Global Journal of Pure and Applied Mathematics.
ISSN 0973-1768 Volume 11, Number 4 (2015), pp. 1991-2008
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Harmonic Analysis of Chaotic Carrier SPWM Techniques for VSI fed IM Drives using FPGA

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Abstarct

The pulse width modulated voltage source inverters dominate in the modern industrial environment. Even the prime advantage of sinusoidal pulse width modulation (SPWM) technique is having an assortment of performances such as high output quality, less total harmonic distortion (THD), low rating filtering requirements and linear control on fundamental component etc. The harmonic components of the output voltage are concerted around switching frequency and its integer multiples. These distinct dominant harmonics result mainly in torque ripples and acoustic noise in drives. These problems are mitigated by spreading the harmonic power in the output voltage through non-deterministic pulse width modulations. A chaos function based random pulse width modulation (RPWM) is proposed in this paper. A random frequency through chaotic number is generated first and then compared with the conventional sinusoidal reference function. The meticulous comparison of SPWM and the proposed chaotic carrier sinusoidal pulse width modulation (CCSPWM) is presented. The distribution of harmonic power in the output voltage of voltage source inverter (VSI) with induction motor (IM) load is studied using MATLAB/SIMULINK software and implemented in voltage source inverter (VSI) using field programmable gate array (FPGA). The discussion includes total harmonic distortion (THD) in output line voltage, DC bus utilization and the harmonic spread factor (HSF).

Keywords: Chaotic carrier sinusoidal pulse width modulation (CCSPWM), Field Programmable Gate Array (FPGA), Harmonic spread factor (HSF), Random pulse width modulation (RPWM). Induction Motor (IM) Drive.

1. Introduction

Adjustable-speed drives (ASDs) based on voltage source inverter (VSI) have become mandatory choice in almost all applications. The motion control in today's industrial process depends largely on ac drives. The basic requirement of any AC drive is a power conversion system which supports variable voltage variable frequency (VVVF) power with high quality. The ac drives can be any one from the well-known choices viz. ac chopper, cyclo converter, matrix converter, rectifier and voltage source inverter (VSI) combination. Due to their merits, VSIs are dominantly used not only as drives but also in applications like induction heating, stand-by aircraft power supplies, uninterruptible power supplies for computers, high voltage dc transmission lines, air conditioners, refrigerators, washers, dryers, static VAR compensators, active filters etc. Pulse width modulation (PWM) is a unanimously accepted technique for controlling power electronic converters [1]. The conventional deterministic PWM in the inverter drive systems, however, results in theconcentration of the output power harmonics at discrete frequencies at the PWM switching frequency and multiples of it. This results in objectionable acoustic noise, electro-magnetic interference, vibration and harmonic heating. If the randomness is introduced (either in pulse position or in the switching frequency) in the pulse generation, the harmonics content will spread over wide range and the specific harmonic parts can be significantly reduced. This is the principle of random pulse width modulation (RPWM) techniques which have received much attention very recently [2]-[4].

A new hybrid random pulse width modulation (PWM) scheme has been proposed inorder to disperse the acoustic switching noise spectra of an induction motor drive [5]. The proposed random PWM pulses are produced through the logical comparison of a pseudo random binary sequence (PRBS) bits with the PWM pulses corresponding to two random triangular carriers. A constant frequency approach, which has gained popularity by introducing the randomness in the position of switching pulses within switching cycles, has been studied [6]. Yash Shrivastava et.al. have suggested a statistical approach to the analysis of random pulse width modulation (RPWM) methods which generate PWM signals by comparing a reference modulating function with random numbers or signals [7]. Chaotic sequences have also been the randomization tool in modulators. Chaotic frequency-spreading technique has been accepted as a prospective technology for EMI suppressing [8]. It has been proved that chaos system poses a continuous spectrum [9] and energy can be distributed around an acceptable range.

The chaotic sequence can always be employed for incorporating randomness in PWM strategies. This paper proposes a novel chaotic carrier sinusoidal pulse width modulation (CCSPWM) method for three-phase VSI drives. The required randomness for carrier signal is achieved through a chaotic function. The conventional sinusoidal reference helps in retaining habitual merits of sinusoidal PWM (SPWM) strategies. The meticulous comparison of SPWM and the proposed chaotic carrier sinusoidal pulse width modulation (CCSPWM) is presented. The distribution of harmonic power in the output voltage of voltage source inverter (VSI) with induction motor load is studied using MATLAB/SIMULINK software and implemented in the designed three phase voltage source inverter through a SPARTAN-6 FPGA (XC6SLX45) kit. The discussion includes total harmonic distortion (THD) in output line voltage, DC bus utilization and the harmonic spread factor (HSF)[10].

2. Study of Harmonic Distribution in SPWM VSI Drive

A typical IGBT based VSI fed induction motor (IM) drive is shown in Figure 1. The drive consists of front end rectifier, dc link filtering components, VSI and the motor. As the PWM techniques are having fabulous merits, PWM had become a most important part of power electronic systems, and there has been considerable research effort over the years to determine optimum PWM strategies and operating criteria for various applications. Much of this work has investigated the benefits of alternative theoretical approaches, but there has been somewhat less emphasis on the more practical issues of implementation. The practical issues are output filter design, device thermal behavior, EMI issues, occurrence of non-dominant even harmonics, spectral errors etc.The basic SPWM considers triangular signal as carrier and the sinusoidal signal as reference. The conventional deterministic PWM in the VSI drive systems, however, results in the concentration of the output power harmonics at discrete frequencies related to the fixed switching frequency [11]-[13].These harmonic powers may cause the undesired electromagnetic noise and psycho acoustic noise for human beings.

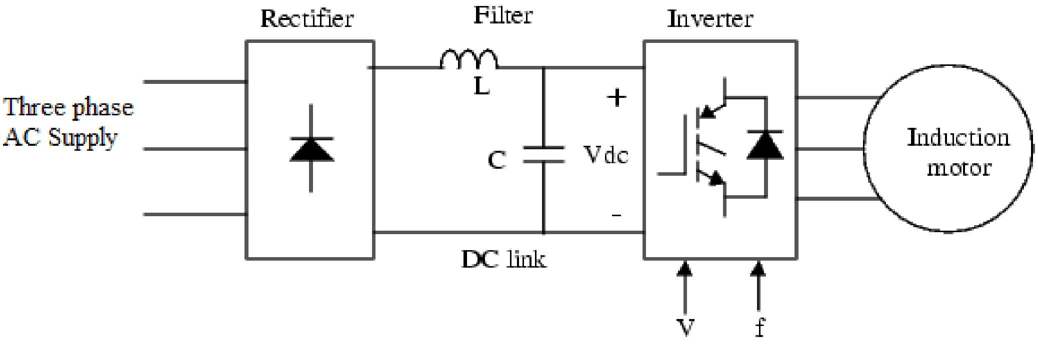

Figure 1: IGBT based VSI fed IM Drive

The harmonic spreading effects of conventional SPWM is evaluated in this section. The simulation study is performed in MATLAB/Simulink software. A three-phase VSI inverter with induction motor load is considered. The input dc voltage (V_{dc}) is 415V and the output frequency is taken as 50 Hz. The carrier frequency (f_c) is taken as 3 KHz. The load is a three-phase squirrel cage induction motor load (0.75KW and 2.5A) and ODE Solver ode 23tb is used. The line voltage waveform resulted from SPWM is illustrated in Figure 2. for Ma=0.8 and its corresponding harmonic spectrum is shown in Figure 3.

