Artificial Neural Network Based Implementation of Space Vector PWM for Control of Three-Phase Voltage Source Inverter

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ABSTRACT

An artificial neural network based implementation of space vector modulation (SVPWM) of a three phase voltage-source inverter is proposed in this paper. The basic principle of space vector PWM is analyzed, and a novel algorithm for SVPWM based on neural network is developed which is independent of switching frequency. Basically, it uses two multilayer perceptron (MLP) type neural networks. The first ANN is used to determine the sector in which reference voltage vector localize. The second ANN is used to calculate the duty cycles and turn-on time of the three space vectors. A computer simulation program is developed using MATLAB/ Simulink together with the Neural Network Toolbox for training the ANN-controller. The ANN controller has the advantage of very fast implementation by using SVPWM algorithm and avoids the direct computation of trigonometric and non-linear functions. Simulation and experimental results are presented to show reliable estimates of voltage THD for three phase inverter. The performance of the inverter is compared for conventional SPWM and SVPWM technique.

Keywords - **Artificial Neural Network (ANN), Modulation Index, Space vector Pulse-Width Modulation (SVPWM), Total Harmonic Distortion (THD), Voltage Source Inverter (VSI)**

1. INTRODUCTION

Space Vector modulation (SVM) has recently grown as a very popular pulse width modulation (PWM) method for voltage – source inverters because of its very good harmonic quality and extended linear range of operation [1]. However, a drawback of SVM is that it requires complex online computation that usually limits its operation only up to several kilohertz of switching frequency. Switching frequency can be extended by using a high –speed DSP and simplifying computation with the help of lookup tables which is very large and tends to reduce the pulse width resolution. Power switches recently have been improved in term of switching frequency. Modern ultra-fast IGBT's allow operation at 50 kHz. However, the DSP- based SVM practically fails in this region where artificial- neural – network (ANN) –based SVM would probably take over [2], [3]. Because of the high voltage utilization ratio and easy to realize, space vector pulse width modulation (SVPWM) has widespread application. In linear modulation condition, the highest output line voltage peak value of PWM inverter is equal to direct current voltage theoretically, but it cannot use the DC link voltage fully. In order to obtain the output voltage value as high as possible, over-modulation mode must be carried on in inverter, increase the utilization ratio of DC link voltage. In SVPWM voltage inverter, the status transform from the linear modulation mode to six-step mode [4]-[7]. The SVPWM algorithm gives higher fundamental voltage amplitude and better harmonic spectrum compared to conventional carrier-based sine-triangle PWM (SPWM). However, application of SVPWM algorithm to multi-level inverters is more complex because of large number of inverter switching states.

The application of artificial neural networks (ANN) in power electronics area is recently growing. Several researches of ANN implementation of SVPWM have been worked out [9]-[11]. Although this ANN-SVM controller has the advantage of fast calculation, the limitation of this approach is the difficulty of training in the overmodulation range with nonlinearity of modulation technique. To avoid this, the proposed ANN-SVM algorithm (Fig. 1) in this paper has been successfully trained by using individual training strategy with various subnets to overcome the complexity of SVM for both undermodulation and overmodulation modes.

This paper describes feedforward ANN based SVPWM that fully covers the undermodulation and overmodulation regions extending operation up to square wave. In the first section, the basic principle of SVPWM has been briefly reviewed with mathematical analysis for all the modulation index range. Then, the equations for switching/ turn-on time for each sector have been developed in detail. The ANN is trained offline with the data generated by this simple algorithm, to determine the sector in which reference voltage vector localize and to calculate the turn-on time of the three space vectors using modulation index and vector position as input. Modeling and simulation of this ANN based SVPWM multilevel inverter circuit configuration has been done using Simulink/ MATLAB package program. The algorithm is suitable for a very simple practical implementation, and can gain almost linear characteristic, and can avoid of looking-up table.

