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A Tactical Chaos based PWM Technique for Distortion Restraint and Power Spectrum Shaping in Induction Motor Drives

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ABSTRACT

The pulse width modulated voltage source inverters (PWM-VSI) dominate in the modern industrial environment. The conventional PWM methods are designed to have higher fundamental voltage, easy filtering and reduced total harmonic distortion (THD). There are number of clustered harmonics around the multiples of switching frequency in the output of conventional sinusoidal pulse width modulation (SPWM) and space vector pulse width modulation (SVPWM) inverters. This is due to their fixed switching frequency while the variable switching frequency makes the filtering very complex. Random carrier PWM (RCPWM) methods are the host of PWM methods, which use randomized carrier frequency and result in a harmonic profile with well distributed harmonic power (no harmonic possesses significant magnitude and hence no filtering is required). This paper proposes a chaos-based PWM (CPWM) strategy, which utilizes a chaotically changing switching frequency to spread the harmonics continuously to a wideband and to reduce the peak harmonics to a great extent. This can be an effective way to suppress the current harmonics and torque ripple in induction motor drives. The proposed CPWM scheme is simulated using MATLAB / SIMULINK software and implemented in three phase voltage source inverter (VSI) using field programmable gate array (FPGA).

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1. INTRODUCTION

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, cycloconverter, matrix converter, and 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 etc. Pulse width modulation (PWM) control strategies have been the subject of intensive research since its development by professor David Prince in the year 1925, particularly in dc-ac power conversion. Past four decades, the industry has seen the development of numerous PWM patterns with associated theories for improving the performance of the VSIs [1]-[4]. It is desirable for a PWM inverter application to employ PWM switching strategy that not only addresses the primary issues viz, less total harmonic distortion (THD), effective dc bus utilization etc. but also take cares of secondary issues like electromagnetic interference reduction, switching loss, better spreading of harmonic power over the spectrum etc [1]-[8]. Although the basic inverter is simple, the mode of switching is challenging in controlling them towards improving the performance indices.

From the literature survey, it is understood that enormous amount of effort has been put in improving the VSI's performance in terms of fundamental fortification, THD minimization, harmonics elimination etc. On the other side issues like electromagnetic interference (EMI), harmonic distribution etc. need further investigation and remedies. The random pulse width modulation (RPWM) techniques are becoming popular and well accepted in industrial motor drives and electric vehicles. The RPWM techniques effectively reduce the acoustic noise, radio interference and mechanical vibration caused by harmonics with low switching frequency [9]. A new random position space vector PWM (RPSVPWM) scheme with C167 microcontroller to reduce audible switching noise has been presented [10]. As reported in [11], the power spectra of a randomized pulse position PWM (RPP-PWM) can be predicted and optimized by suitably positioning the switching pulse. A hybrid RPWM scheme which generates the random pulse position PWM signals with a randomized frequency triangular carrier for improving the harmonic spectra spreading effect has been reported [12]. A randomization technique for conducted EMI reduction in flyback converter has been proposed [13]. Pseudo-random sequence generator (PRSG) is used to provide automatic dynamic dithering for removing undesired idle tones in the output of the sigma delta modulator (SDM). Performance enhancement of evolutionary algorithms (EAs) has been revealed through chaotic sequence [14]. Numerical examples indicating the performance comparison of the EA using random and chaotic generators has been presented. The chaos time series analysis has been involved to capture characteristics of complicated load behavior and developed a new short term power load forecasting model based on chaos theory [15]. The random PWM using random carrier and random position has been discussed [16]-[18].

The existing RPWM methods can improve the harmonic spreading ability of the VSI undoubtedly while their performance is not appreciable. Hence it is understood that the randomness created by the existing random carrier PWM and random position PWM is not efficient. Further improving the spreading effect, the randomness can be generated through triumph chaotic sequences. The proposed chaos-based PWM (CPWM) strategy, which utilizes a chaotically changing switching frequency to spread the harmonics continuously and performs suitably for ac drives. The proposed CPWM scheme is simulated using MATLAB/SIMULINK software and implemented in the designed three phase VSI through a SPARTAN-6 FPGA (XC6SLX45) kit.

1.1. 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 [19]-[21]. 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:

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

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.

