Comparison of PWM Control Techniques for a Three Phase Inverter using Field Programmable Gate Array

Valantina Stephen , L.PadmaSuresh

Department of Electrical and Electronics, Noorul Islam Centre for Higher Education, Kumaracoil, 629180, Thuckalay, Tamilnadu, India
valantina2000@yahoo.com

Abstract: A comparison of pulse width modulation techniques for three phase motor drive systems based on the fundamental voltage, total harmonic distortion and harmonic spread factor are presented. This paper proposes different PWM strategies such as Sinusoidal PWM, Sixty Degrees PWM, Third Harmonic Injection PWM and Random Frequency PWM synchronized for a three phase inverter and applied to a 1-hp induction motor drive system for the reduction of harmonics and improvement of fundamental peak voltage. For providing alternating output voltage with a specific magnitude and frequency to industrial applications, three-phase inverter is preferred. The gating signals to the inverter are produced by means of Sinusoidal PWM, Sixty Degrees PWM, Third Harmonic Injection PWM and Random Frequency PWM to significantly reduce harmonics in comparison to currently used PWMs. FPGA is used to produce gating signals to the switches in a three-phase bridge inverter since a faster speed of operation is needed. The simulation is carried on VHSIC (Very High Speed Integrated Circuits) Hardware Description Language (VHDL) using ModelSim. Then, this VHDL model is imported into Matlab environment and co-simulated using HDL Cosimulation toolbox**.** The simulation and experimental results are presented with a view to show the differences between different PWM techniques and to determine that Random Frequency PWM technique performs better in terms of fundamental voltage, Total Harmonic Distortion and Harmonic Spread Factor.

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Keywords: Field Programmable Gate Array (FPGA), Sinusoidal-PWM (SPWM),Sixty Degrees PWM, Random Frequency PWM (RFPWM), Third Harmonic Injection (THI) PWM, Inverter, Total Harmonic Distortion (THD), Harmonic Spread Factor (HSF), VHSIC Hardware Description Language (VHDL)

1. Introduction

Solid state power devices have reached a state where PWM inverter-fed induction motor drives have become more popular in many industrial applications (Mekhilef and Rahim, 2002). In solid state power devices many technologies are being improved including the pulse width modulation since it is important for the drive performance. Several Pulse Width Modulation techniques share a common aim to reduce the amount of harmonics in general or to eliminate some of them (M.J.Meco-Gutierrez et al., 2007). The significant feature of a random pwm inverter is that the acoustic noise can be reduced since the output harmonic spectra are dispersed and continuously distributed. Out of the existing random PWM schemes, in random pwm switching the triangular wave is replaced by random pwm signal in SPWM but the performance will greatly degrade when the modulation index is low (Ki-Seon Kim et al., 2009).

By different types of control techniques like SPWM, RFPWM, THIPWM and Sixty degrees PWM, fundamental component, total harmonic distortion (THD) and Harmonic Spread Factor (HSF) can be controlled. Each of the above methods possesses different patterns of pulse width modulation, and harmonic components (Boost et al., 1998), (J.Holtz, 1996). Although sinusoidal pulse width modulation has many advantages, its foremost disadvantage is the limitation of fundamental magnitude which can be overcome through over modulation by increasing duty cycle (Kerkman et al., 1996). But when this method is operated beyond a particular modulator voltage it introduces lower order harmonics. In order to minimise unwanted harmonic content, i.e., a THD, a number of pwm techniques have been developed to reduce THD, HSF and switching losses (Jeevananthan et al., 2005). Since a three-phase bridge inverter provides adjustable frequency power than any other type of inverters it is preferred for industrial applications. In power electronics, various pulse width modulation (PWM) techniques are widely employed to control the output of inverters. The gating signals to the inverter are produced by means of SPWM, RFPWM, THIPWM and Sixty degrees PWM techniques. The Field Programmable Gate Array is used to produce the gating signals.

