



Comparative Study of SPWM & SVPWM Based Three Phase Voltage Source Inverter for an Ups System Operating Under Non Linear Loads

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ABSTRACT: This research paper present the design, comparison of two different PWM techniques i.e. The sinusoidal PWM (SPWM) technique, and the space vector PWM (SVPWM) technique for three phase uninterruptible power supply (UPS) systems that are operating under nonlinear loads. First a model for Sinusoidal PWM is made and simulated using Matlab/Simulink software and its performance is compared with Space vector PWM. Matlab/Simulink is used to analyse, design & develop, the controller of the inverter. The controller is designed & compared by discussing their ease of implementation and by analysing the output harmonic spectra of various output voltages poles voltages, line to neutral voltages, and line to line voltages Power factor (PF) & their Total harmonic distortion (THD). Designing of the controller adds inner loops to the closed loop control system effectively that enables successful reduction of harmonics and compensation of distortion at the outputs. The performance is simulated using a three phase 10 kVA UPS Systems under all types of load conditions.

KEYWORDS: Space Vector Pulse Width Modulation (SVPWM), Sinusoidal Pulse Width Modulation (SPWM), Uninterruptible Power Supply (UPS), Voltage Source Inverter (VSI), Total Harmonic Distortion (THD).

I. INTRODUCTION

The increased use of rectifiers in critical loads employed by the information technologies, medical and military equipment mandate the design of uninterruptible power supplies (UPS) with high quality outputs. The highly nonlinear currents drawn especially by high power single phase rectifier loads greatly distort the UPS outputs. The distorted UPS voltages cause generation of low dc voltage at the output of the rectifier loads, which causes high current flow, increased power losses, and possibly the malfunction of the critical load or the UPS. In a UPS system, the inverter is responsible for synthesizing sinusoidal voltages from a dc source through the pulse width modulation (PWM) of the dc voltage. The inductive element here is needed to remove the switching frequency harmonics from the current waveform that are generated by the PWM operation of the inverter. The inductance value can be reduced if the switching frequency is increased. But, in practice, it has an upper limit at high power inverters due to the efficiency concerns and the switching device limitations. So, for the selected switching frequency and the power level, an optimum filter with a smallest inductance can be designed, but the distortion cannot be completely avoided, and the regulations and the customer specifications may not be satisfied.[1]

The solution to this problem is to design a proper inverter controller such that it generates a control signal with multiple functionalities. This signal must carry information to produce sinusoidal voltages with small steady state RMS error, to provide fast transient response and corrective actions to reduce distortion even under highly nonlinear loads. Therefore, a major research has been conducted to design such controllers for the high performance UPS systems. The high performance controllers in general employed multi loop state feedback control strategies to achieve the regulation specifications.

The stationary or synchronous frame space vector PWM (SVPWM) based controllers are the primary choice of many researchers and the applications currently used in industry, today. However, the sinusoidal PWM (SPWM)

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method is still preferred by many manufacturers because of its implementation simplicity, easy tuning even under load, flexibility, and most importantly the advantages of controlling each phase independently.[1]

II. SYSTEM MODEL AND ASSUMPTIONS

The Block diagram of a typical three phase four wire transformer isolated UPS system is given in Fig. 1. The three phase thyristor based controlled rectifier converts the mains voltages into a constant dc and also provides standalone charge to the batteries. Then, a six switch PWM voltage source inverter (VSI) creates balanced three phase sinusoidal voltages across the load terminals at the utilization frequency and magnitude. The LC low pass filter removes the harmonics generated by the PWM switching. The winding of the transformer blocks the third harmonic currents at the inverter side, and the zigzag winding provides a neutral point and zero phase difference for the load side voltages. The load can be a three phase or a single phase load ranging from linear to nonlinear load with a crest factor up to 3. The UPS uses a digital controller implemented in a fixed point DSP controller.[3]