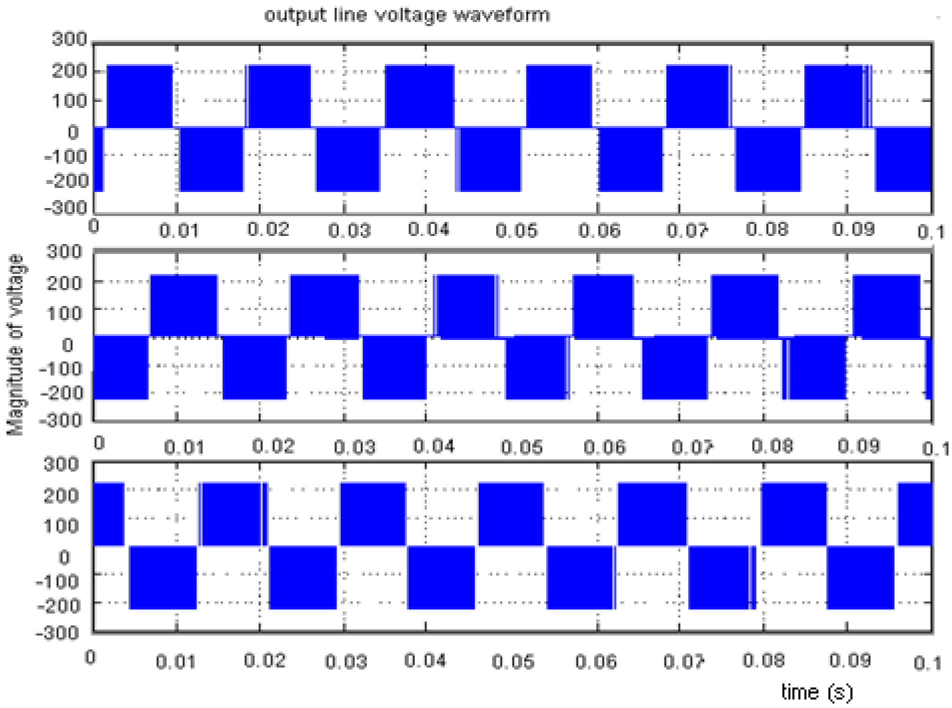

Figure 2: Line voltage waveform-SPWM

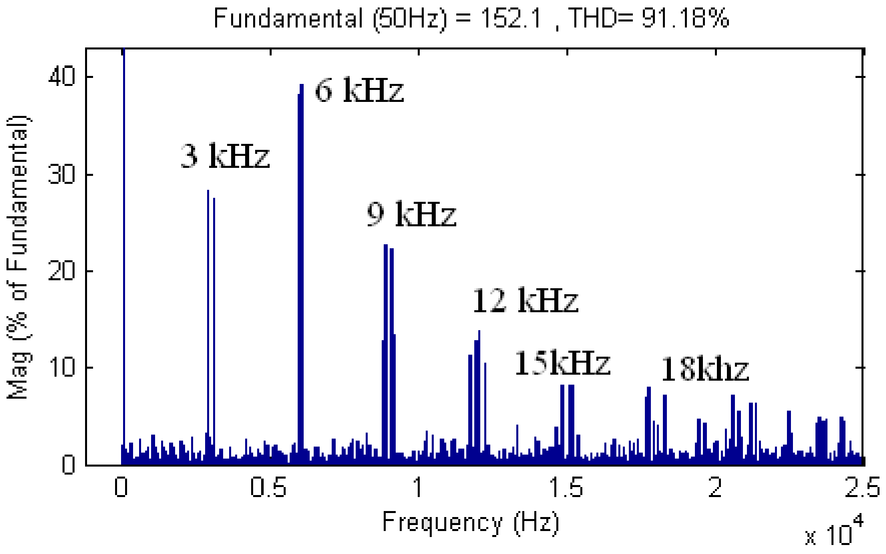

Figure 3: Harmonic spectrum of line-line voltage – SPWM

The THD, HSF and fundamental component (V_{O1}) of the output voltage are list for the complete working range in Table 1. The variation HSF with respect to modulation index is shown in Figure 4. The linear relation between V_{O1} and Ma, and indirect proportionality of THD with Ma are studied. The variation of HSF with Ma is an interesting result and worth to note.

Table1: Performance of SPWM

Ma	V_{O1}(V)	THD %	HSF
0.2	49.059	257.97	8.312
0.4	75.86	164.31	6.142
0.6	114.00	121.10	5.880
0.8	153.30	90.60	5.566
1.0	190.90	68.42	4.952
1.2	280.22	58.30	4.733