For real time control of power inverters, Very Large Scale Integrated Circuits (VLSI) is used because of its extensive availability. Field Programmable Gate Array (FPGA) offers the most preferred way of designing PWM signals for power inverter applications. When a design is implemented in FPGA they are designed in such a way that they can be easily modified if any need arises in future. We have to just change the interconnection between the logic blocks in FPGA. This feature of reprogramming capability is an added advantage of FPGA. Also by using FPGA we can implement design within a short time. Thus FPGA is the best way of designing digital PWM Generators. Also implementation of FPGA-based digital control schemes proves to be less costly and hence they are economically suitable for small designs (Koutroulis.E et al., 2006).

In the present study we investigate both the simulation and experimental results of Sinusoidal PWM, Sixty Degrees PWM, Third Harmonic Injection PWM and Random Frequency PWM in terms of fundamental voltage, total harmonic distortion and harmonic spread factor for various modulation index ranging from 0.2 to 1.2.

2. Material and Methods

Sine pulse width modulation (SPWM): The selective-harmonic-elimination techniques are used to control the amount of time required to switch the power valves on and off. SPWM technique is used only when the amplitude of the output voltage has to be greatly improved.

In the sinusoidal pulse width modulation technique, a high frequency triangular carrier wave, *Vc* is compared with a sinusoidal reference wave *Vr* of the desired frequency. The intersection of *Vc* and *Vr* waves determines the switching instants and the commutation of the modulated pulse. The carrier and the reference waves are mixed in a comparator. When the magnitude of the sinusoidal wave is higher than the triangular wave the comparator output is high, otherwise it is low. The comparator output is processed in a trigger pulse generator in such a manner that the output voltage wave of the inverter has a pulse width in agreement with the comparator output pulse width. The ratio of *Vr/Vc* is called the modulation index (MI) and it controls the harmonic content of the output voltage waveform. In the proposed configuration, modulation index (ratio of peak value of the reference wave to peak value of the carrier wave) is varied in the range 0.2 to 1.2.

Out of the various modulation modes available, Sinusoidal PWM (SPWM) has been commonly used today. The major problem encountered in the above method is the larger harmonic content (A.Kawamura et al., 1986).

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Random Frequency Pulse Width Modulation (RFPWM): In power electronic systems, pulse width modulation techniques operate at a fixed switching carrier frequency which produces unwanted effects as well as harmonic spikes. The significant importance of a power electronic system employing RFPWM is that its output harmonics are dispersed and distributed. This popular scheme can be achieved by many ways such as varying the switching number in a cycle, the carrier frequency or the slope of the triangular wave (H.Hussin et al., 2010).

In the proposed method, a randomly chosen carrier frequency signal with the help of random generator is used instead of a fixed carrier frequency as in the case of SPWM to perform the PWM switching scheme. It is preferred for high switching frequencies, owing to its simple architecture. However if the modulation index is low then the performance of the power electronic system will greatly degrade (Berrezzek Farid et al., 2009).

Third Harmonic Injection (THI-PWM): Many techniques were developed for harmonic elimination especially for suppressing the lower order harmonics. The Third Harmonic Injection PWM (THI-PWM) is a modification over the SPWM Technique wherein a suitable amount of third harmonic signal is added to the sinusoidal modulating signal of fundamental frequency (Janyavula Deepthi et al., 2011).

Then the resultant waveform (modified modulating waveform) is compared with the high frequency triangular carrier waveform. The comparator output is used for controlling the inverter switches exactly as in SPWM inverter. In other words, if a fundamental frequency signal having peak magnitude slightly higher than the peak magnitude of the carrier signal, is mixed with suitable amount of 3^{rd} harmonic it may result in a modified signal of peak magnitude not exceeding that of the carrier signal which is suitable for three phase inverters. Thus the peak of the modulating signal remains lower than the peak of carrier signal and still the fundamental component of output voltage has a magnitude higher than what a SPWM can output by varying the modulation index. The maximum amplitude of fundamental in the reference and in the output voltages can be increased by the addition of third harmonic signal (Bin Huo et al., 1999).

Sixty Degrees PWM: This method is similar to SPWM; the only difference is that the reference sine wave is flat topped for a period of sixty degrees during each half cycle.