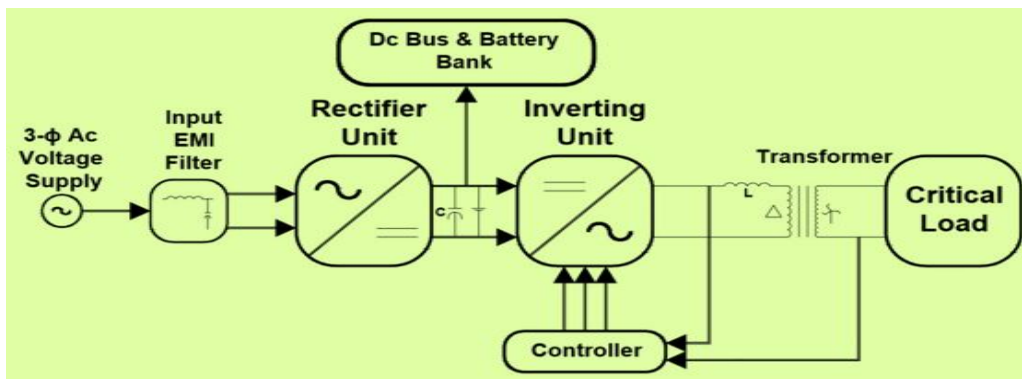


Fig. 1. Block diagram of a typical three phase four wire transformer isolated UPS system.

III. METHODOLOGY

The below Figure.2 indicates the methodology process used in this research which consist of five main stages. One after the other each stage is accomplished in a neat & simple manner

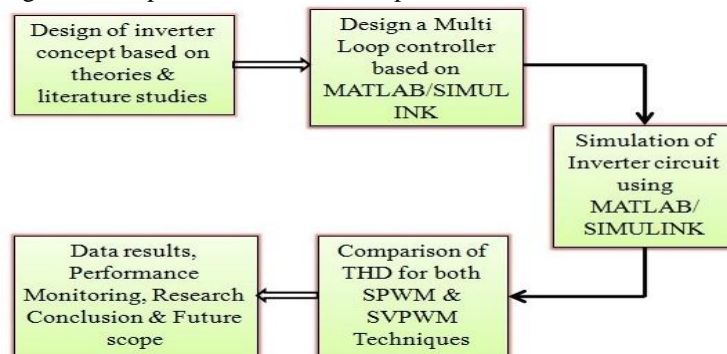


Fig. 2. The Research Methodology

IV. DESIGN OF THE INVERTER POWER STAGE

The design process initially assumed a resistive load and used the classical methods and the rule of thumbs suggested in the power electronics literature. However, this design did not give a good performance under nonlinear loads. Then, it is improved via simulation studies until the desired performance is achieved for all load cases. The improvements included determination of the proper dc bus voltage, switching frequency, transformer parameters, and

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the element values of the LC filter. For that reason, selecting the nominal modulation ratio around 0.7 is considered optimum since it guarantees the linear PWM operation under the worst case.

The simulation studies have shown that if the controller goes into over modulation region, the THD specification cannot be satisfied. Therefore, the nominal dc bus voltage is maintained at 405 V when grid is okay and it is allowed to reduce down to 300 V when grid is gone and the UPS operates from the battery pack. One string of the battery pack consists of 30 pieces of 12V lead acid batteries connected in series. The switching frequency is selected as 10.05 KHz. and based on our simulation studies, it has been realized that the output impedance of an inverter plays an important role in reducing the THD of the output voltage. Finally, the schematic of the inverter with the parameter values optimized for all load conditions is shown in Fig. 3.

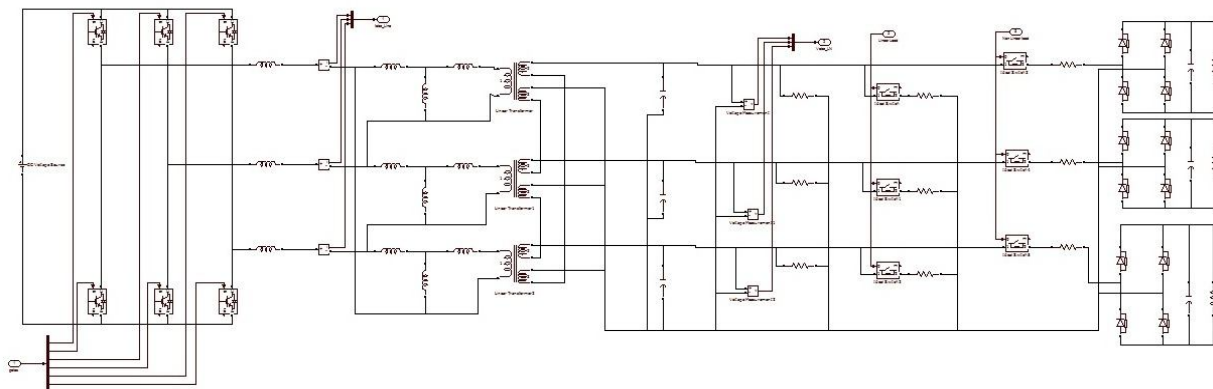


Fig. 3. Simulink model of the designed inverter power stage including delta zigzag transformer, the LC filter, the measurements, and the linear and nonlinear loads.