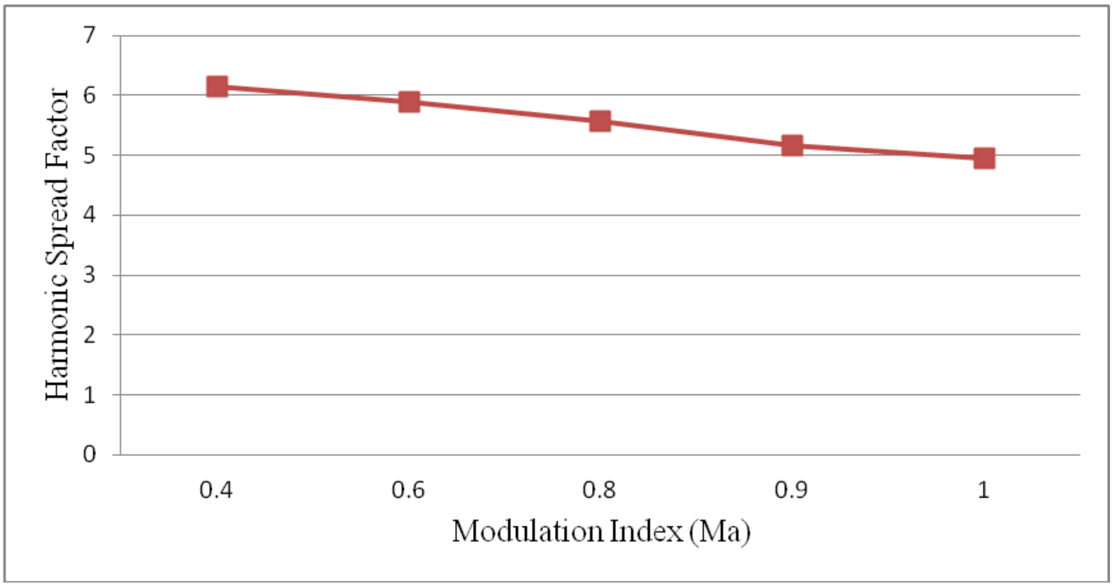

Figure 4: Harmonic Spread Factor (HSF) versus Modulation index- SPWM

From the results it is understood that the harmonic spectrum resulted in SPWM has clustered harmonics at its switching frequency and multiples. Both THD and HSF are decreased at higher Ma values. The HSF at Ma=0.8 is 5.566.

3. Chaotic Sequence and Randomness

Chaos, apparently disordered behavior which is none the less deterministic, is a universal phenomenon which occurs in many systems in all areas of science and engineering. For it to take place the equations describing the situation must be nonlinear and, therefore they are rarely solvable in closed form. Chaos is bounded, noise-like oscillation with an infinite period, found in nonlinear deterministic systems.

It is characterized by extreme sensitivity to initial conditions that is an infinitesimal perturbation to the initial conditions can give rise to macroscopically diverging solutions. The behavior of a chaotic system is a collection of many orderly behaviors, none of which dominates under ordinary circumstances. Chaotic systems are more flexible than non-chaotic ones since the attractor spans a large volume of the state space and with proper control, one can rapidly switch among many different behaviors. This gives a clue to improving the response as well as the domain of operation in systems that exhibit chaos for some parameter values. Chaos theory is a field of study in mathematics, with applications in several disciplines including meteorology, sociology, physics, engineering, economics, biology, and philosophy. Chaotic sequences have good correlation properties and they can be used as address sequences in Spread Spectrum Communication. Chaotic functions are highly sensitive to initial condition and exhibit non-linear behavior. In Chaotic spread spectrum communication systems, different user may be assigned different sequences generated with different initial conditions. Methods to implement the idea of chaos in the field of power electronic circuits and systems have been detailed [14]-[16]. Bifurcation diagram is the most powerful tool to investigate the chaos and bifurcation behavior. In a bifurcation diagram, a periodic steady state of the system is represented as a single point or several points equal to the periodicity of the system for a fixed parameter. For chaos, numerous points are plotted in the diagram because chaos means period infinity and the points never fall at the same position. Therefore, the change of behavior of a system is clearly shown as a parameter is varied. So we can utilize the bifurcation diagram to visualize the route to chaos. One issue with random or chaotic operation is that the maximal time excursions of waveforms of the system's state variables increase. Thus, random and chaotic operation may have superior spectral (frequency domain) but inferior ripple (time domain) performance with respect to periodic operation of power electronic converters. A common and simple chaotic function, the logistic equation is:

$$X_{n+1} = \lambda X_n (1 - X_n) \tag{1}$$

The properties of the logistic function are well known, but we briefly discuss them here. For values of λ in (0, 3), Equation (1) will converge to some value x. For λ between three and about 3.56 the solution to (1) bifurcates into two, then four, then eight (and so on) periodic solutions. For λ between 3.56 and four the solutions to (1) become fully chaotic neither convergent nor periodic, but variable with no discernible pattern. As λ approaches four, the variation in solutions to (1) appears increasingly random. Thus chaotic sequences are highly unpredictable random functions, which can help in generating random numbers. These numbers can pave a way to generate random frequency carriers for PWM schemes. This can be explained with the help of Figure 1. The random signal $n_S(t)$ varies between the upper and the lower boundaries. Its samples are indicated at three points A, B and C. These values are taken as guidelines of the carrier triangular waves generated. The sampling A is a negative value, B is a zero and C is a positive number. Their respective frequencies are low, medium and high. More number of samples needs to be considered while used in a PWM technique.

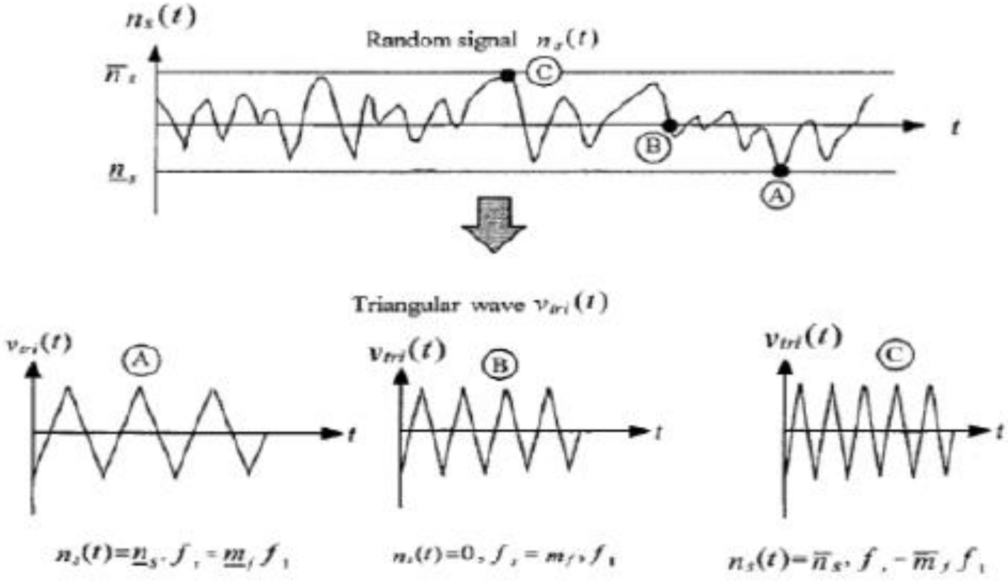

Figure 5: Random signal, $n_s(t)$ guided generation of triangular wave carrier

The basic tool available for quantifying the merit of any PWM technique in its harmonic power Spreading effect is harmonic spreading factor (HSF).

$$HSF = \sqrt{\frac{1}{N} \sum_{j>1}^{N} (Hj - Ho)^2} \tag{2}$$

Where, N denotes the total number of frequency components considered, Hj is the amplitude of the j^{th} component and H_O is the average value of all components. It is given by the equation

$$H_0 = \frac{1}{N} \sum_{j>1}^{N} H_j \tag{3}$$

The HSF quantifies the spread spectra effect of the random PWM scheme and it should be small. For ideally flat spectra of white noise, the HSF would be zero.