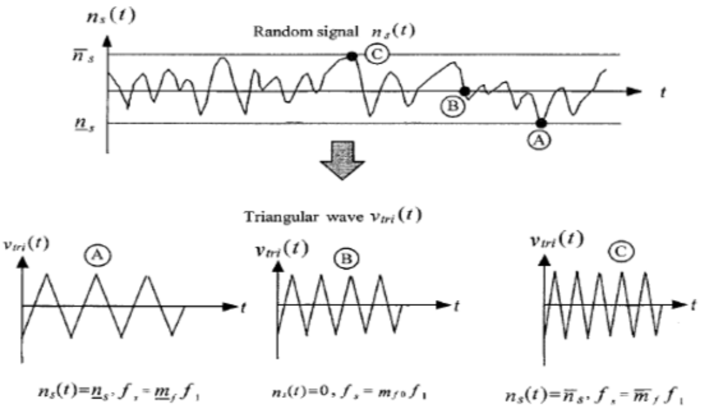


Figure 1. Random signal, $n_s(t)$ guided generation of triangular wave carrier

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

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

Where, N denotes the total number of frequency components considered, H_j is the amplitude of the jth component and H_0 is the average value of all components. It is given by the equation:

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

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.

2. PROPOSED METHOD

The basic idea of the proposed CPWM is in tow fold. First a chaotically frequency modulated-fixed magnitude triangular carrier (CFMFMTC) is generated. Then the CFMFMTC is compared with the traditional sinusoidal reference for pulse generation. The complete scheme is described in the Figure 2. The chaotic sequence is generated and passed to the triangular oscillator. The triangular oscillator generates CFMFMTC. The modulation index corrected three phase sinusoidal references are compared with triangular waves. The pulses obtained and their inverted forms are fed to the VSI after driving unit. The sequence of random numbers generated by chaotic sequence does not exhibit the limitation of other random carrier PWM (RCPWM) methods i.e. restricted repetition rate (limited number of distinct patterns). The word "the random carrier" will get its flawless meaning if the frequency is varied cycle to cycle randomly like shown in Figure 3.

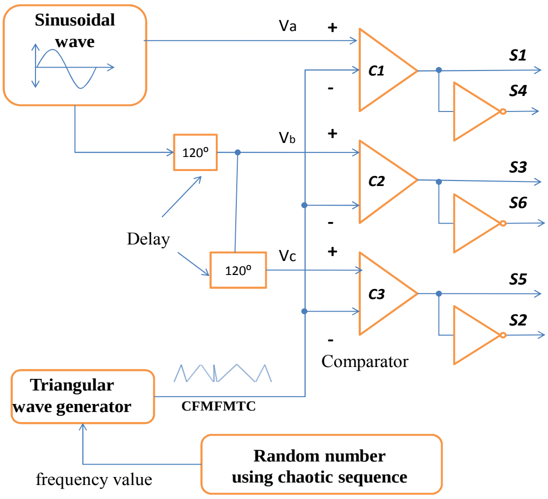


Figure 2. Proposed Chaos based PWM

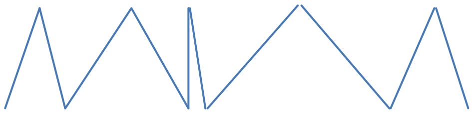


Figure 3. CFMFMTC with cycle to cycle variation

2.1. Chaotic Sequence and CFMFMTC

The basic principle of chaos-based PWM is to use a chaotic signal to vary the switching or carrier frequency. The chaotic sequence described in the Equation (4) is employed in this paper.

$$f_{\mathrm{n}} = f_{\mathrm{low}} + (f_{\mathrm{high}} - f_{\mathrm{low}} + 1)\frac{x(n)}{0.5(5^{c} - 1)} \tag{4}$$

$$x(n+1) = \begin{cases} 2x(n) \quad if \quad x(n) = 0 \; and \; x(n) \le 5^{c} \\ 5^{c} - 2x(n) \; else \end{cases}$$

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}. Arbitrary periodic orbit can be obtained by using different value of c. The flow chart for generation of chaotic sequence is shown in Figure 4 and one of the positive integer sequences generated by iteration in MATLAB environment corresponds to c = 6 is shown in Figure 5.

