CHAPTER 4

A CHAOS BASED RPWM TECHNIQUE FOR INDUCTION MOTOR DRIVE

4.1 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 VVVF power with high quality. The AC drives can be any one from the well-known choices viz. ac chopper, cycloconverters, MC, and rectifier and VSI combination. Due to their merits, VSIs are dominantly used not only as drives but also in applications like induction heating, standby air craft power supplies, UPS for computers, FACTS etc. 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 (Cho et al 2007; Sutikno et al 2010; Hava et al 1998). It is desirable for a PWM inverter application to employ PWM switching strategy that not only addresses the primary issues viz, less THD, effective DC bus utilization etc. but also take cares of secondary issues like EMI reduction, minimization of switching loss, better spreading of harmonic power over the spectrum etc. (Habetler & Divan 1991; Sutikno & Facta 2010; Kirlin et al 1994; Ibrahim et al 2014). 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. and the conventional PWM methods are designed for it. On the other side issues like EMI, harmonic distributions etc. need further investigation and remedies. There are number of clustered harmonics around the multiples of switching frequency in the output of conventional deterministic methods like SPWM, SVPWM, DPWM, etc. This is due to their fixed switching frequency while the variable switching frequency makes the filtering very complex. The 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. RPWM methods are the host of PWM methods, which use randomness in any one the characteristics and result in a harmonic profile with well distributed harmonic power (no harmonic possesses significant magnitude and hence no filtering is required). Very common way of introducing the randomness in the PWM process is either making the random carrier or randomizing the pulse position. The RPWM methods are also known as non-deterministic PWM methods.

4.2 PROBLEM DEFINITION

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 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.

4.3 CHAOTIC SEQUENCE AND RANDOMNESS

Chaos, apparently disordered behaviour 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
behaviour of a chaotic system is a collection of many orderly behaviours,
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 behaviours. This gives a clue to improve 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 behaviour. 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 (Wang & Smith 1998; Determan & Foster 1999; Marcelle Merhy et al 2013). Bifurcation diagram is the most powerful tool to investigate the chaos and bifurcation behaviour. 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 behaviour of a system is clearly shown as a parameter is varied. The bifurcation diagram is used 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:

\[ X_{n+1} = \lambda \cdot X_n (1 - X_n) \]  

(4.1)

The properties of the logistic function are well known, but briefly reviewed here. For values of \( \lambda \) in (0, 3), Equation (4.1) will converge to some value x. For \( \lambda \) between three and about 3.56 the solution to Equation (4.1) bifurcates into two, then four, then eight (and so on) periodic solutions. For \( \lambda \) between 3.56 and four the solutions to Equation (4.1) become fully chaotic neither convergent nor periodic, but variable with non discernible pattern. As \( \lambda \) approaches four, the variation in solutions to Equation (4.1) 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 4.1. 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 4.1 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 HSF. The HSF is detailed in chapter 1. The HSF quantifies the spread spectra effect of the RPWM scheme and it should be small. For ideally flat spectra of white noise, the HSF would be zero.
4.4 EXISTING RANDOM CARRIER PWM

Figure 4.2 represents the existing RCPWM, where randomized triangular carrier generation is done by a shift register with limited distinct binary patterns. As shown in Figure 4.2 the triangular carrier with fixed frequency ‘fc+’ and the triangular carriers with fixed frequency but opposite phase ‘fc’ are given as input to the 2×1 multiplexer. The frequencies of waveforms fc+ and fc- are same.

The randomized triangular carrier ‘f_R’ is obtained by randomly selecting the fc+ and fc- with the help of the Pseudo Random Binary Sequence (PRBS) output bits 0 or 1 of the random bit generator. The PRBS is basically a Linear Feedback Shift Register (LFSR). In order to obtain the random bit number for selecting the winning triangle, a triumph sequential digital circuit with large number of distinct states (bigger repetition cycle) is required. This is because the randomness does not rely only on two distinct carriers but also on the sequential pattern used for selection. LFSR is the best solution to offer
the above requirement (good randomness). Typical 16 bits LFSR with a feedback of four tapings is worth considering. The choice of taps determines how many values there are in a given sequence before the sequence repeats. The optimum tapping bit numbers are used for logical XOR operation (Bits 11, 13 and 14, 16). Repetition is depends upon the length of LFSR and the clock frequency used. The winning triangle carrier cycle is compared with sinusoidal reference to get the gating pulses. This method is referred as RCPWM in this thesis.

