uniformly throughout the spectrum. The developed scheme works for the entire range of modulation index and it does resemble the primary behaviors of the SPWM viz. fundamental magnitude, THD etc. The developed scheme has paved the way to have vibration reduced, acoustic noiseless BLDC drive system.

Appendix:

Number of Poles : 8
Type of connection : Star
Rated speed : 1500 rpm
Resistance/phase : 70 Ω
Back EMF constant :1.4V sec/rad
Flux linkage
established by magnets: 0.175 (V.s)
Inductance (Ls) : 4.3e-3 H/phase
Moment of Inertia (J) : 0.0008Kg-m2
Viscous damping :0.0001N.m.s

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