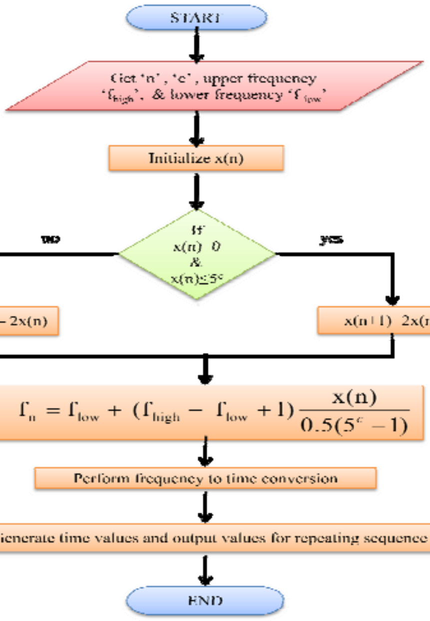
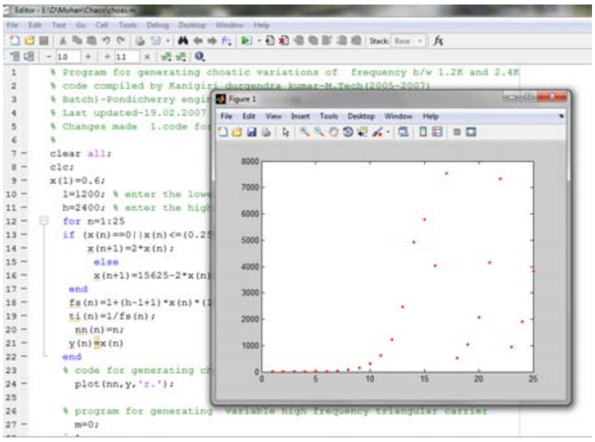


Figure 4. Flowchart for generation of chaotic sequence



```
% Program for generating choatic variations of  frequency b/w 1.2K and 2.4K
% code compiled by Kanigiri durgendra kumar-M.Tech(2005-2007)
% Batch)-Pondicherry engi
% Last updated-19.02.2007
% Changes made  1.code fo
%
clear all;
clc;
x(1)=0.6;
  l=1200; % enter the lowe
  h=2400; % enter the high
  for n=1:25
  if (x(n)==0||x(n)<=(0.25
      x(n+1)=2*x(n);
       else
       x(n+1)=15625-2*x(n)
   end
   fs(n)=l+(h-l+1)*x(n)*(1
   ti(n)=1/fs(n);
    nn(n)=n;
   y(n)=x(n)
  end
  % code for generating ch
    plot(nn,y,'r.');

  % program for generating  variable high frequency triangular carrier
    m=0;
```

Figure 5. Generation of positive integer sequences with uniform distribution for c= 6

3. RESULTS AND DISCUSSION

Simulations are carried out using MATLAB software. The chaotic sequence is coded in m-file while the VSI schematized in Simulink model (.mdl) file. The main aim of this section is comparing the performances of SPWM and the developed CPWM. The input dc voltage (V_{dc}) is 415V and the output frequency is taken as 50Hz. The switching frequency of SPWM is 3KHz while for chaos based PWM carrier frequency is varied form 2KHz to 4KHz. The load is 3HP, 220V, 3 phase squirrel cage induction motor. Simulation results such as fundamental magnitude, THD and HSF are considered for study. Figure 6 represents output line voltages while Figure 7 indicates line currents. Figure 8 illustrates the harmonic spectrum of line voltage and Figure 9 shows the Power spectral density for SPWM.