4. Proposed Method

The basic principle of the CCSPWM is described in Figure 6. The chaotic algorithm generates a random number, which decides the carrier frequency of next cycle. After having decided on the carrier cycle, the pulses are generated for all the three-phases through the comparison with the conventional sinusoidal reference.

The basic principle of CCSPWM is to use a chaotic signal to vary the switching (or carrier) frequency. The following chaotic function is involved in generating the variable frequency carrier signal.

$$f_n = f_{low} + (f_{high} - f_{low} + 1)\frac{x_n}{0.5(5^c - 1)} \qquad (4)$$

Where, f_n is the n^{th} switching frequency of chaotic PWM, chaotic sequences x_n may be generated simply by iteration. Thus the switching frequency may be varied from f_{low} to f_{high}. The constant c is assumed as 6.

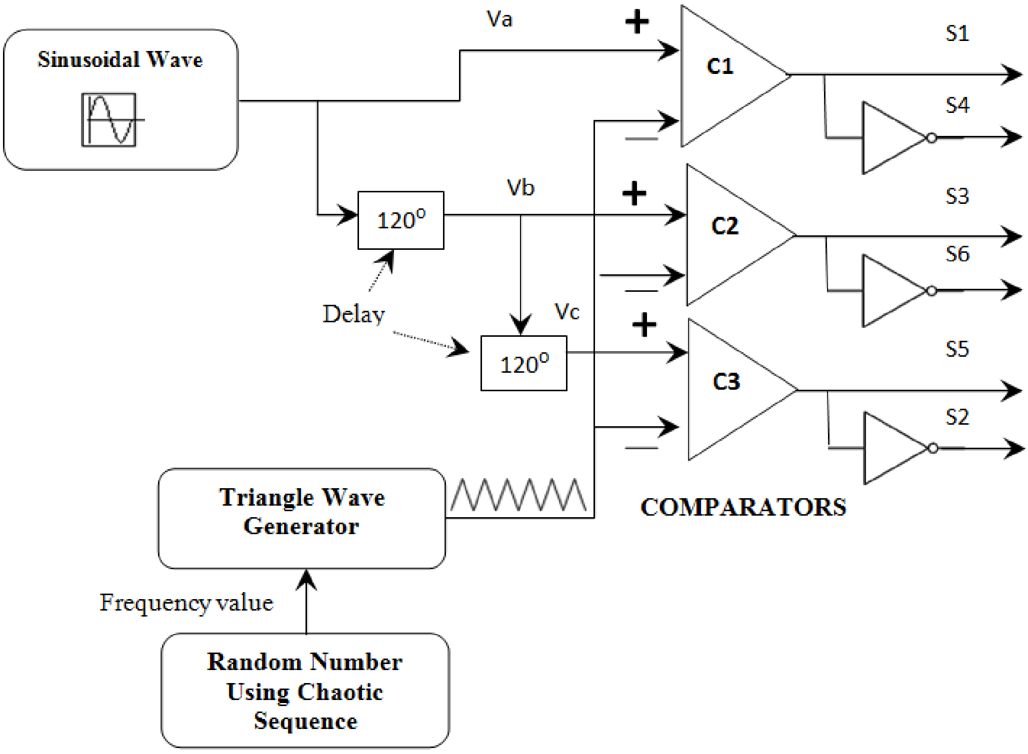

Figure 6: Proposed chaotic carrier sinusoidal pulse width modulation

5. Results and Discussion

The simulated waveforms of three-phase motor line voltages and currents are represented in Figure 7. and Figure 8. respectively. The harmonic sprectum and power spectral density (PSD) for two representative modulation indices viz. 0.8 and 1.2 are diagrammed as from Figure 9. to Figure 12.