V. SINUSOIDAL PULSE WIDTH MODULATION

The sinusoidal pulse width modulation (SPWM) technique produces a sinusoidal waveform by filtering an output pulse waveform with varying width. The desired output voltage is achieved by varying the frequency and amplitude of a reference or modulating voltage. The variations in the amplitude and frequency of the reference voltage change the pulse-width patterns of the output voltage but keep the sinusoidal modulation. The switches are controlled in pairs (S_1, S_4), (S_3, S_6), and (S_5, S_2) and the logic for the switch control signals is:[4]

$$\begin{aligned} S_1 \text{ is ON when } V_a > V_T \quad S_4 \text{ is ON when } V_a < V_T \\ S_3 \text{ is ON when } V_b > V_T \quad S_6 \text{ is ON when } V_b < V_T \\ S_5 \text{ is ON when } V_c > V_T \quad S_2 \text{ is ON when } V_c < V_T \end{aligned}$$

VI. SPACE VECTOR PULSE WIDTH MODULATION

Space Vector Modulation (SVM) was originally developed as vector approach to Pulse Width Modulation (PWM) for three phase inverters. It is a more sophisticated technique for generating sine wave that provides a higher voltage to the motor with lower total harmonic distortion. The main aim of any modulation technique is to obtain variable output having a maximum fundamental component with minimum harmonics. The six switching power devices can be constructed using power BJTs, GTOs, IGBTs etc. The choice of switching devices is based on the desired operating power level, required switching frequency, and acceptable inverter power losses. Two switches on the same leg cannot be closed or opened at the same time. SVPWM is a different approach from PWM modulation, based on space vector representation of the voltages in the α - β plane. The α - β components are found by Clark's transformation. Space Vector PWM (SVPWM) refers to a special switching sequence of the upper three power transistors of a three phase power inverter.[4]

6.1 Principle of Space Vector PWM

The basic principle of SVPWM is based on the eight switch combinations of a three phase inverter. In this modulation technique the three phase quantities can be transformed to their equivalent two phase quantity either in

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synchronously rotating frame (or) stationary frame. From these two phase components, the reference vector magnitude can be found and used for modulating the inverter output. The process of obtaining the rotating space vector is explained in the following section, considering the stationary reference frame. Considering the stationary reference frame let the three phase sinusoidal voltage component be,

$$V_a = V_m \sin(\omega t) \tag{1}$$

$$V_b = V_m \sin(\omega t - 2\pi/3) \tag{2}$$

$$V_c = V_m \sin(\omega t - 4\pi/3) \tag{3}$$

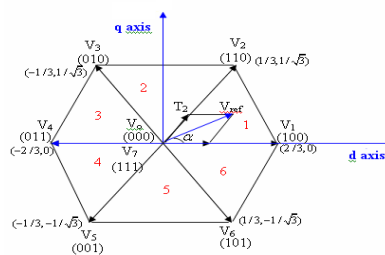


Fig. 4. Basic switching, vectors and sectors.

Table. 1. Voltage & Switching Vectors, Line - Neutral and L-L Voltages as a function of dc bus voltage V_{dc}

Voltage Vectors	Switching Vectors			Line To Neutral Voltages			Line To Line Voltages		
	a	b	c	V_{an}	V_{bn}	V_{cn}	V_{ab}	V_{bc}	V_{ca}
V_0	0	0	0	0	0	0	0	0	0
V_1	1	0	0	$2V_{dc}/3$	$-V_{dc}/3$	$V_{dc}/3$	V_{dc}	0	$-V_{dc}$
V_2	1	1	0	$V_{dc}/3$	$V_{dc}/3$	$-2V_{dc}/3$	0	V_{dc}	$-V_{dc}$
V_3	0	1	0	$-V_{dc}/3$	$2V_{dc}/3$	$-V_{dc}/3$	$-V_{dc}$	V_{dc}	0
V_4	0	1	1	$-2V_{dc}/3$	$V_{dc}/3$	$V_{dc}/3$	$-V_{dc}$	0	V_{dc}
V_5	0	0	1	$-V_{dc}/3$	$-V_{dc}/3$	$2V_{dc}/3$	0	$-V_{dc}$	V_{dc}
V_6	1	0	1	$V_{dc}/3$	$-2V_{dc}/3$	$V_{dc}/3$	V_{dc}	$-V_{dc}$	0
V_7	1	1	1	0	0	0	0	0	0