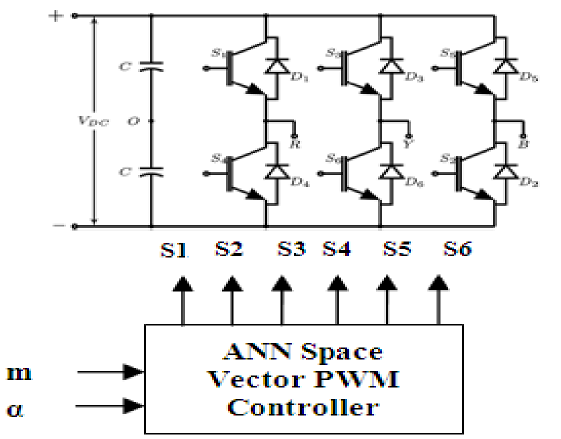
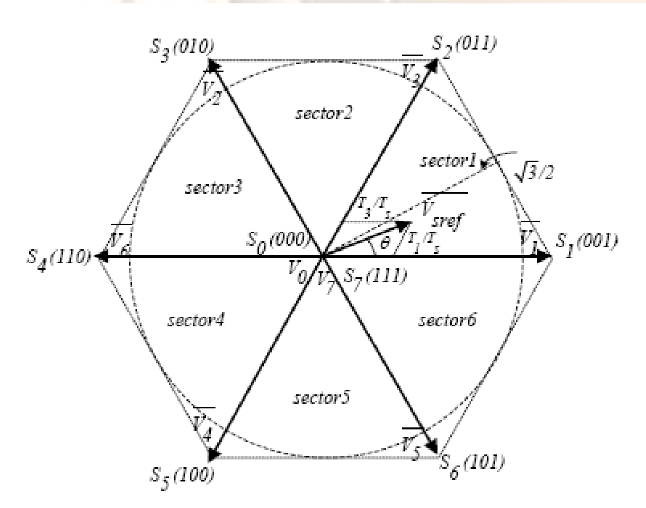


Fig 1: ANN-SVPWM Based Three-Phase VSI

2. SPACE VECTOR PULSE WIDTH MODULATION

The three phase two level voltage source SVPWM inverter is shown in Fig. 1. Its switching operation is characterized by eight switch states $S_i = (S_a, S_b, S_c)$, i= 0, 1,.., 7, where S_a represents the switching status of inverter Leg-A. It is "1", when switch Q_1 is ON & Q_4 is OFF and "0", when switch Q_1 is OFF & Q_4 is ON. Similarly, S_b & S_c is defined for inverter Leg-B and Leg-C. The output voltages of the inverter are controlled by these eight switching states. The objective of space vector PWM technique is to approximate the reference voltage vector V_{ref} using the eight switching patterns.

Fig 2: Voltage Space Vectors & Sectors



These eight vectors form the voltage vector space which is divided into six sectors as depicted in Fig. 2. S_1 to S_6 are the six power switches that shape the output, which are controlled by the switching pulses S_a, S_b and S_c. The SVPWM strategy is based on generating three consecutive switching voltage vectors in a sampling period (Ts) so that the average output voltage matches with the reference voltage.

The performance of pulse width modulation is characterized mainly by the modulation index, given switching frequency, and the harmonic distortion. The modulation index is the normalized fundamental voltage, defined as:

$$m = \frac{V^*}{V_{1sw}} \qquad (1)$$

Where V* - magnitude of reference voltage vector, V_{1sw} -the peak value of six step voltage wave, $V_{1sw} = 2Vdc/\pi$ and V_{dc} - the DC link voltage of the inverter.

Therefore, space vector PWM can be implemented by the following steps:

2.1 Determine sector for different value of modulation index (m) and angle (α)

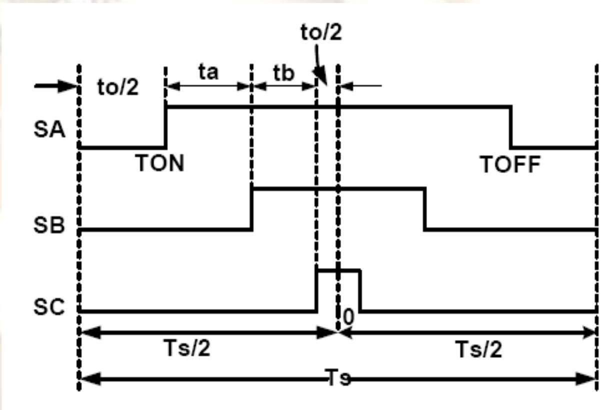
2.2 Determine time duration T_a, T_b, T_0

2.3 Determine the duty cycle and switching (turn-on) time of each transistor S_1 to S_6 shown in Fig. 3.

2.4 Generate the inverter output voltages (V_{AB}, V_{BC}, V_{CA}) by simulation

Fig 3: SV-PWM Pulse Generation in Sector 1

In a sampling/switching interval, the output voltage vector V is expressed as:



$$V = \frac{t_0}{Ts} V_0 + \frac{t1}{Ts} V_1 + \ldots + \frac{t_7}{Ts} V_7 \qquad (2)$$

The equations for effective time interval of the inverter switching states can be described as follows:

$$\begin{aligned} T_a &= \frac{\sqrt{3}}{\Pi} T_s \bullet m \bullet \sin\left(\frac{\Pi}{3} - \alpha\right) \\ T_b &= \frac{\sqrt{3}}{\Pi} T_s \bullet m \bullet \sin(\alpha) \\ T_0 &= \frac{T_s}{2} - (T_a + T_b) \end{aligned} \qquad (3)$$

The duty cycles are obtained by multiplying timing intervals by $2/T_s$ respectively. The time periods need to be distributed such that symmetrical PWM pulses are produced. To produce such pulses, the instant of switching on for each phase and each sector is calculated as shown in Fig. 3 and Table 1.