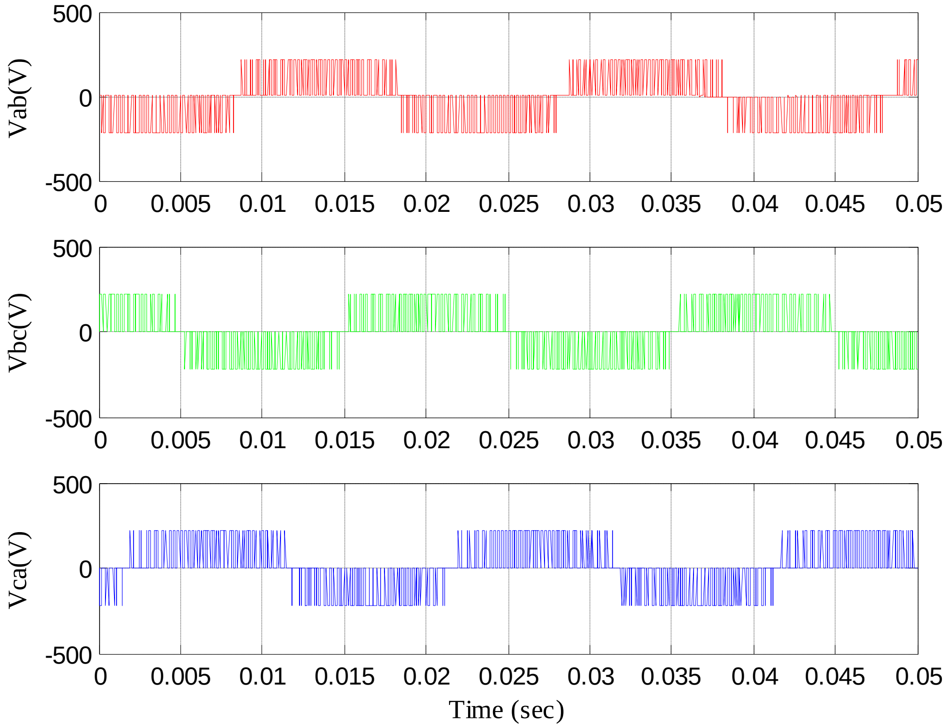

Figure 7: Simulated line-line voltage waveforms of SPWM for Ma=0.8

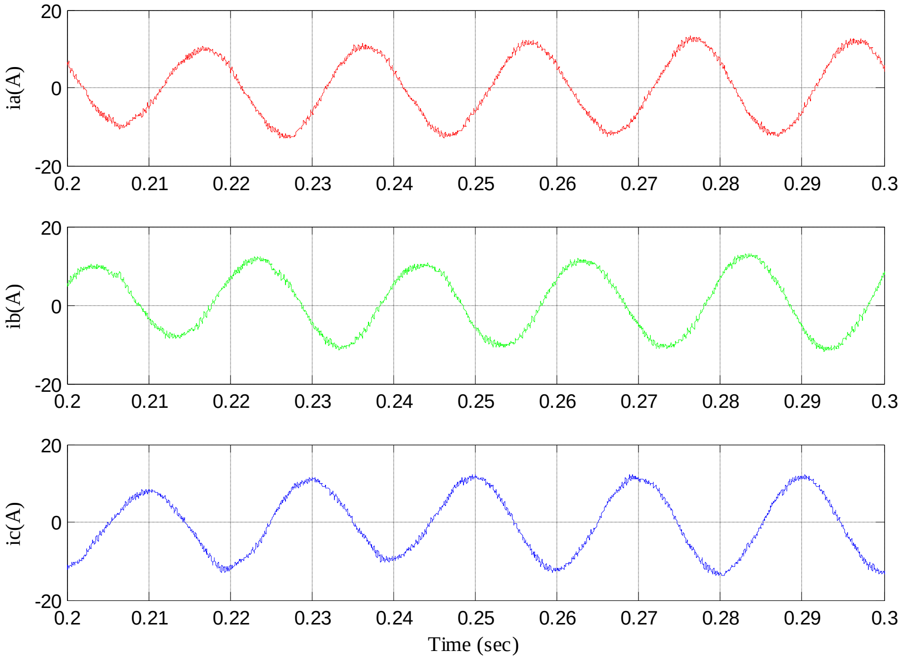

Figure 8: Simulated line current waveforms of SPWM for Ma=0.8

Harmonic spectrum of CCSPWM at Ma=0.8 and Ma=1.2 are presented in Figure 13. and Figure 14. respectively. In the proposed CCSPWM scheme the cluster of harmonic spectra peak appears at switching frequency (fs) and the residual dominant harmonics occur at multiples of switching frequency are considerably reduced at the switching frequency and odd multiples of it. In general, the 1-10 kHz range is the region of the greatest annoyance for human listeners. Unfortunately, this region may coincide with the switching frequency of the power converters.