The switches being ON or OFF, meaning 1 or 0 are determined by the location of the reference vector on this d-q plane. The switches 1, 3, 5 are the upper switches, and if these are 1 (separately or together) it turns the upper inverter leg ON and the terminal voltage (V_a, V_b, V_c) is positive ($+V_{dc}$). If the upper switches are zero, then the terminal voltage is zero. The lower switches are complementary to the upper switches, so the only possible combinations are the switching states: 000, 001, 010, 011, 100, 110, 110, 111. This means that there are 8 possible switching states, for which two of them are zero switching states and six of them are active switching states. Six non zero vectors (V_1 - V_6) shape the axes of a hexagonal as depicted in Figure 4, and supplies power to the load. The angle between any adjacent two non zero vectors is 60° degrees. Meanwhile, two zero vectors (V_0 and V_7) and are at the origin and apply zero voltage to the load. The eight vectors are called the basic space vectors and are denoted by ($V_0, V_1, V_2, V_3, V_4, V_5, V_6, V_7$). The same transformation can be applied to the desired output voltage to get the desired reference voltage vector, V_{ref} in the d-q plane. The objective of SVPWM technique is to approximate the reference voltage vector using the eight switching patterns. The relationship between the switching variable vectors [a b c] and the line to line output voltage vector [$v_{ab} v_{bc} v_{ca}$] and the phase line to neutral output voltage vectors [$V_a V_b V_c$] is

given by below equation.[5]

$$\begin{bmatrix} V_{ab} \\ V_{bc} \\ V_{ca} \end{bmatrix} = V_{dc} \begin{bmatrix} 1 & -1 & 0 \\ 0 & 1 & -1 \\ -1 & 0 & 1 \end{bmatrix} \begin{bmatrix} a \\ b \\ c \end{bmatrix} \quad (4)$$

$$\begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} = \frac{1}{3}V_{dc} \begin{bmatrix} 1 & -1 & 0 \\ 0 & 1 & -1 \\ -1 & 0 & 1 \end{bmatrix} \begin{bmatrix} a \\ b \\ c \end{bmatrix} \quad (5)$$

Where V_{dc} is the supply voltage or bus voltage. the eight combinations & the derived output line to line & phase voltage in terms of dc supply voltage V_{dc} according to equations as shown in Table 1.

VII. CONTROLLER DESIGN

This section presents the design of the proposed inverter controller. The controller is based on the multi loop SPWM method as shown in Fig.5. The controller topology is very similar to the classical state feedback multi loop controllers, except that all the loops are combined instead of cascade connection before they are applied to the PWM generator. This feature basically adds the relative benefits of each loop and creates a more effective multi loop strategy. In order to facilitate the understanding of the proposed controller, the reasoning behind the selected control topology can be explained as follows. The control system shown in Fig.5 consists of one outer voltage loop and three inner loops. The outer loop is the main voltage loop, which regulates the fundamental frequency component of the output voltage and its steady state RMS value using a PI compensator.[1]

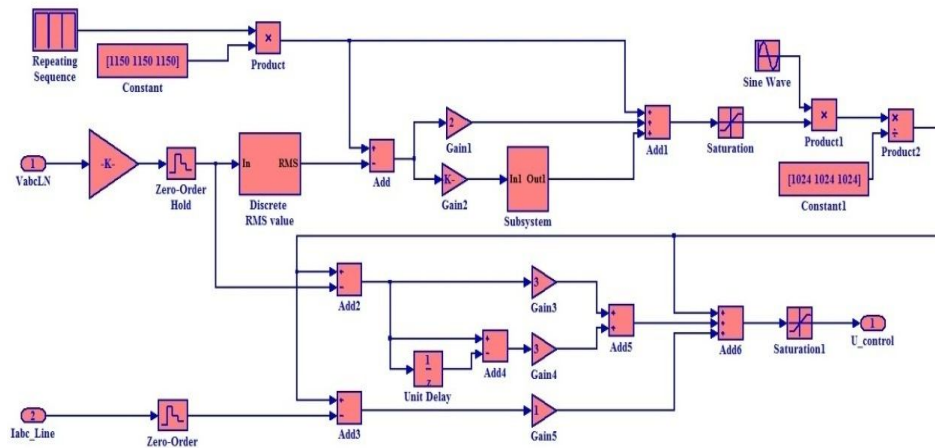


Fig. 5. Simulink model of the proposed Multi loop controller.