Table 1: Switching Time Calculation at Each Sector

Sector	Turn-on Time (Upper Switches)	Turn-on Time (Lower Switches)
1	$S_1=T_0/2$ $S_3=T_a+T_0/2$ $S_5=T_a+T_b+T_0/2$	$S_4=T_a+T_b+T_0/2$ $S_6=T_b+T_0/2$ $S_2=T_0/2$
2	$S_1=T_b+T_0/2$ $S_3=T_0/2$ $S_5=T_a+T_b+T_0/2$	$S_4=T_a+T_0/2$ $S_6=T_a+T_b+T_0/2$ $S_2=T_0/2$
3	$S_1=T_a+T_b+T_0/2$ $S_3=T_0/2$ $S_5=T_a+T_0/2$	$S_4=T_0/2$ $S_6=T_a+T_b+T_0/2$ $S_2=T_b+T_0/2$
4	$S_1=T_a+T_b+T_0/2$ $S_3=T_b+T_0/2$ $S_5=T_0/2$	$S_4=T_0/2$ $S_6=T_a+T_0/2$ $S_2=T_a+T_b+T_0/2$
5	$S_1=T_a+T_0/2$ $S_3=T_a+T_b+T_0/2$ $S_5=T_0/2$	$S_4=T_b+T_0/2$ $S_6=T_0/2$ $S_2=T_a+T_b+T_0/2$
6	$S_1=T_0/2$ $S_3=T_a+T_b+T_0/2$ $S_5=T_b+T_0/2$	$S_4=T_a+T_b+T_0/2$ $S_6=T_0/2$ $S_2=T_a+T_0/2$

The generalized equation for turn on instant/ switching time calculation for phase A, B and C are calculated as below:

$$\begin{aligned} T_{A\_ON} &= \left(\frac{T_s}{4}\right) + \frac{\sqrt{3}}{\Pi} \bullet m \bullet h_{10}(\alpha^*) \\ T_{B\_ON} &= \left(\frac{T_s}{4}\right) + \frac{\sqrt{3}}{\Pi} \bullet m \bullet h_{20}(\alpha^*) \\ T_{C\_ON} &= \left(\frac{T_s}{4}\right) + \frac{\sqrt{3}}{\Pi} \bullet m \bullet h_{30}(\alpha^*) \end{aligned} \tag{4}$$

Where,

V^* - Magnitude of command or reference voltage vector
T_a - Time period of switching vector that lags V^*
T_b - Time period of switching vector that leads V^*
T_0 - Time period of zero switching vector
T_S - Switching time period
α^* - Angle of V^* in a 60° sector
fs - Switching frequency = $1/T_s$
V_{dc} - DC link voltage

The $h_{10}(\alpha^*)$, $h_{20}(\alpha^*)$ and $h_{30}(\alpha^*)$ is defined as the turn on pulse width function of phase A, B and C respectively and is calculated as:

$$h_{10}(\alpha^*) = \begin{cases} -\sin(\frac{\Pi}{3}-\alpha)-\sin(\alpha) \rightarrow \theta = 1,6 \\ -\sin(\frac{\Pi}{3}-\alpha)+\sin(\alpha) \rightarrow \theta = 2 \\ +\sin(\frac{\Pi}{3}-\alpha)+\sin(\alpha) \rightarrow \theta = 3,4 \\ +\sin(\frac{\Pi}{3}-\alpha)-\sin(\alpha) \rightarrow \theta = 5 \end{cases} \tag{5}$$

$$h_{20}(\alpha^*) = \begin{cases} \sin(\frac{\Pi}{3}-\alpha)-\sin(\alpha) \rightarrow \theta = 1 \\ -\sin(\frac{\Pi}{3}-\alpha)-\sin(\alpha) \rightarrow \theta = 2,3 \\ -\sin(\frac{\Pi}{3}-\alpha)+\sin(\alpha) \rightarrow \theta = 4 \\ +\sin(\frac{\Pi}{3}-\alpha)+\sin(\alpha) \rightarrow \theta = 5,6 \end{cases} \tag{6}$$

$$h_{30}(\alpha^*) = \begin{cases} \sin(\frac{\Pi}{3}-\alpha)+\sin(\alpha) \rightarrow \theta = 1,2 \\ +\sin(\frac{\Pi}{3}-\alpha)-\sin(\alpha) \rightarrow \theta = 3 \\ -\sin(\frac{\Pi}{3}-\alpha)-\sin(\alpha) \rightarrow \theta = 4,5 \\ -\sin(\frac{\Pi}{3}-\alpha)+\sin(\alpha) \rightarrow \theta = 6 \end{cases} \tag{7}$$

To maintain the symmetry of switching, the turn off instant for phase A is calculated using (4) and given below:

$$T_{A\text{-}OFF} = T_s - T_{A\text{-}ON} \tag{8}$$

For phases B and C, the switching instants are calculated using (4) to (8) but phase shifted by 120° each.