Generation of Pulses Using Fpga: Sine Wave Generation: The first and foremost aspect in generating sine PWM is to generate voltage-controlled oscillations. As the entire process is in digital format, it is not possible to generate the conventional analog sine wave. Further, this sine wave serves as a reference signal for comparison. Hence, if we know the values of the voltage controlled oscillations at any instant, then the purpose could be served. In this scheme, the controlled sinusoidal oscillations are generated in the form of a look up table and the amplitude block controls the voltage magnitude.

The regular sampling has certain advantages when implemented using digital techniques (T.C.Green et al., 1992). The block diagram of hardware prototype is shown in Figure 1. Let the clock frequency be 50MHz which is the set frequency that the sine wave generator receives. It's quite a common thing to generate sine wave of set frequency using the governing equation given by, $V(t) = Vm \sin 2\pi ft$.

But in digital logic, the problem arises in describing the limits for *t*, the time for which the wave has to be generated and the period of oscillations. Hence, the methodology we have adopted for creating the lookup table is that the instantaneous values of sinusoidal oscillations are fragmented to 200 values at equal intervals. These values are stored as an integer array named as memory. Further instead of the factor $2\pi ft$ it is multiplied with an offset value and an integer which would in turn point to the value stored in the sine wave array.

The sine array is incremented in steps of one so that to represent a half cycle of the oscillation corresponding to 360°, it is essential to make 199 increments of the counter. Since we are in need of three phase sine wave, we need to have three sine wave generators, whose outputs are displaced by 120° each. That means, the output of the second generator must start from the initial value of zero when the first generator has swept an angle of 120 degrees. Similarly the third and second generators should follow the same fashion.

This is achieved by correlating the relation between the angular displacement and the sine array. Initially the output of first sine wave generator alone is activated and the remaining two are maintained at zero output condition. We have 360 degrees of the sine wave corresponds to 199 increments of the counter. Hence, 120 degrees of the wave would correspond to

$$\frac{199}{360}(120) = 66$$

Therefore, at the 66th increment of the sine array of first generator, the output of second generator is activated. Similarly, at the 66th increment of the sine counter of the second generator, the output of third one is activated. Once they are activated in this manner, then throughout the process, they are all displaced by 120° or 66 counts.

Ramp wave Generation: The high frequency carrier chosen for comparison is of ramp in nature. This is also digitally generated. The frequency of the ramp is chosen as a high value of 5 kHz or any value greater than this can be chosen. Unlike the sine wave, the frequency of the ramp is maintained constant. This carrier frequency would be the deciding factor of the output frequency.

Generation of PWM: Pulse width modulation is achieved by comparing the triangular wave and the sine wave. The instantaneous value of the sine wave is compared with the corresponding triangular wave in a comparator. The comparator provides active high output whenever the magnitude of the sine wave is greater than that of the ramp otherwise it is low.

This pulse width modulation technique is described by VHDL and simulated using modelsim environment. Since this method is flexible an important advantage of VHDL is that it is technology independent (Faa-Jeng Lin et al., 2010). The pulses which are obtained as output is fed to the three phase bridge inverter using HDL co-simulation block. Here a three phase inverter is controlled by SPWM, RFPWM, THI-PWM, and Hybrid RF- THIPWM.

The simulation model of the control circuit is shown in Figure 2. Subsystem1 block generates pulses for the inverter as shown in Figure 3. Powergui block given in the circuit measures the fundamental voltage, THD, HSF for various values of modulation index ranging from 0.2 to 1.2.