VII. EXPERIMENTAL RESULTS

The simulations are done in the MATLAB/Simulink environment using the Simulink model of the inverter and the controller as shown in Fig.5. The results are evaluated based on steady state error, transient response, and the THD of the output voltage. Below Fig shows the voltage & current wave form for single & three phase and the percent THD of the output voltage versus three different loads. In addition, the RMS voltages are very well regulated at 220 V for each phase with an excellent transient response for the linear load but a fair response for the nonlinear load case.

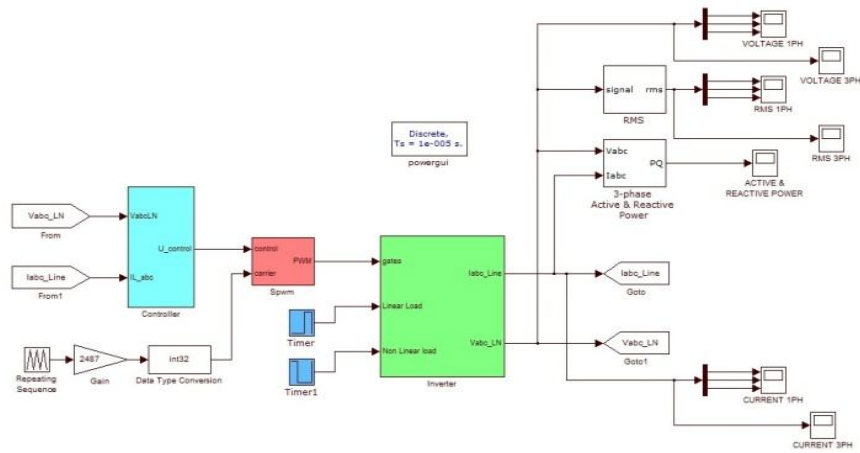


Fig. 6. Simulink model of the SPWM inverter system.

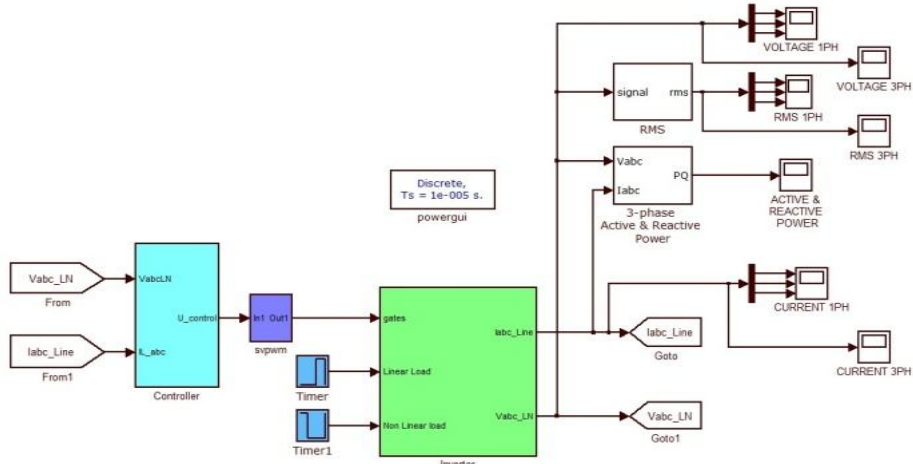


Fig. 7. Simulink model of the SVPWM inverter system.