3. ANN BASED SV-PWM IMPLEMENTATION

In order to realize SVPWM function by neural networks, two sub-neural networks respectively ANN_1 and ANN_2 are designed. In sub-neural networks, $|V^*|$ and α can be got by two quadrature component computation under two static coordinate systems according to the reference voltage.

3.1 Sector Determination Module

"Sector" is the sector number which the reference voltage vector locates, α is angle between reference voltage vector and first basic switch vector in same sector. The SVPWM algorithm described in the previous section will be utilized to generate training data for ANN- SVPWM. Vectors localizing module (Fig. 4) can determine the sector in which reference voltage vector localize.

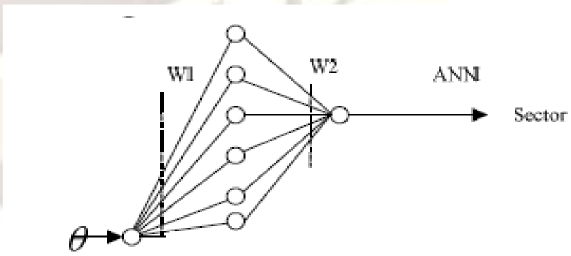


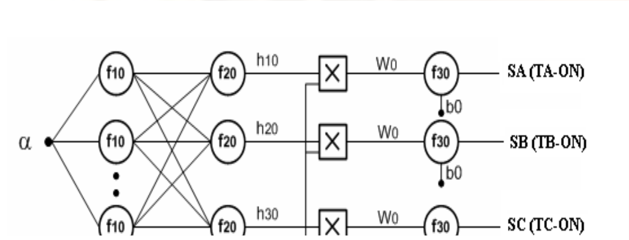
Fig 4: ANN_1 – Sector Determination Module

ANN_1 is a compound neural network which is a 3 perception network model. In this network model, the weights are w_1, w_2, but the activation function of output level need to adjust, the hard restriction function is replaced by the linear function. ANN_1 does not need to train, the weight and bias are fixed, the w_1, w_2 both are 1 and bias value is b_1: [0; -π/3; -2π/ 3; -π; -4π/3; -5π/3], bias b_2 for "sector" output neuron is 0, the network actual output "sector" is integer from 1 to 6, which represents 6 sectors separately.

3.2 Turn-on Time Calculation Module

Turn-on time calculating module (ANN_2) is composed of multilayer feed-forward structure. Its realization step as follows: firstly, calculate two neighboring switches vector T_i, T_{i+1} and the null vector T_0 according to reference voltage. Then calculate turn-on time T_{AON}, T_{BON}, T_{CON}, of S_a , S_b, S_c by integrating V_i, V_{i+1}, V_0, V_7. The input to the network is the modulation index (m) and phase angle (α) of the reference voltage vector V* and the outputs are the turn-on pulse width functions $h_{10}*(\alpha)$, $h_{20}*(\alpha)$ and $h_{30}*(\alpha)$ for the phases A, B, and C as shown in Fig. 5. These input-target patterns have been used for creating databases which are needed for training. Give modulation index a range of 0-1, takes a sample data in step 0.01. Give α range of 0~60°, and takes a sample data in step 1°. So, the training data set is generated using SV-PWM algorithm (3) to (7). The network is trained offline independent of switching frequency and the weights and bias of different layers are obtained.

Fig 5: ANN_2 – Turn-on Time Calculation Module



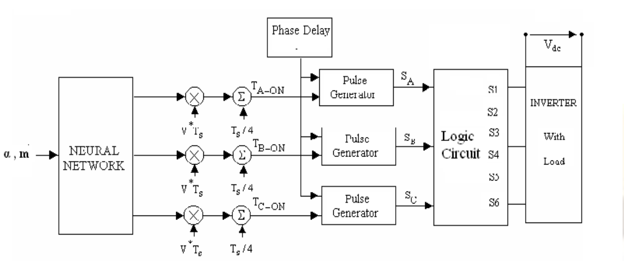


Fig 6: ANN-SVPWM System

The network is obtained by supervised training method with trainlm function using Levenberg -Marquardt algorithm. The mean squared error acceptable for training is 10e-4. The number of neurons of 1st layer is 10 tansig neurons, the 2nd layer has 3 purelin neurons. So, the total number of neurons is 13 (convergence obtained for 1672 epochs). For implementing it, the network further uses turn-on (switching) time S_A, S_B and S_C as output and $h_{10,20,30}*(\alpha)$ and modulation index (m) as input with one purelin neuron having values of weight = (√3/ Π) and bias = (T_s/4) as shown in Fig. 5.