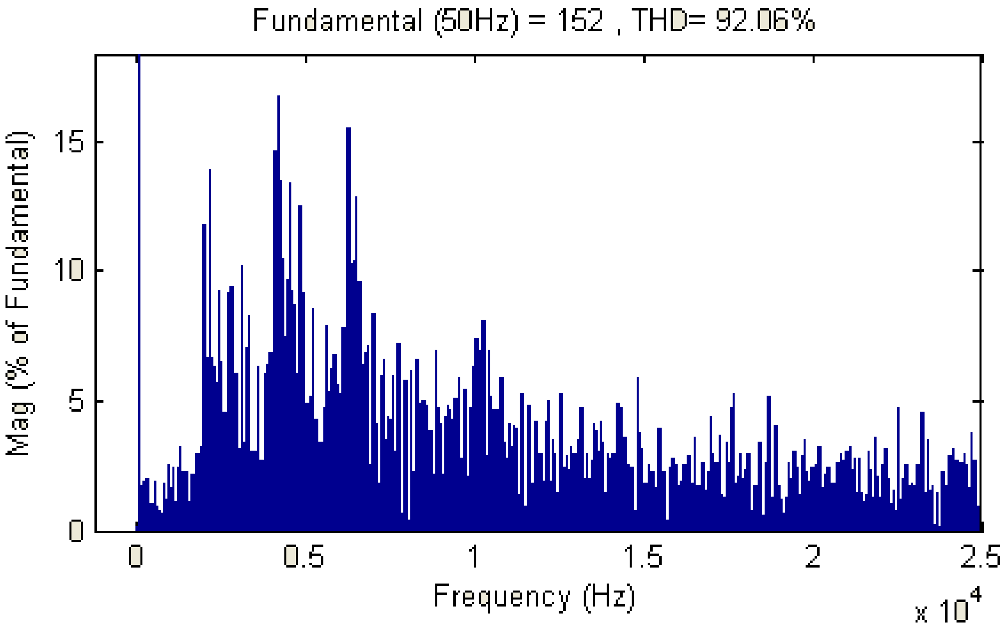

Figure 9: Simulated harmonic spectrum of SPWM for Ma= 0.8

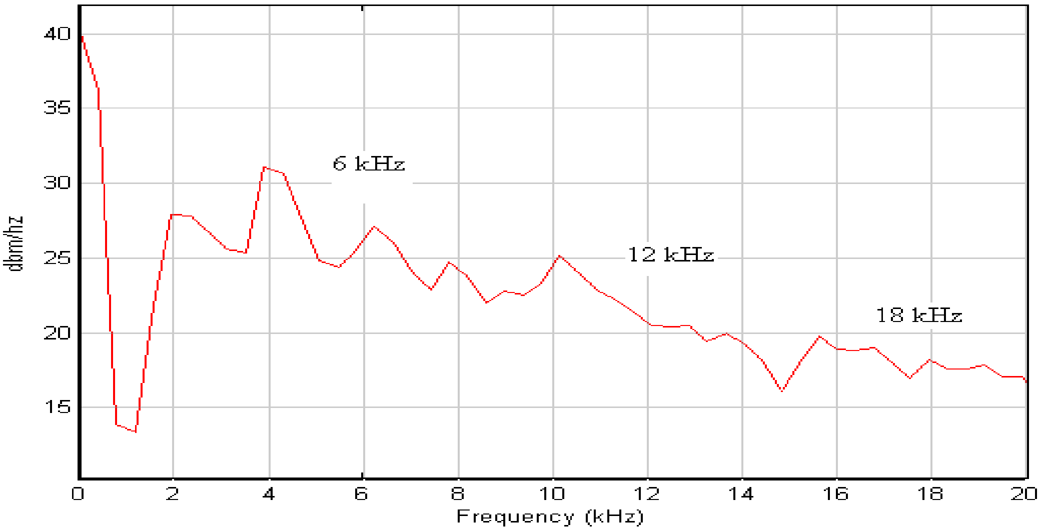

Figure 10: Power spectral density (PSD) of SPWM for Ma= 0.8

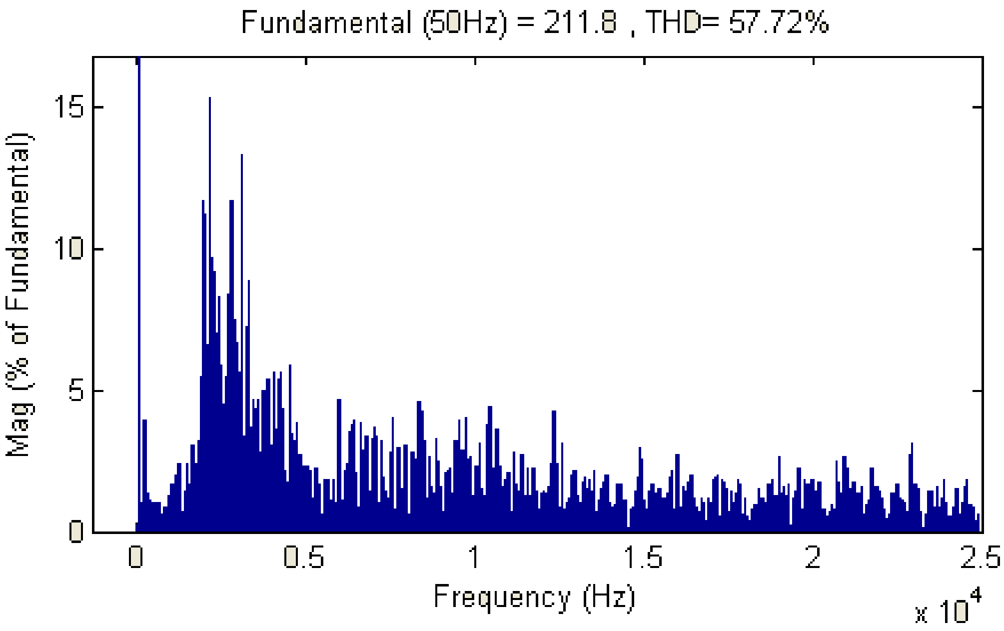

Figure 11: Line voltage harmonic spectrum of SPWM for Ma=1.2

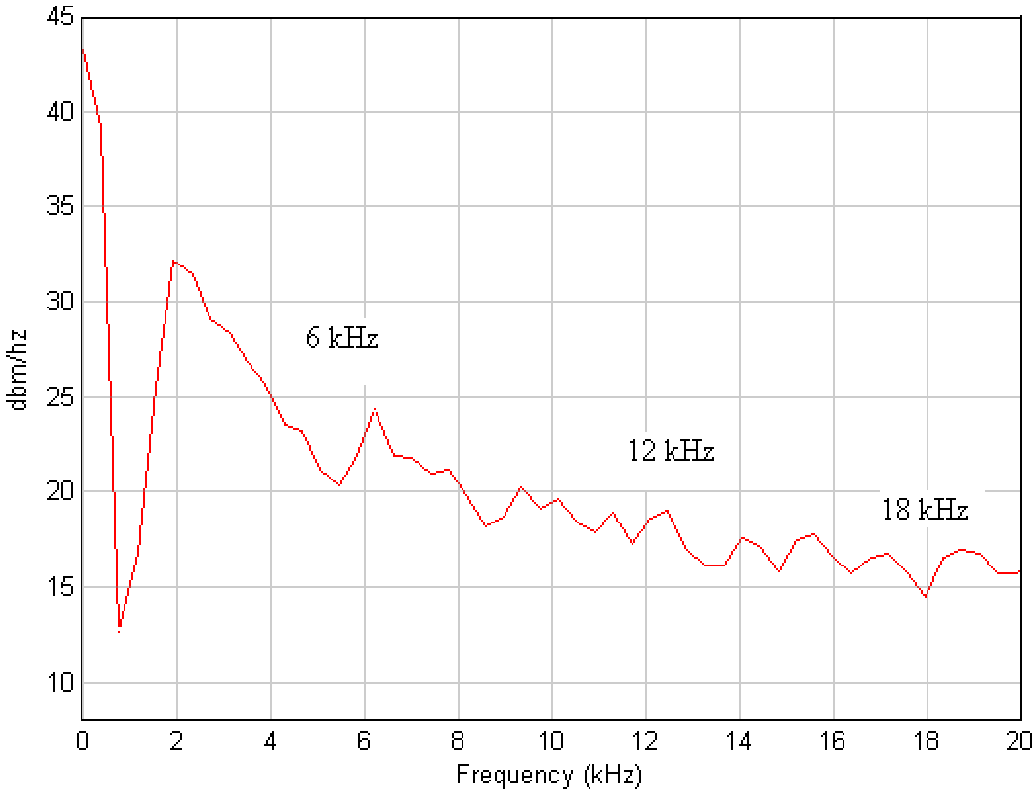

Figure 12: Power spectral density (PSD) of SPWM for Ma= 1.2

Hence it is important that the acoustic noise with a frequency below 10 kHz should be reduced. Their harmonic spectrum is shaped a half circle appear around fs and peak cluster appears at 2fs and its multiples.

Table2: Performance comparison of SPWM and CCSPWM

Ma	V_{O1}		THD (%)		HSF		Reduction HSF (%)
	SPWM	CCSPWM	SPWM	CCSPWM	SPWM	CCSPWM	
0.2	49.059	52.28	257.97	255.41	8.312	4.1416	50.17
0.4	75.86	76.10	164.31	162.44	6.142	3.9262	36.08
0.6	114.00	114.5	121.10	120.74	5.880	3.8430	34.64
0.8	146.60	149.70	90.60	92.06	5.566	3.7899	31.91
1.0	190.90	192.10	68.42	67.50	4.952	3.5380	28.55
1.2	211.80	215.90	58.30	57.72	4.733	3.3225	29.80

From the Table 2. it is understood that the value of the fundamental component (V_{O1}), THD and HSF of the proposed CCSPWM are reduced for the entire range of Ma. At the modulation depth of 0.2, the reduction HSF is about 50.17% in the CCSPWM. The percentage reduction in HSF is more at lower modulation depths in linear modulation and also at higher depths in over modulation region.