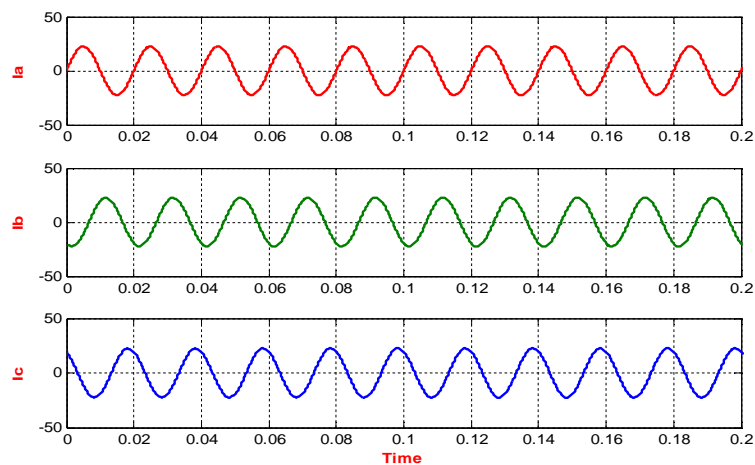


Fig. 8. Inverter output Line-Line Current I_a , I_b , I_c

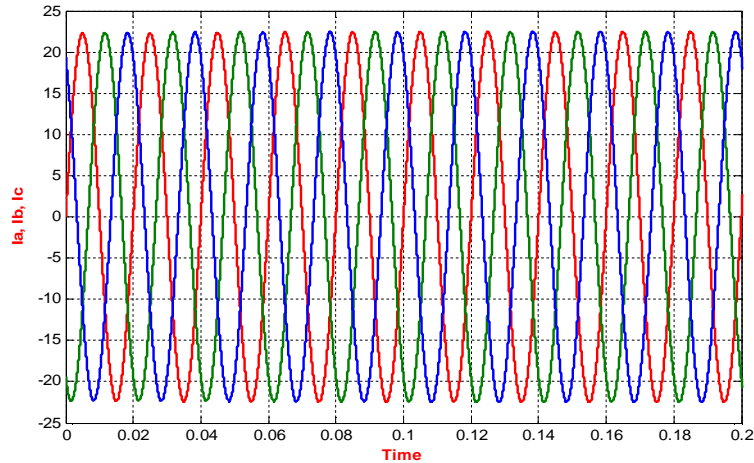


Fig. 9. Three Phase inverter output Current I_a, I_b, I_c

In fig 10,11. Inverter output Current are shown for both three phase system & single phase system of the voltage source inverter of the UPS system for both SPWM & SVPWM modulation techniques under all types of load conditions.

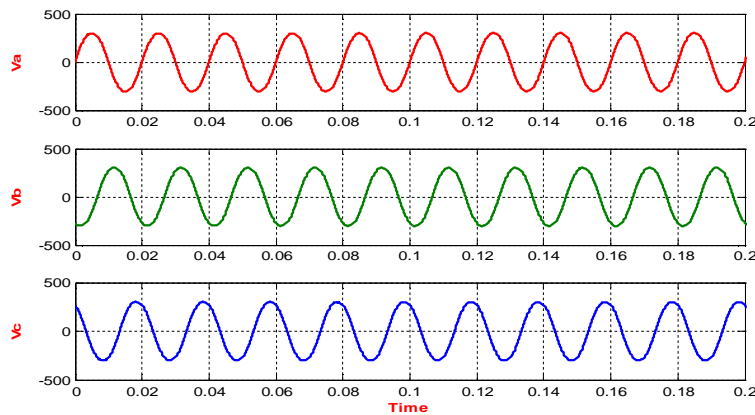


Fig. 10. Inverter output line to line Voltage V_a, V_b, V_c

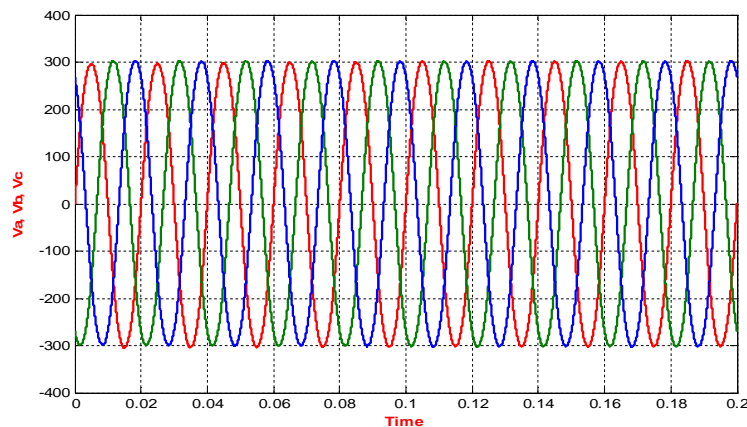


Fig. 11. Three Phase Inverter output Voltage V_a, V_b, V_c

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In Fig 10,11. Inverter output voltages are shown for both three phase system & single phase system of the voltage source inverter of the UPS system for both SPWM & SVPWM modulation techniques under all types of load conditions.