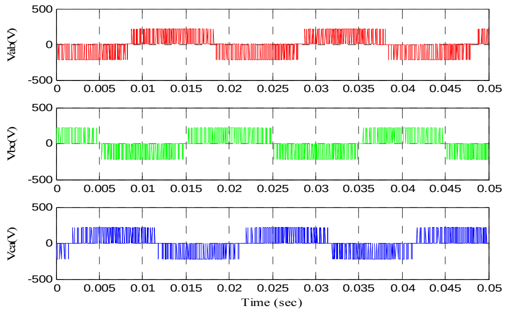


Figure 6. Simulated line-line voltage waveforms of SPWM for Ma = 0.8

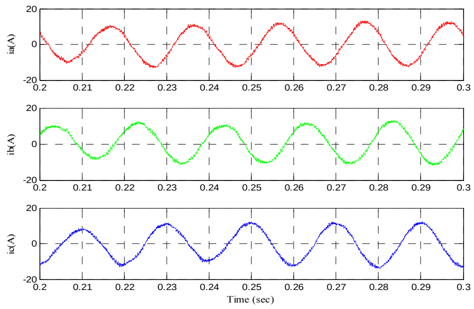


Figure 7. Simulated current waveforms of SPWM for Ma = 0.8

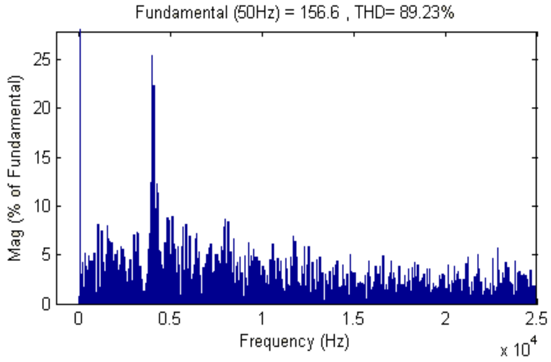


Figure 8. Simulated harmonic spectrum of SPWM for Ma = 0.8

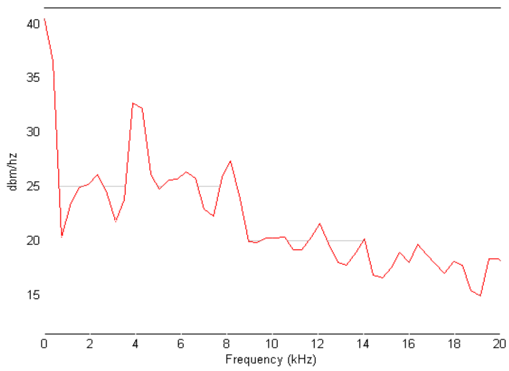


Figure 9. Power spectral density (PSD) of SPWM for Ma=0.8

Harmonic spectrum of CPWM at Ma=0.8 and Ma=1.2 are presented in Figure 10 and Figure 11 respectively. In the proposed CPWM scheme the cluster of harmonic spectra peak appears at switching frequency (f_s) 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. 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 f_s and peak cluster appears at $2f_s$ and its multiples.

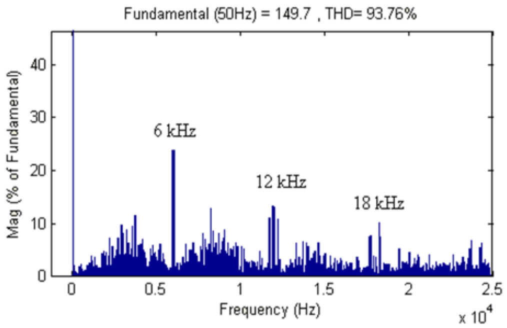


Figure 10. Simulated harmonic spectrum of CPWM for Ma=0.8

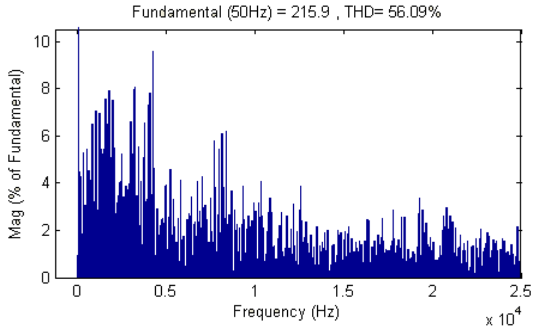


Figure 11. Simulated harmonic spectrum of CPWM for Ma= 1.2

Table 1 and 2 provide the comprehensive details of results obtained from both SPWM and CPWM. The value of the fundamental component (V_{01}), THD and HSF of the output voltage are listed at different modulation index values (M_a). For the entire working range CPWM offers lesser HSF and THD, and higher V_{01}. At Ma=0.2 about 50% reduction at HSF is obtained. The THD reduction is marginal while the fundamental enhancement is noticeable. At higher modulation indices the improvement gained in HSF is getting reduced.