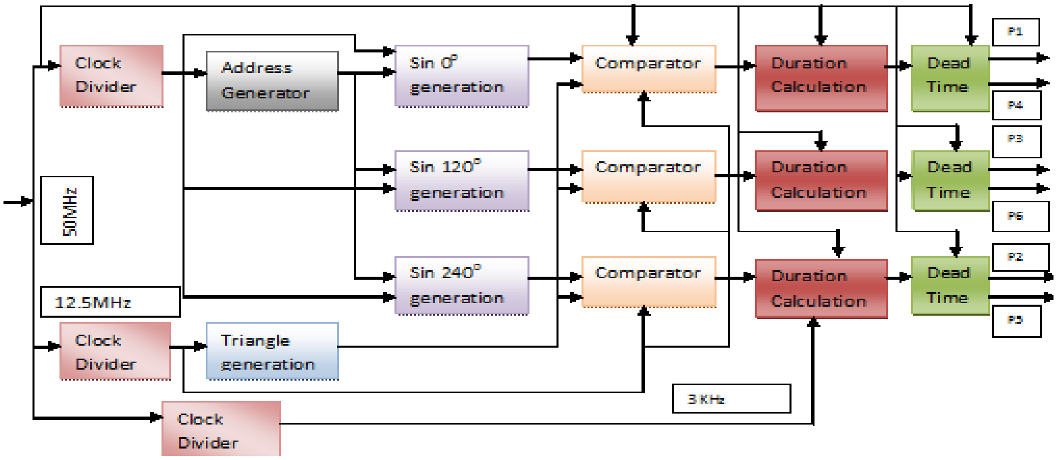

Figure 1.FPGA implementation of the proposed scheme

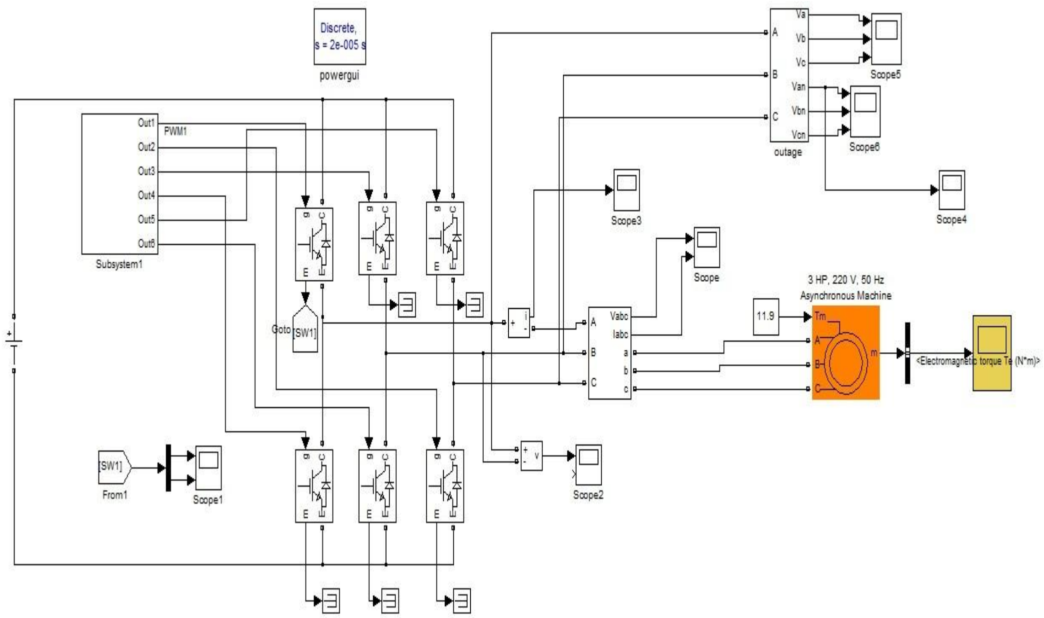

Figure 2. Matlab Simulation model of the Inverter circuit

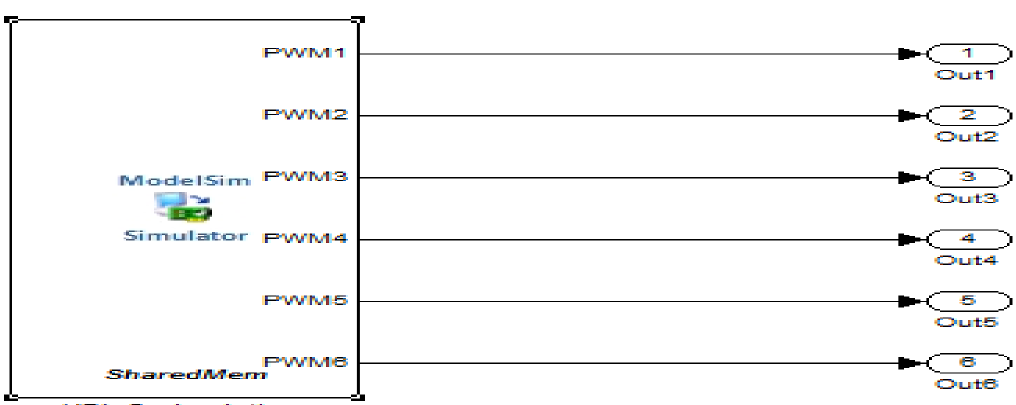

Figure 3. MATLAb/ModelSim Co-simulation

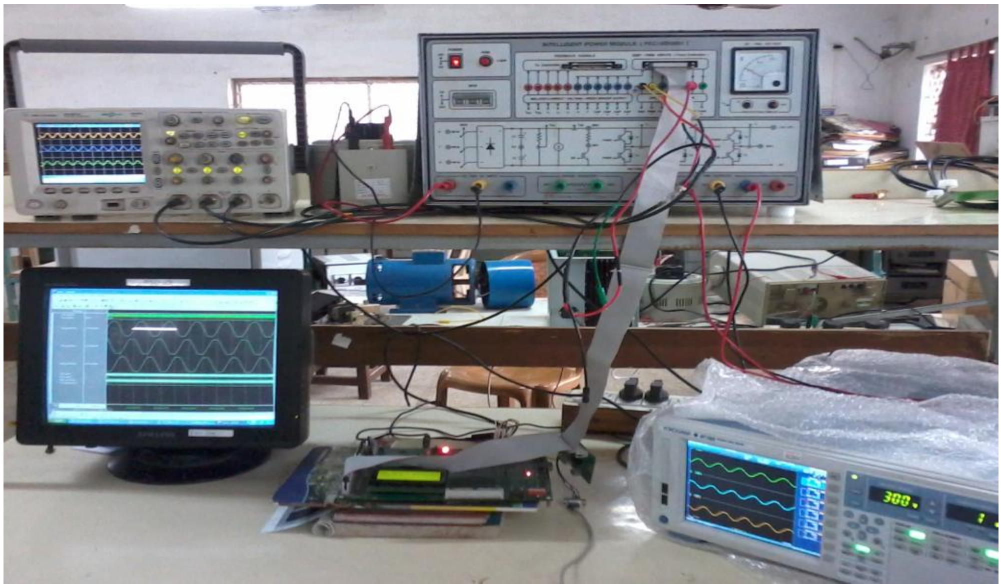

Figure 4. Diagram of the experimental assembly

The experimental setup is based on the 0.75kW three-phase induction motor drive and is used for testing the proposed scheme as shown in the Figure 4. Inorder to produce the inverter pwm pulses using SPWM, Sixty Degrees PWM, RFPWM and Sixty Degrees PWM, a Spartan FPGA processor is used. Table I summarizes the experimental parameters. The inverter is fed by a voltage of 300V with the help of an auto transformer and is connected to the induction motor with the help of a three phase inverter.

TABLE I
EXPERIMENTAL PARAMETERS

Fundamental Frequency	f=50Hz
Carrier Frequency	$f_{c=}$6 kHz,9Khz
Modulation Index	0.2, 0.4, 0.6, 0.8, 1.0, 1.2
Motor	Three phase squirrel cage induction motor (0.75 kw)
Rated Current	1.8A
Rated Speed	1440 rpm