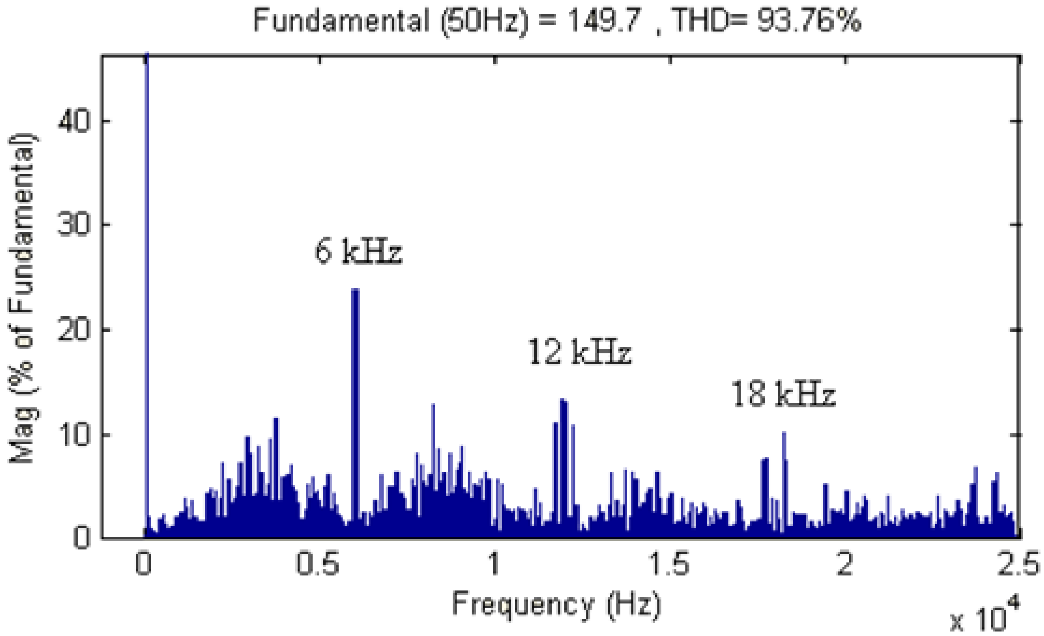

Figure 13: Simulated harmonic spectrum of CCSPWM for Ma=0.8

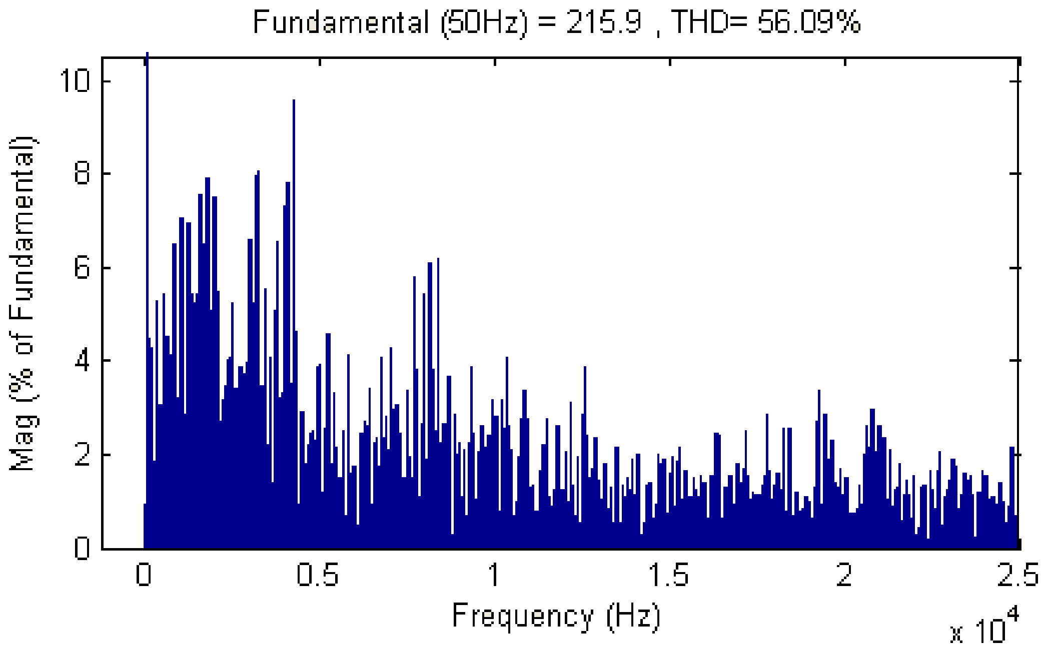

Figure 14: Simulated harmonic spectrum of CCSPWM for Ma=1.2

4. Hardware Implementation

The proposed Chaotic Carrier Sinusoidal PWM architecture has been designed using the VHDL language. The functional simulation of the architecture has been carried out using the tool Modelsim 9.3f. The Register Transfer Level (RTL) level verification and implementation are done using the synthesize tool Xilinx ISE 12.1. Then the designed architecture has been configured to the SPARTAN-6 FPGA (XC6SLX45) device.

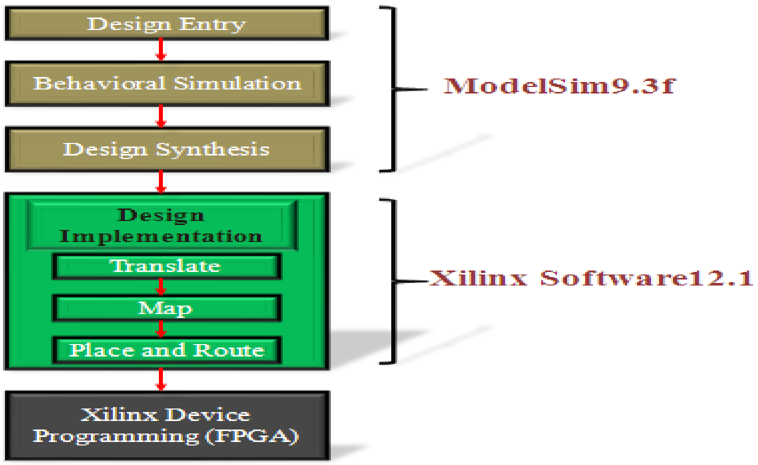

Figure 15: FPGA Design flow for SPWM and RPWM schemes

The functionality of each block in the architecture is simulated thoroughly using the Modelsim software. The detailed flow is represented in the Figure 15. as a flow chart. The Register Transfer Level (RTL) view of the developed architecture is given in figure 16. The Complete timing analysis is presented in Figure 17. The hardware harmonic spectrum of CCSPWM presented for modulation index values 0.8 and 1.2 in Figure 18. and Figure 19. respectively. The captured line voltage and line current waveforms are shown in Figure 20. at modulation index 0.8.