Table 1. Results of SPWM

Ma	V_{01}	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	146.60	98.23	5.566
1.0	190.90	68.42	4.952
1.2	211.80	62.23	4.243

Table 2. Results of CPWM

Ma	V_{01}	THD	HSF
0.2	52.28	255.41	4.1416
0.4	76.10	162.44	3.9262
0.6	114.5	120.74	3.8430
0.8	149.70	93.76	3.7899
1.0	192.10	67.50	3.5380
1.2	215.90	56.09	3.3225

3.1. HARDWARE IMPLEMENTATION

The designed CPWM logic is incorporated as an architecture using the VHDL language. Modelsim 9.3f is employed as a tool for performing functional simulation while Xilinx ISE 12.1 is the synthesize tool for the Register Transfer Level (RTL) level verification and implementation. The functional verified code of the architecture is downloaded to the SPARTAN-6 FPGA (XC6SLX45) device. The flowchart illustrated in Figure 12 represents the responsibilities of Modelsim and Xilinx. The code algorithm follows the conceptual diagram presented in Figure 12.

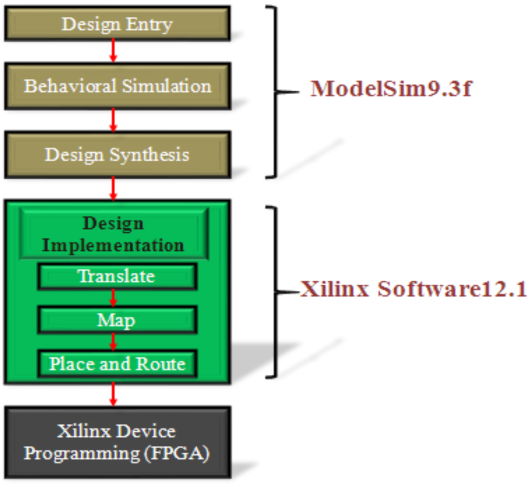


Figure 12. FPGA Design flow for SPWM and RPWM schemes

The register transistor logic (RTL) view of the developed architecture is given in Figure 13. The device utilization summary is found in Figure 14. The complete timing analysis is diagrammed in Figure 15. Representative hardware harmonic spectra are presented for Ma=0.8 and 1.2 in Figure 16 and Figure 17 respectively. The captured line voltage and current waveforms are shown at Figure 18. The pulse pattern is represented in Figure 19.

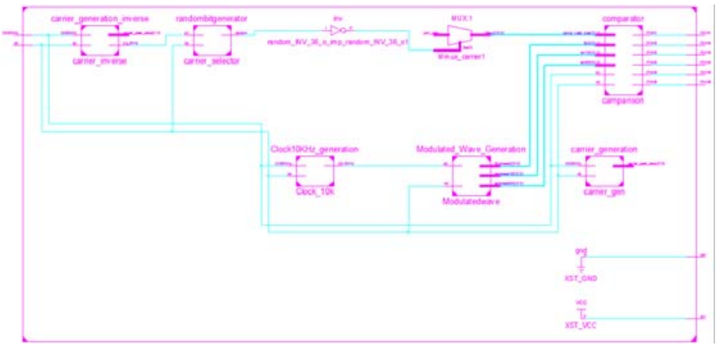
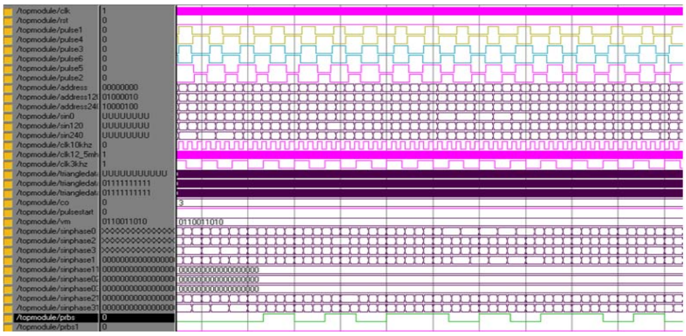