3. Results

For the purpose of testing the advantages of the random pwm, it will be compared with the most commonly used pwm techniques such as SPWM, Sixty Degrees PWM and THIPWM. To compare different pwm techniques, a set of parameters must be defined to measure them. The parameters adopted are as follows:

i. Fundamental Voltage and Total Harmonic Distortion: The fundamental voltage is varied as a function of modulation index ranging from 0.2 to 1.2. When compared with RF-PWM the fundamental component value is higher than SPWM, Sixty Degrees PWM and THI-PWM for the entire range of modulation index. The impact is much significant in the higher values of modulation index. The important sources of distortion in power electronic systems are: the type of modulation technique employed and the nonlinearities in the output voltage. Total Harmonic Distortion (THD) is a standard measure used to characterize the distortion in the output (A.Olivia et al., 2005). Table II and III shows the proposed scheme's advantage in the variation in the fundamental and THD. Along with this linearity is retained between the fundamental voltage and modulation index. It is found that when the THD is lower, the more the signal approximates a perfect sine wave since the contribution from harmonics will be very weak.

ii. Harmonic Spread Factor: Harmonic Spread Factor is one of the deciding factors to indicate noise generation in the motor. The harmonic spread factor can be calculated for evaluating the quality of voltage spectra of inverters using the formula,

$$\text{HSF}=\sqrt{\frac{1}{N}\sum_{j=2}^{N}\left(H_j - H_0\right)^2}$$

Where H_j – Value of jth harmonic

H_0 – Average value of all N Harmonics

From Figure 7 as the modulation index changes, the HSF also gets changed. Considering an asynchronous machine, RF-PWM technique provides the lowest Harmonic Spread Factor as shown in Table IV shows the improvement in HSF in Random Frequency PWM.

TABLE II COMPARISON OF FUNDAMENTAL VOLTAGE FOR DIFFERENT MODULATION INDEX

PWM Technique	Fundamental Voltage					
	Simulation (DC Voltage=220V)			Experimental(DC Voltage=300V)		
	0.2	0.8	1.2	0.2	0.8	1.2
SPWM	38.55	150.3	209.5	99.99	216.15	237.55
RF-PWM	**38.86**	**150.4**	**218.1**	**101.8**	**221.47**	**261.93**
THIPWM	37.52	140	209.8	78.17	160.55	194.76
Sixty Degree	30.43	138.3	209.6	94.39	197.08	237.85

TABLE III COMPARISON OF TOTAL HARMONIC DISTORTION FOR DIFFERENT MODULATION INDEX

PWM Technique	Total Harmonic Distortion					
	Simulation			Experimental		
	0.2	0.8	1.2	0.2	0.8	1.2
SPWM	252.16	92.66	58.73	97.702	40.176	29.781
RF-PWM	**249.57**	**92.5**	**58.04**	**95.21**	**29.161**	**17.924**
THIPWM	250.79	97.69	51.74	95.53	94.053	30.513
Sixty Degree	286.26	101.49	59	93.99	77.491	15.276

TABLE IV COMPARISON OF HARMONIC SPREAD FACTOR FOR DIFFERENT MODULATION INDEX

PWM Technique	Harmonic Spread Factor					
	Simulation			Experimental		
	0.2	0.8	1.2	0.2	0.8	1.2
SPWM	3.78	5.52	4.94	7.51	1.79	1.54
RF-PWM	**2.72**	**4.35**	**3.95**	**7.09**	**1.786**	**1.1322**
THIPWM	2.96	5.355	4.179	7.2481	3.5919	1.249
Sixty Degree	4.07	8.43	10.36	8.00	2.7855	1.249