4.5 PROPOSED METHOD

The basic idea of the proposed CPWM is in two fold. First a Chaotic 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 4.3.

Figure 4.3 Proposed chaos based PWM
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 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 4.4.

Figure 4.4 CFMFMTC with cycle to cycle variation

4.6 CHAOTIC SEQUENCE AND CFMFMTC

The basic principle of CPWM is to use a chaotic signal to vary the switching or carrier frequency. The chaotic sequence described in the Equation (4.2) is employed in this work.

\[
f_n = f_{\text{low}} + (f_{\text{high}} - f_{\text{low}} + 1) \frac{x(n)}{0.5(5^c - 1)}
\]  

(4.2)

\[
x(n + 1) = \begin{cases} 
2x(n) & \text{if } x(n) = 0 \text{ and } x(n) \leq 5^c \\
5^c - 2x(n) & \text{else}
\end{cases}
\]  

(4.3)

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 \(f_{\text{low}}\) to \(f_{\text{high}}\). Arbitrary periodic orbit can be obtained by using
different value of c. The flow chart for generation of chaotic sequence is shown in Figure 4.5 and one of the positive integer sequences generated by iteration in MATLAB programming environment corresponds to c = 6 is shown in Figure 4.6.

Figure 4.5 Steps for generation of chaotic sequence
4.7 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 performance 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 3 KHz while for chaos based PWM carrier frequency is varied from 2 KHz to 4 KHz. The load is a three-phase squirrel cage induction motor (0.75 KW) and 2.5 A load is considered.

Table 4.1 shows the detailed specification of the induction motor used.
Table 4.1 Induction Motor Specification

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power (P)</td>
<td>0.75 KW</td>
</tr>
<tr>
<td>Line-Line Voltage (V_{L})</td>
<td>415 V</td>
</tr>
<tr>
<td>Frequency (f)</td>
<td>50 Hz</td>
</tr>
<tr>
<td>Stator Resistance (R_s)</td>
<td>1.435 Ω</td>
</tr>
<tr>
<td>Stator Inductance (L_s)</td>
<td>0.005839 H</td>
</tr>
<tr>
<td>Rotor Resistance (R_r)</td>
<td>1.395 Ω</td>
</tr>
<tr>
<td>Rotor Inductance (L_r)</td>
<td>0.005839 H</td>
</tr>
<tr>
<td>Inertia (J)</td>
<td>0.0131 Kgm²</td>
</tr>
<tr>
<td>Friction factor</td>
<td>0.0029 Nms</td>
</tr>
<tr>
<td>Pole Pairs</td>
<td>2</td>
</tr>
</tbody>
</table>

Simulation results such as fundamental magnitude, THD and HSF are considered for study. Figure 4.7 represents output line voltages while Figure 4.8 indicates line currents. Figure 4.9 illustrates the harmonic spectrum of line voltage and Figure 4.10 shows the PSD for SPWM.

Figure 4.7 Simulated line-line voltage waveforms of SPWM for M_d = 0.8
Figure 4.8 Simulated current waveforms of SPWM for $M_a = 0.8$

Figure 4.9 Simulated harmonic spectrum of SPWM for $M_a = 0.8$
Figure 4.10 PSD of SPWM for $M_a = 0.8$

Harmonic spectrum of CPWM at $M_a = 0.8$ and $M_a = 1.2$ are presented in Figure 4.11 and Figure 4.12 respectively.

Figure 4.11 Simulated harmonic spectrum of CPWM for $M_a = 0.8$
Figure 4.12 Simulated harmonic spectrum of CPWM for \( M_a = 1.2 \)

In the proposed CPWM scheme the cluster of harmonics appearing at switching frequency \( f_s \) are considerably reduced. 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. The CPWM helps greatly in reducing the acoustic noise.

Table 4.2 lists the performance of SPWM while the Table 4.3 provides the comprehensive details of results obtained from both RCPWM and CPWM. The value of the fundamental component \( (V_1) \), 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 \( V_1 \). At \( M_a = 0.2 \) about 41% reduction in HSF when compared with SPWM is obtained while the reduction compared with RCPWM is 31%. The THD reduction is
marginal while the fundamental enhancement is noticeable. At higher modulation indices the improvement gained in HSF is getting reduced.