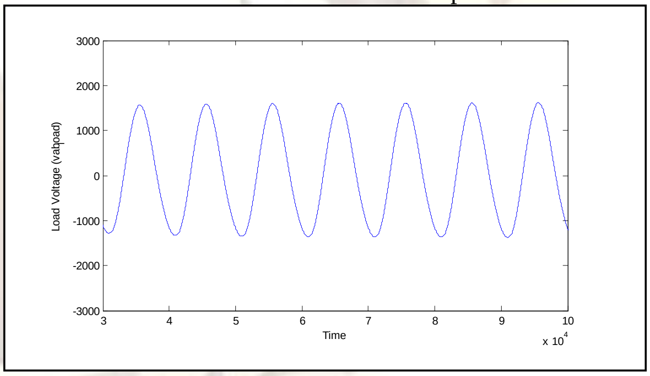
The turn-on times as generated by the neural network are then used to generate the SV-PWM signals by feeding the calculated duty cycle values and the corresponding phase delays of the three pulses S_A, S_B and S_C into the pulse generator available in the Simulink library which generates six pulses S1 to S6 for six switches as shown in Fig. 6.

4. SIMULATION RESULTS

The schematic of the ANN based space vector modulated voltage source inverter is shown in the Fig. 6. The high considered inverter is simulated with ANN implementation of the SVPWM algorithm with the following system parameters:

DC Link voltage = 400V, Load resistance = 10 Ω, Load inductance = 101mH, Load Capacitance=20μF and switching frequency = 50Hz.

The various performance waveforms are recorded for modulation index=0.5 and shown in Fig. 7(a) - 7(o). The load voltages shown in Fig. 7 (a) demonstrate the three-phase inverter operation. The load voltage (V_{ab_load}) and the phase voltage (V_{an}) waveforms shown in Fig. 7(a)-7(d) and 7(k)-7(m) respectively, demonstrate the inverter operation for star connected load. The THD of the load voltage is chosen as the inverter performance index. So, a load voltage THD waveform of the inverter for three phases is shown in



the Fig. 7(h)-7(j).

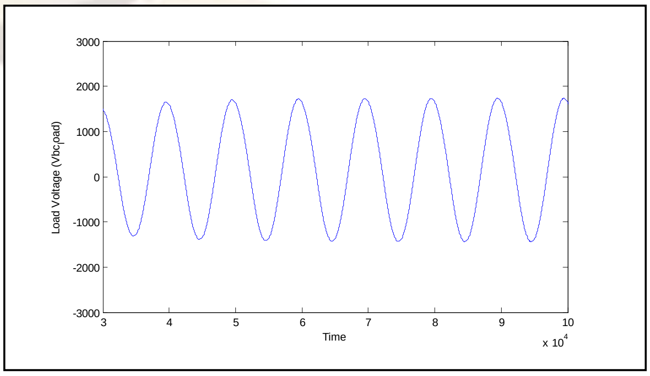


Fig 7(a): Load Voltage (Vab_load)

Fig 7(b): Load Voltage (Vbc_load)

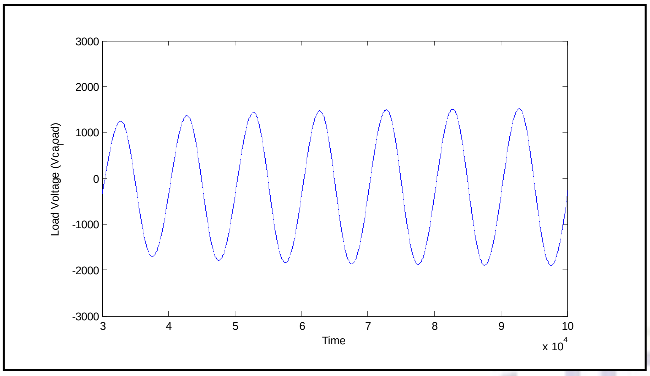
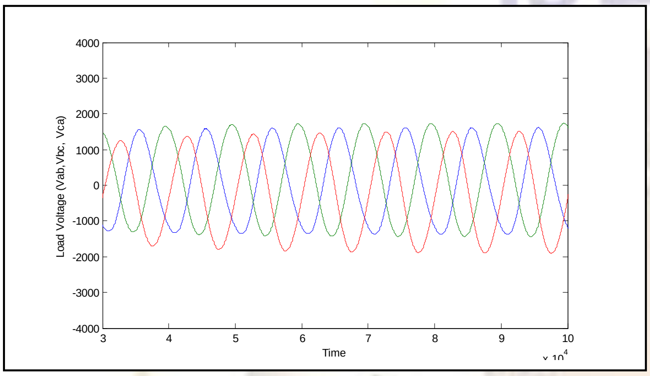


Fig 7(c): Load Voltage (Vca_load)



For the conventional SPWM technique and SV-PWM technique, THD of load voltage is given in Table 2 for comparison.