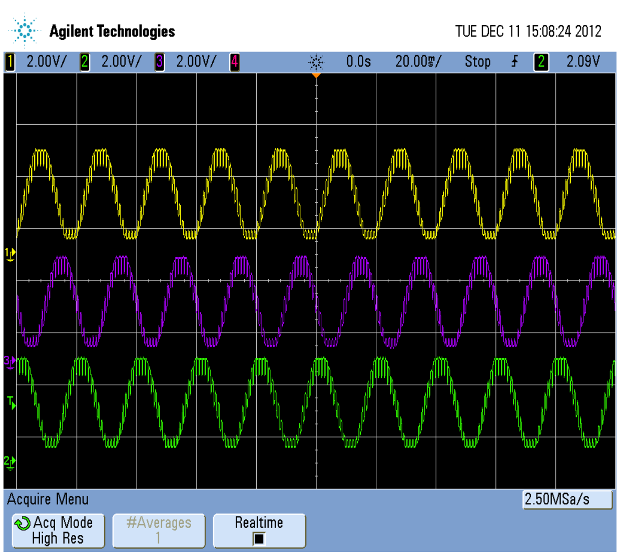

Figure 5. DSO Output of Sine Wave

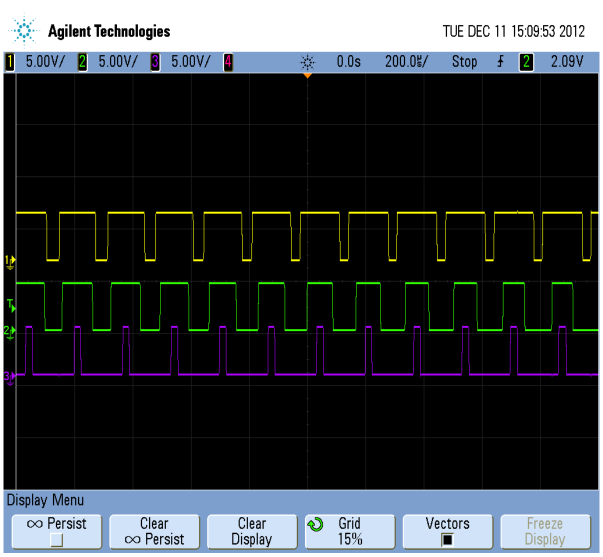

Figure 6.DSO Output of Triangular Wave

Figure 7 shows the randomly generated PWM when the sine wave generated in Figure 5 and the carrier wave generated in Figure 6 are compared and this RF-PWM is performing better when compared to other PWM techniques.

The four PWM techniques were experimentally verified for different modulation index ranging from 0.2 to 1.2.

Likewise it has been shown that the RF-PWM method produces a very significant increase in the fundamental term of the output voltage as well as a substantial decrease in harmonics, thereby causing the motor which is connected to the inverter to heat up less.

Figure 8 and Figure 9 show the measured line to line voltage (V_{ab}) and line to neutral voltages (V_{an}) respectively. The total harmonic distortion and harmonic spread factor are measured with a Yokogawa Precision Power Analyser.

Figure 5 and Figure 6 shows the sine wave and triangular wave generated by using FPGA which will be in turn used as the reference wave signal and carrier wave signal in all PWM techniques.