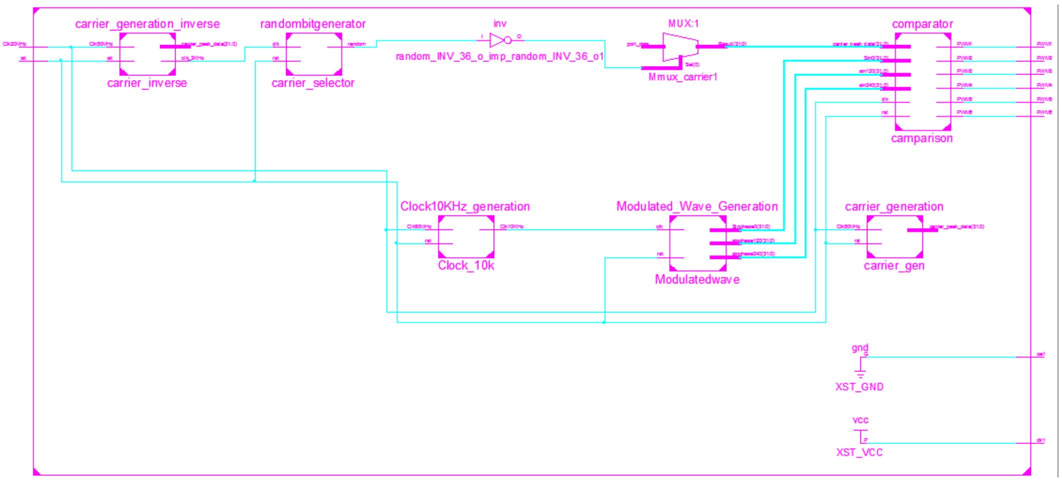

Figure 16: RTL Diagram for CCSPWM

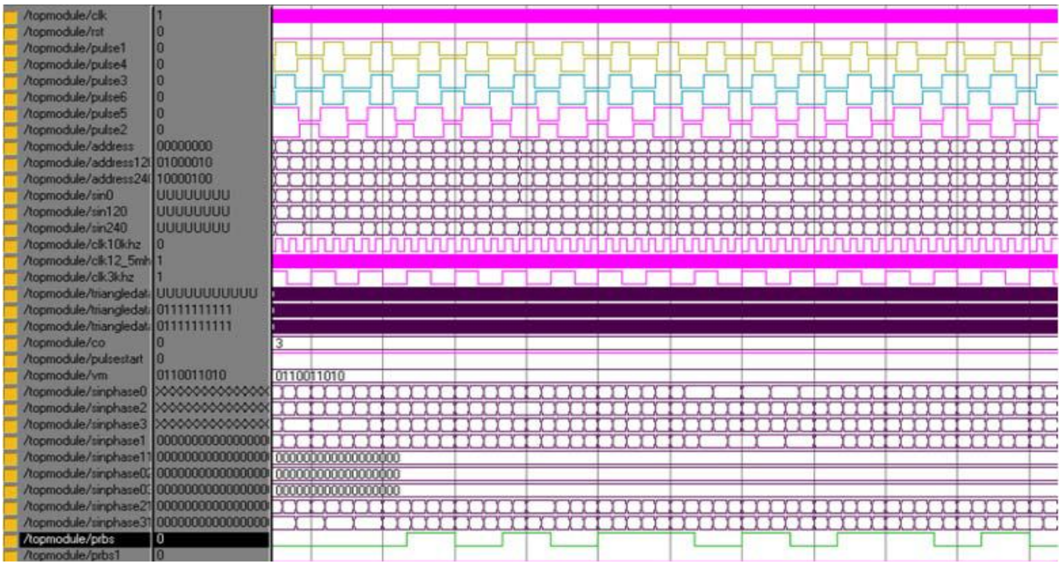

Figure 17: Complete timing analysis

PLL1: 4.9408 kHz
PLL2: 58.366 Hz
Start Order 0
Update 3 (500msec)
2012/05/08 18:13:53

Figure 18: Harmonic spectrum of CCSPWM for Ma = 0.8

PLL1: 4.8546 kHz
PLL2: 50.020 Hz
Start Order 0
Update 1 (500msec)
2012/05/08 18:13:59

Figure 19: Harmonic spectrum of CCSPWM for Ma = 1.2

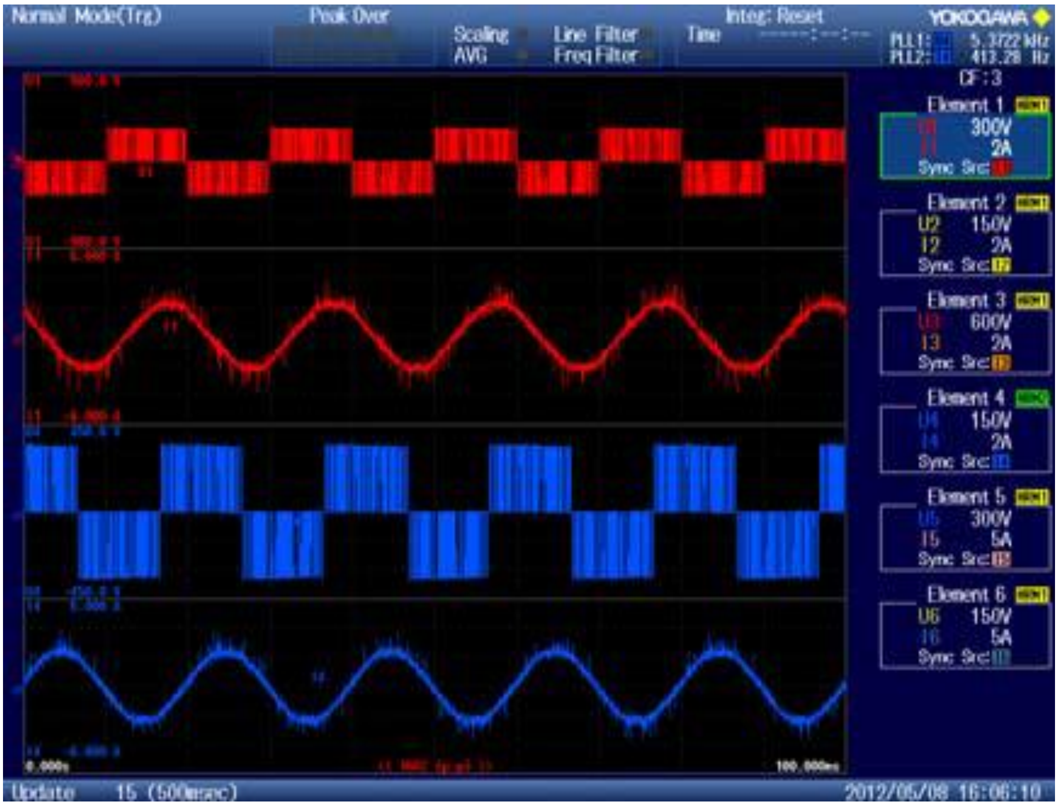

Figure 20: Line voltages and line currents of phases a & b for Ma=0.8

6. Conclusion

A novel random pulse width modulator, which employs a chaotic triangular signal of continuously varying switching frequency and conventional sinusoidal reference, is developed for three-phase voltage source inverters fed induction motor drives. Random pulse width modulation techniques aim in reducing the HSF. HSF is the indicator for harmonic power spreading ability of a PWM technique. Randomness added into the PWM waveform can cause the harmonic power to spread over the harmonic spectrum so that no harmonic component has a significant magnitude. The proposed method is the modified version of conventional sinusoidal pulse width modulation and hence it retains all the merits of it, while the harmonic spreading effect is enhanced. Harmonic Spread Factor is computed for quality evaluation of voltage spectra of inverters with the proposed chaotic carrier sinusoidal pulse width modulation and SPWM. For the entire working range the proposed scheme CCSPWM helps in reducing the HSF and THD, and higher V_{O1}. At the modulation index Ma=0.2 about 50.17% reduction at HSF is obtained. This offers the reduction in acoustic noise and vibration in ASDs. At higher modulation indices the improvement gained in HSF is getting reduced.

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