Table 4.2 Results of SPWM

<table>
<thead>
<tr>
<th>( M_a )</th>
<th>( V_1 )</th>
<th>THD</th>
<th>HSF</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.2</td>
<td>74</td>
<td>242</td>
<td>8.3</td>
</tr>
<tr>
<td>0.4</td>
<td>136</td>
<td>168</td>
<td>6.1</td>
</tr>
<tr>
<td>0.6</td>
<td>211</td>
<td>123</td>
<td>5.9</td>
</tr>
<tr>
<td>0.8</td>
<td>293</td>
<td>90</td>
<td>5.6</td>
</tr>
<tr>
<td>1.0</td>
<td>366</td>
<td>66</td>
<td>5.2</td>
</tr>
<tr>
<td>1.2</td>
<td>394</td>
<td>59</td>
<td>5.0</td>
</tr>
</tbody>
</table>

Table 4.3 Comparison of RCPWM and CPWM

<table>
<thead>
<tr>
<th>( M_a )</th>
<th>( V_1 )</th>
<th>THD</th>
<th>HSF</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>RCPWM</td>
<td>CPWM</td>
<td>RCPWM</td>
</tr>
<tr>
<td>0.2</td>
<td>74.2</td>
<td>75</td>
<td>241.9</td>
</tr>
<tr>
<td>0.4</td>
<td>135.5</td>
<td>137</td>
<td>168.0</td>
</tr>
<tr>
<td>0.6</td>
<td>210.3</td>
<td>211</td>
<td>122.2</td>
</tr>
<tr>
<td>0.8</td>
<td>293.2</td>
<td>294</td>
<td>89.2</td>
</tr>
<tr>
<td>1.0</td>
<td>366.7</td>
<td>367</td>
<td>66.7</td>
</tr>
<tr>
<td>1.2</td>
<td>394.0</td>
<td>395</td>
<td>58.3</td>
</tr>
</tbody>
</table>

4.8 HARDWARE IMPLEMENTATION

The designed CPWM logic is incorporated as an architecture using the VHDL language. ModelSim 6.3 is employed as a tool for performing functional simulation while Xilinx ISE 13.2 is the synthesize tool for the RTL
verification and implementation. The functional verified code of the architecture is downloaded to the Spartan-6 FPGA (XC6SLX45) device. The flowchart illustrated in Figure 4.13 represents the responsibilities of ModelSim and Xilinx. The code algorithm follows the conceptual diagram presented in Figure 4.13.

![Diagram of FPGA design flow for SPWM and RPWM schemes](image)

**Figure 4.13 FPGA design flow for SPWM and RPWM schemes**

The RTL view of the developed architecture is given in Figure 4.14. The device utilization summary is found in Figure 4.15. The complete timing analysis is diagrammed in Figure 4.16. Representative hardware harmonic spectra are presented for $M_a = 0.8$ and 1.2 in Figure 4.17 and Figure 4.18 respectively. The captured line voltage and current waveforms are shown at Figure 4.19. The pulse pattern is represented in Figure 4.20.
Figure 4.14 RTL diagram for CPWM

<table>
<thead>
<tr>
<th>Logic Utilization</th>
<th>Used</th>
<th>Available</th>
<th>Utilization</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of Slice Registers</td>
<td>325</td>
<td>30064</td>
<td>1%</td>
</tr>
<tr>
<td>Number of Slice LUTs</td>
<td>793</td>
<td>15032</td>
<td>5%</td>
</tr>
<tr>
<td>Number of fully used LUT-FF pairs</td>
<td>228</td>
<td>890</td>
<td>26%</td>
</tr>
<tr>
<td>Number of bonded IOBs</td>
<td>10</td>
<td>186</td>
<td>5%</td>
</tr>
<tr>
<td>Number of BUFG/BUFGCTRLs</td>
<td>5</td>
<td>16</td>
<td>31%</td>
</tr>
<tr>
<td>Number of DSP48A1s</td>
<td>3</td>
<td>38</td>
<td>8%</td>
</tr>
</tbody>
</table>

Figure 4.15 Device utilization summary
Figure 4.16 Complete timing analysis

Figure 4.17 Harmonic spectrum of CPWM for $M_a = 0.8$
Figure 4.18 Harmonic spectrum of CPWM for $M_a = 1.2$

Figure 4.19 Line voltages and line currents of phases a & b ($M_a = 0.8$)
4.9 SUMMARY

Distribution of harmonic power becomes major topic of interest in PWM-VSI drives. RPWM 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 CPWM confirms that the randomization of carrier frequency offers advantageous features such as reduced THD, 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 $V_1$. At $M_a=0.2$ about 41% reduction at HSF is obtained. At higher modulation indices the improvement gained in HSF is getting reduced.