Fig 7(d): Load Voltage (Vab,Vbc, Vca)

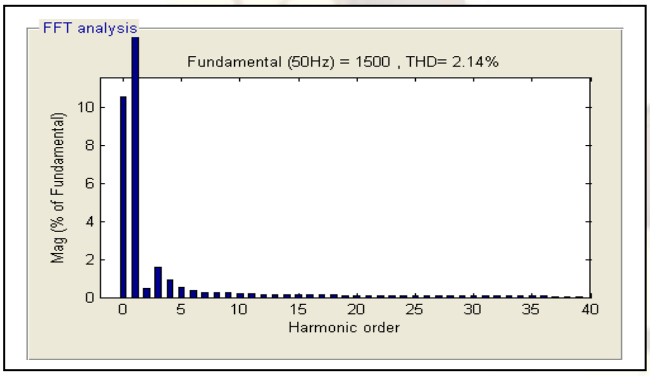


Fig 7(e): FFT Analysis of Vab_load

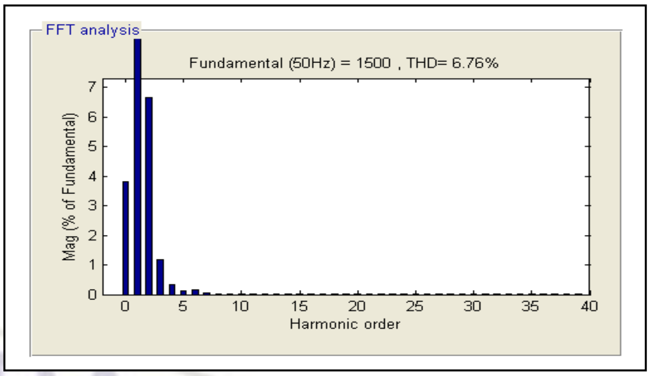


Fig 7(f): FFT Analysis of Vbc_load

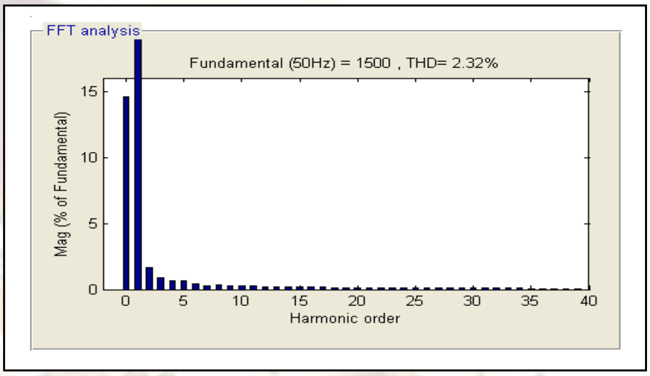


Fig 7(g): FFT Analysis of Vca_load

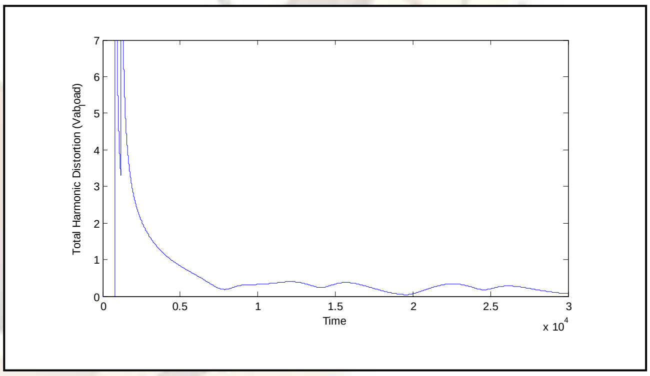


Fig 7(h): THD Analysis of Vab_load

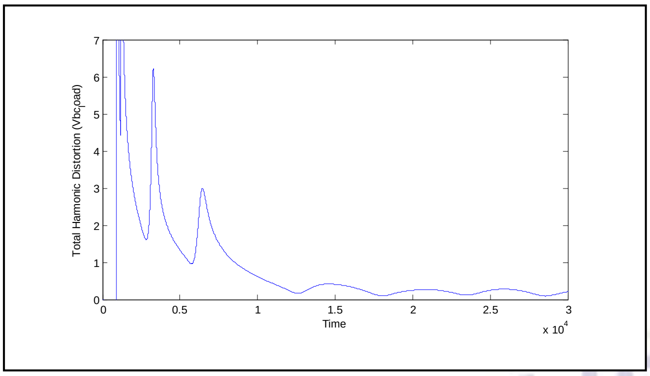


Fig 7(i): THD Analysis of Vbc_load