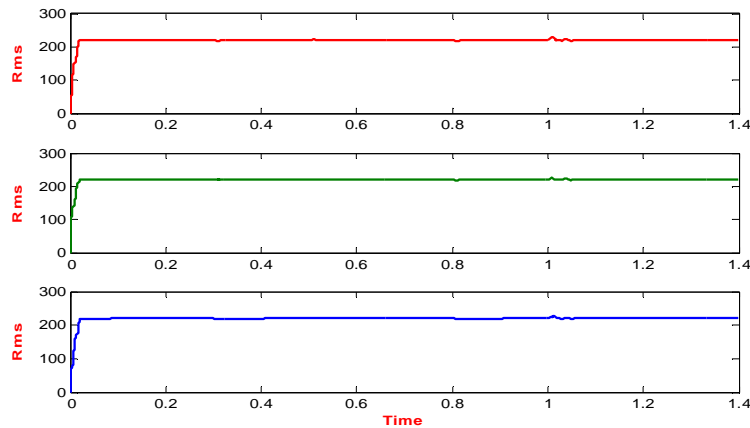


Fig. 12. Simulation results of Rms voltage (V)

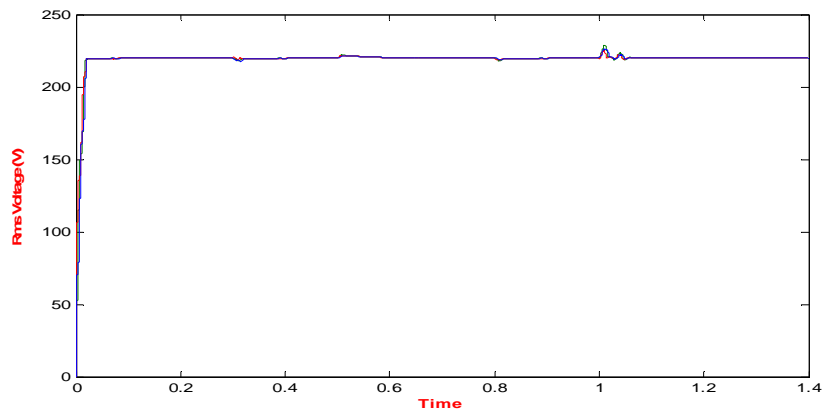


Fig. 13. Simulation results of Rms voltage (V) for 3-ph system

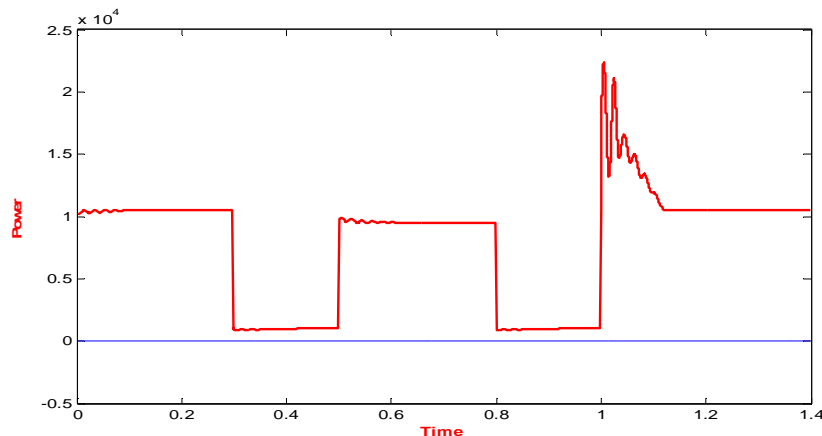


Fig. 14. Three Phase Instantaneous Active & Reactive Power Wave Form for SPWM

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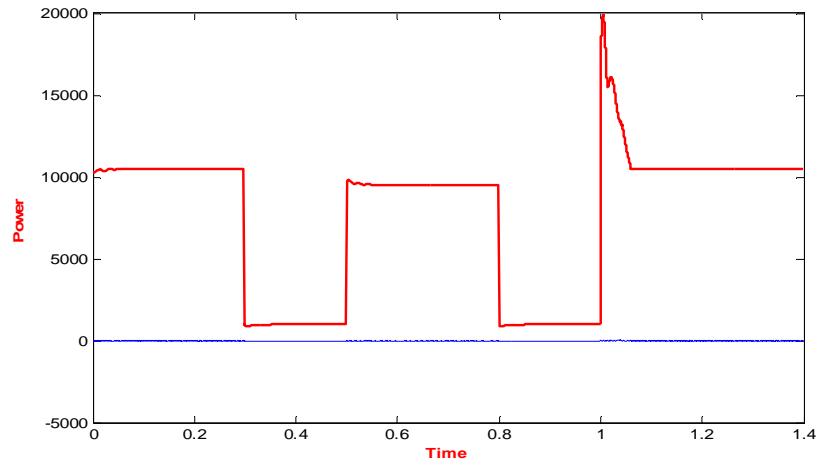