Figure 13. RTL Diagram for CPWM

Device Utilization Summary (estimated values)			
Logic Utilization	**Used**	**Available**	**Utilization**
Number of Slice Registers	325	30064	1%
Number of Slice LUTs	793	15032	5%
Number of fully used LUT-FF pairs	228	890	26%
Number of bonded IOBs	10	186	5%
Number of BUFG/BUFGCTRLs	5	16	31%
Number of DSP48A1s	3	38	8%

Figure 14. Device utilization summary



```
/topmodule/clk          1
/topmodule/rst          0
/topmodule/pulse1       0
/topmodule/pulse4       0
/topmodule/pulse3       0
/topmodule/pulse6       0
/topmodule/pulse5       0
/topmodule/pulse2       0
/topmodule/address      00000000
/topmodule/address12(   01000010
/topmodule/address24(   10000100
/topmodule/sin0         UUUUUUUU
/topmodule/sin120       UUUUUUUU
/topmodule/sin240       UUUUUUUU
/topmodule/clk10khz     0
/topmodule/clk12_5mh    1
/topmodule/clk3khz      1
/topmodule/triangledat  UUUUUUUUUUU
/topmodule/triangledat  01111111111
/topmodule/triangledat  01111111111
/topmodule/co           0
/topmodule/pulsestart   0
/topmodule/vm           0110011010
/topmodule/sinphase0    XXXXXXXXXXXXXXX
/topmodule/sinphase2    XXXXXXXXXXXXXXX
/topmodule/sinphase3    XXXXXXXXXXXXXXX
/topmodule/sinphase1    0000000000000000
/topmodule/sinphase11   0000000000000000
/topmodule/sinphase02   0000000000000000
/topmodule/sinphase03   0000000000000000
/topmodule/sinphase21   0000000000000000
/topmodule/sinphase31   0000000000000000
/topmodule/prbs         0
/topmodule/prbs1        0
```

Figure 15. Complete timing analysis

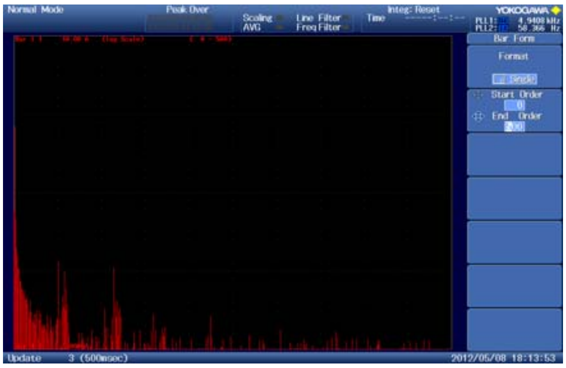


Figure 16. Harmonic spectrum for of CPWM Ma = 0.8

Figure 17. Harmonic spectrum of CPWM for Ma = 1.2

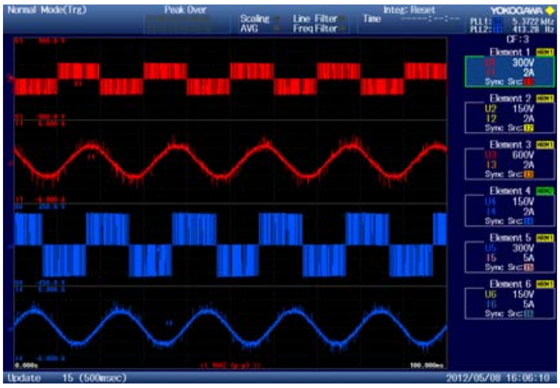


Figure 18. Line voltages and line currents of phases a & b (Ma =0.8)

Figure 19. Gating pulses

4. CONCLUSION

Distribution of harmonic power becomes major topic of interest in PWM-VSI 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 chaos based PWM confirms that the randomization of carrier frequency offers advantageous features such as reduced total harmonic distortion, EMI emission from converter equipment, acoustic and vibration effects and improved harmonic power spectrum in electronic drive systems. For the entire working range CPWM offers lesser HSF and THD, and higher V_{01}. At Ma=0.2 about 50% reduction at HSF is obtained. At higher modulation indices the improvement gained in HSF is getting reduced.

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