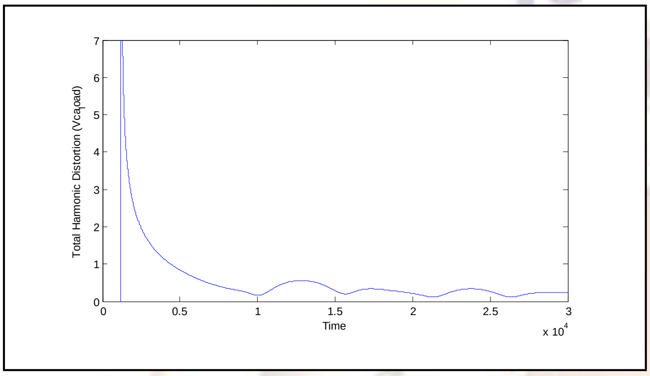


Fig 7(j): THD Analysis of Vca_load

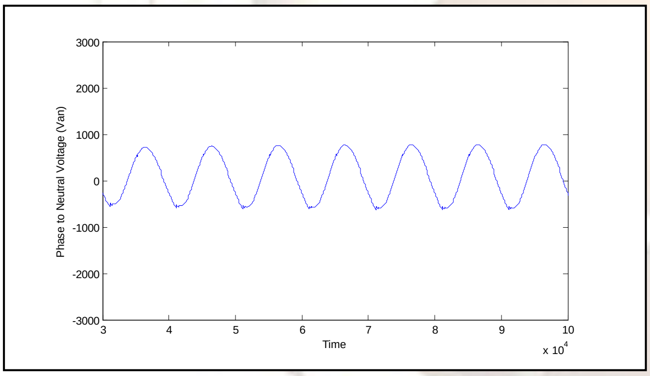
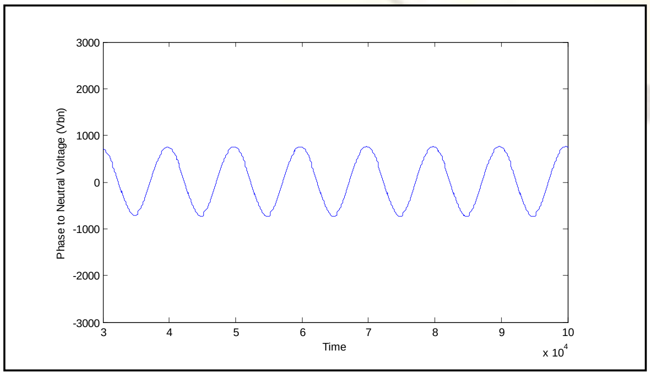


Fig 7(k): Phase Voltage Van



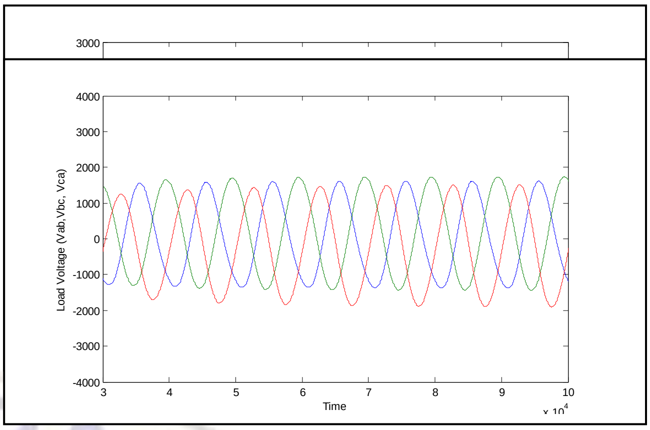


Fig 7(l): Phase Voltage Vbn

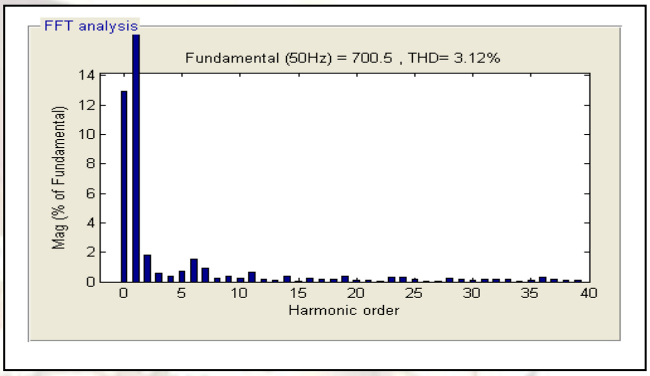


Fig 7(h): Phase Voltage Vcn

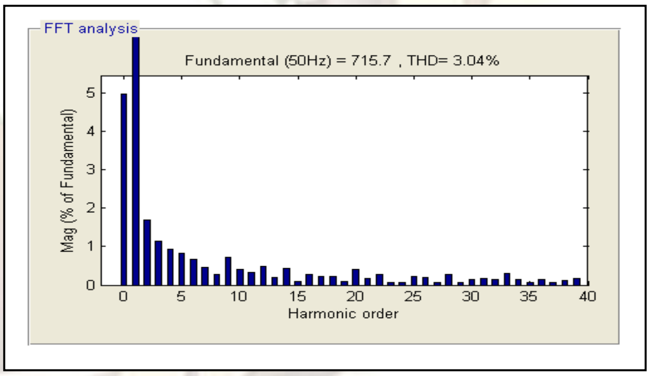


Fig 7(m): Phase Voltage (Van, Vbn, Vcn)