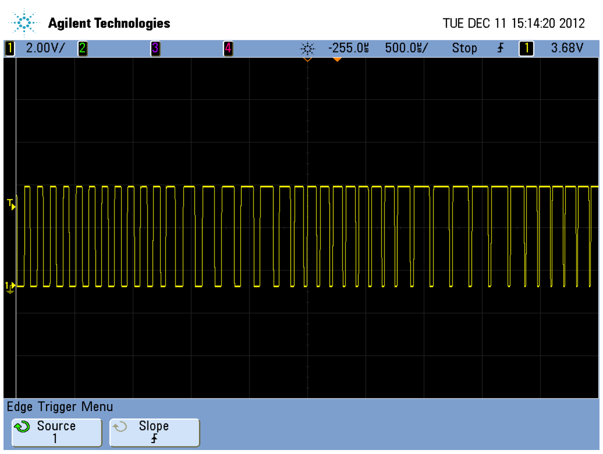

Figure 7. DSO Output of RFPWM

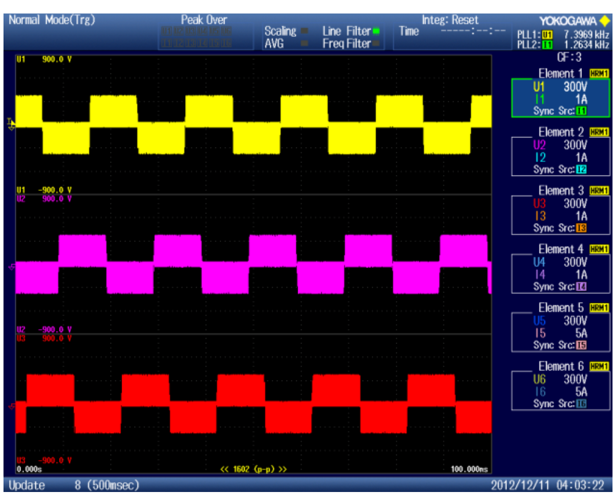

Figure 8. SPWM; M.I.=0.8; Line to Line Voltage

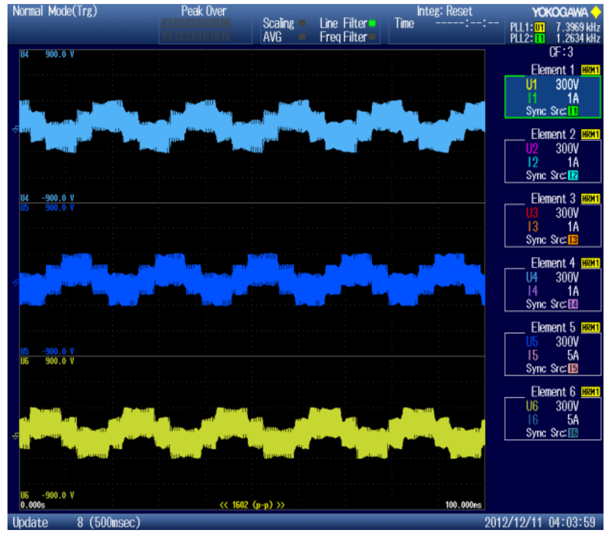

Figure 9. SPWM; M.I.=0.8; Line to Neutral Voltage

Figure 10. SPWM; M.I. =0.8; Line to Line Current

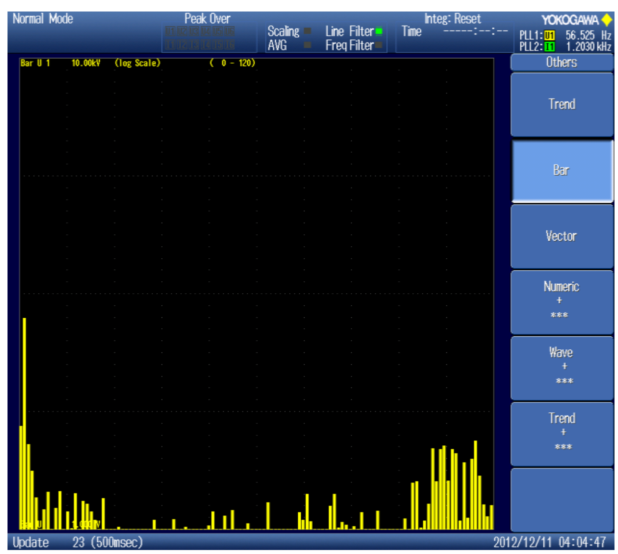

Figure 11. SPWM; M.I. =0.8; Harmonic Graph

4. Discussions

In this paper, a comparative study on pwm techniques such as SPWM, Sixty Degrees PWM, Third Harmonic Injection PWM and Random PWM for three phase inverters was done aiming for the improvement in fundamental voltage, total harmonic distortion and harmonic spread factor.

The four methods were applied to a FPGA-based 0.75kW three phase induction motor drive under the condition of fundamental frequency f=50 Hz and with a minimum carrier frequency of either 6kHz and maximum carrier frequency of 9kHz. Likewise it has been shown that the random pwm strategy produces a very significant increase in the fundamental term of the output voltage with a maximum of 218.1V during simulation and 261.93 as experimental value as well as a substantial decrease in total harmonic distortion and harmonic spread factor when the modulation index changes.

The different pwm strategies were compared using experimental and simulation results in support of the fundamental voltage, THD characteristics and HSF results, and the accuracy of the simulation and implementation techniques used has been established.

Corresponding Author:
Mrs.Valantina Stephen,
Department of Electrical and Electronics, Noorul Islam Centre for Higher Education, Kumaracoil, Thuckalay-629180, Tamilnadu, India.
E-mail: valantina2000@yahoo.com

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