Fig. 15. Three Phase Instantaneous Active & Reactive Power Wave Form for SVPWM

In Fig 14,15. Three Phase Instantaneous Active & Reactive Power are shown for three phase system of the voltage source inverter of the UPS system for both SPWM & SVPWM modulation techniques under all types of load condition

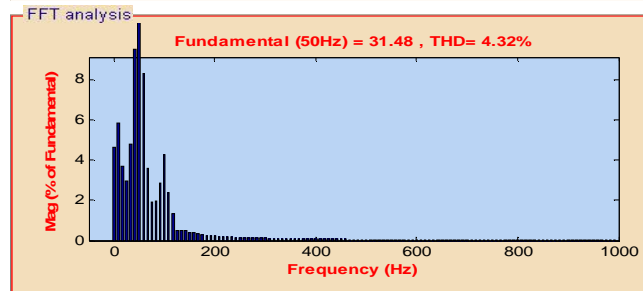


Fig. 16. Harmonic analysis of SPWM current

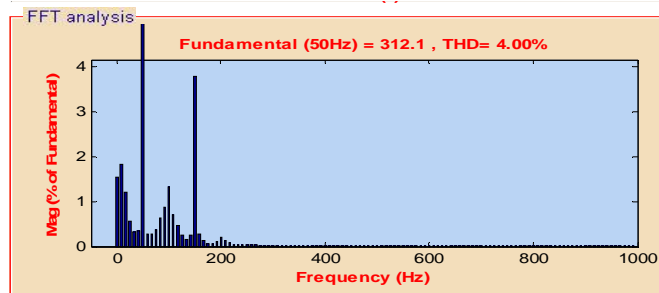


Fig. 17. Harmonic analysis of SPWM voltage

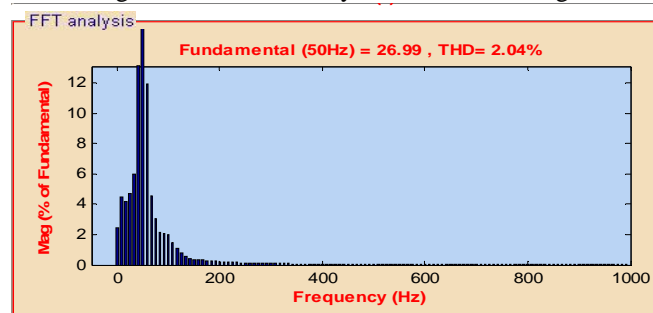


Fig. 18. Harmonic analysis of SVPWM current

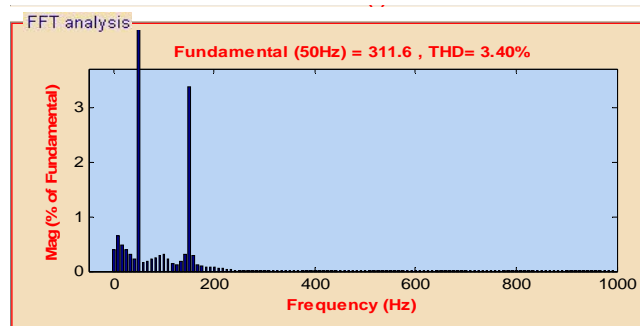


Fig. 19. Harmonic analysis of SVPWM voltage

Table. 2. Comparison of Current & Voltage %THD for both SPWM & SVPWM Techniques

PWM technique	% Current THD	% Voltage THD
SPWM	4.32%	4.00%
SVPWM	2.04%	3.40%

IX. CONCLUSION

In this paper, SPWM and SVPWM techniques have been investigated and compared, for three phase UPS systems powering nonlinear loads. The load consists of three single phase rectifiers connected between each line and the neutral and absorbing power equal to the rated power of the UPS with a crest factor up to 3. During the investigations, we realized Total harmonic distortion, & Power factor in both techniques. The SPWM & SVPWM technique is applied to a three phase inverter and it is observed that SPWM increases the overall system efficiency.

The controller performance is evaluated experimentally using a three phase 10 kVA transformer isolated UPS. A THD equal to 4.00% & 4.32% at output voltage & current for SPWM is achieved & a THD equal to 3.40% & 2.04% at output voltage & current for SVPWM is achieved. It has been observed that SVPWM has showed superior performances due to less THD, greater PF and less switching losses because SVPWM utilizes advance computational switching technique to reduce THD. Furthermore, at high switching frequencies SVPWM gives better results as compared to SPWM. Thus, based on all obtained results, we concluded that SVPWM technique provides greater overall performance and efficiency as compared to SPWM technique.

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