Fig 7(n): FFT Analysis of Van

Fig 7(o): FFT Analysis of Vbn

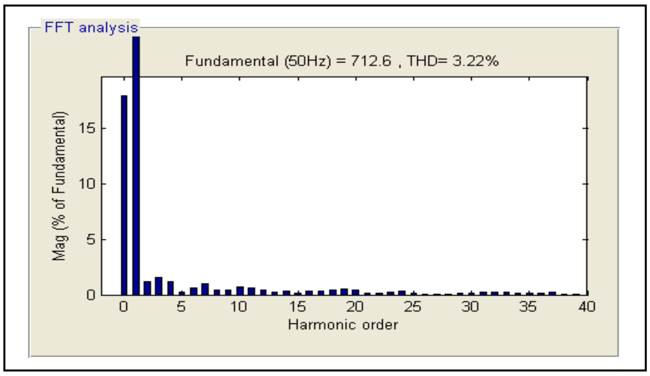


Fig 7(o): FFT Analysis of Vcn

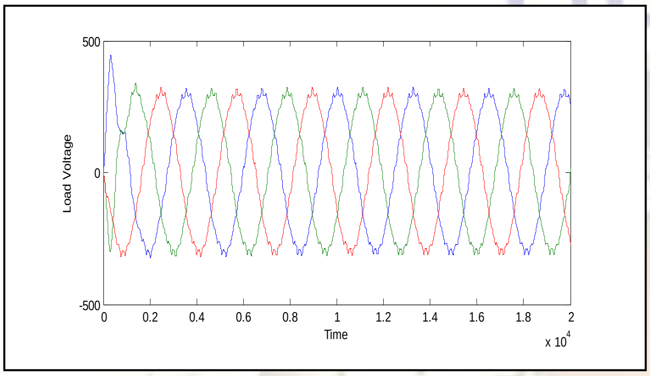


Fig 8(a): Load Voltage Vab_load (SPWM)

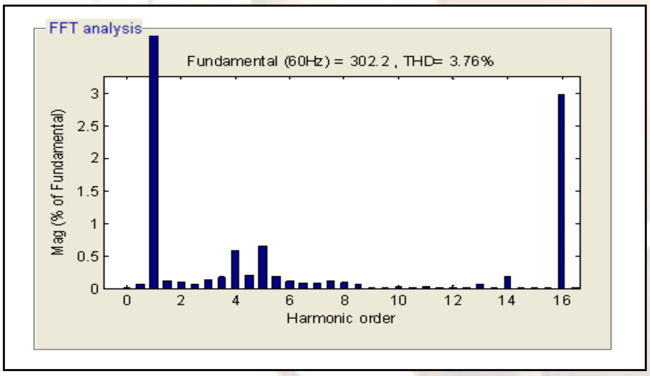


Fig 8(b): FFT Analysis of Van (SPWM)

Table 2: THD Comparison - SPWM and SVPWM

Modulation index	THD (SPWM)	THD (SV-PWM)
M=0.8	4.66%	2.10%
M=0.5	3.76%	2.14%

The THD and FFT analysis of SPWM and SVPWM of the load and phase voltages are shown in Fig. 7 and Fig. 8. The comparison of THD between the two techniques SPWM and SVPWM shows the better performance of SVPWM algorithm with lowest THD for a range of modulation index as shown in Table 2.

5. CONCLUSION

A neural-network-based space-vector modulator has been implemented that gives excellent performance of the inverter in terms of power quality and total harmonic distortion. The turn-on times are generated by the ANN and then converted to pulse widths through a simple logic circuit. The ANN significantly reduces the computational efforts of the modulation technique and makes the implementation of space vector modulation algorithm very fast without losing precision compared to the conventional SVM algorithm implementation using look up table. In practice, the use of DSP can be avoided and simple logic circuits can be used for the generation of PWM pulses. A comparative analysis of the inverter using space vector modulation using ANN implementation and conventional SPWM technique for three phase voltage source inverter is also presented to validate the usefulness of the ANN implementation of space vector modulation. It is found that with the ANN implementation of the SVM algorithm not only results in faster implementation of the algorithm and reduced computational burden on DSP but also better performance of the inverter in terms of THD than that of SPWM algorithm. The principle can be extended to multilevel inverters with certain modifications.

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