Studies and Simulation based Implementation of Various PWM Strategies for Voltage Source Converter

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Abstract - ***This paper presents studies and implementation of various pulse width modulation (PWM) strategies which refers to a method of carrying information on train of pulses and the information be encoded in the width of pulses. Pulse Width Modulation is used to control the inverter output voltage. This is done by exercising the control within the inverter itself by adjusting the ON and OFF periods of inverter. PWM is commonly used in applications like motor speed control, converters, audio amplifiers, etc. For example, it is used to reduce the total power delivered to a load without losses, which normally occurs when a power source is limited by a resistive element. There is no single PWM method that is the best suited for all applications and with advances in solid-state power electronic devices and microprocessors, various pulse-width modulation (PWM) techniques have been developed for industrial applications. For these reasons, the PWM techniques have been the subject of intensive research since 1970s. The paper consists studying various PWM strategies divided into basic and advanced modulation strategies. Same strategies are implemented on voltage source converter in MATLAB.***

Key Words: *Sinusoidal PWM (SPWM), Selected Harmonic Elimination PWM (SHE PWM), Space Vector PWM (SVPWM).*

1. INTRODUCTION

Pulse width modulation refers to a method of carrying information on train of pulses and the information be encoded in the width of pulses. The AC voltage is dependent on two parameters i.e. amplitude and frequency. It is essential to control these two parameters. The most efficient to control these parameters are by using Pulse Width Modulation techniques. In order to generate the gating signals using Pulse Width Modulation Techniques we compare the reference signal amplitude (Ar) with carrier signal amplitude (Ac). The fundamental frequency of output voltage is determined using the reference signal frequency. The inverter output voltage is determined by the following way:

When Ar > Ac :VAO = Vdc/2, When Ar < Ac:VAO = Vdc/2

The ratio of Ar to Ac is called Modulation index. The Pulse width can be varied from 0 to180 (degrees) by varying Ar from 0 to Ac. [1] PWM is commonly used in applications like motor speed control, converters, audio amplifiers, etc. For example, it is used to reduce the total power delivered to a load without losses, which normally occurs when a power source is limited by a resistive element. There is no single PWM method that is the best suited for all applications and with advances in solid-state power electronic devices and microprocessors, various pulse-width modulation (PWM) techniques have been developed for industrial applications. For these reasons, the PWM techniques have been the subject of intensive research since 1970s. [2]

1.1 Basic Pulse Width Modulation Strategies

***A.** Single Pulse Width Modulation*

In Single Pulse Width Modulation control, the width of the pulse is varied to control the inverter output voltage and there is only one pulse half per cycle. By comparing the rectangular reference signal with the triangular carrier wave the gating signals are generated as shown in Fig-1. The frequency of reference signal determines fundamental frequency of output voltage. The advantages of this technique are the even harmonics are absent due to the symmetry of the output voltage along the x-axis and Nth harmonics can be eliminated from inverter output voltage if the pulse width is made equal to $2\pi/n$. But the disadvantages are the output voltage introduces a great deal of harmonic content and at a low output voltage the distortion factors increases significantly.

***B.** Multiple Pulse Width Modulation*

In Multiple Pulse Width Modulation several equidistant pulses per half cycle are generated as shown in Fig-2. By using several pulses in each half cycle of output voltage the harmonic content can be reduced. In this technique the amplitudes of lower order harmonics are reduced and derating factor is reduced significantly. But the fundamental component of output voltage is less, the amplitudes of higher order harmonics increases significantly and switching losses are increased.[1]

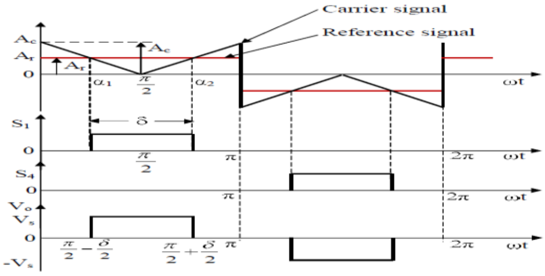

Fig-1: Single Pulse Width Modulation

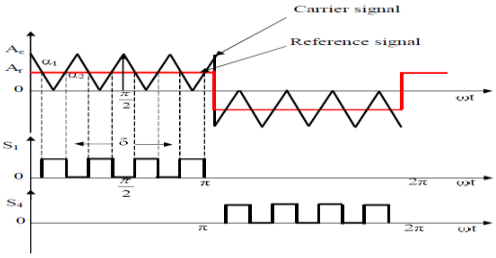

Fig-2: Multiple Pulse Width Modulation

C. Sinusoidal Pulse Width Modulation

The sinusoidal pulse-width modulation (SPWM) technique produces a sinusoidal waveform by filtering an output pulse waveform with varying width. A high switching frequency leads to a better filtered sinusoidal output waveform. 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. As shown in Fig-3, a low-frequency sinusoidal modulating waveform is compared with a high-frequency triangular waveform, which is called the carrier waveform. The switching state is changed when the sine waveform intersects the triangular waveform. The crossing positions determine the variable switching times between states.[2]

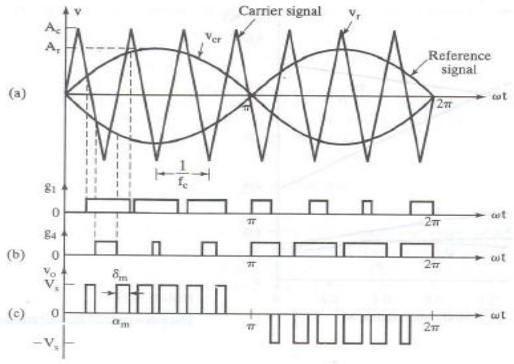

Fig-3: Sinusoidal Pulse Width Modulation

1.2 Advanced Modulation Strategies

A. Hysteresis band current control PWM

The Hysteresis band PWM (HBPWM) is basically an instantaneous feedback current control method of PWM where the actual current continually tracks the command current within a specified hysteresis band. The Fig-4 explains the operation principle of HBPWM for a half bridge inverter. The control circuit generates the sine reference current wave of desired magnitude and frequency, and it is compared with the actual phase current wave. As the current exceeds a prescribed hysteresis band, the upper switch in the half-bridge is turned off and the lower switch is turned on. As a result the output voltage transitions from +0.5Vd to -0.5Vd, and the current starts to decay. As the current crosses the lower band limit, the lower switch is turned off and the upper switch is turned on. The actual current wave is thus forced to track the sine reference wave within the hysteresis band by back- and-forth switching of the upper and lower switches. The inverter then essentially becomes a current source with peak to peak current ripple, which is controlled within the hysteresis band irrespective of Vd fluctuation. The peak-to peak current ripple and the switching frequency are related to the width of the hysteresis band.[3]

B. Selected Harmonic Elimination PWM

In the Sinusoidal PWM technique, a large number of switchings are required, with the consequent associated switching losses. With the method of Selected Harmonic Elimination, only selected harmonics are eliminated with the smallest number of switchings. For a two level PWM waveform with odd and halfwave symmetries and n chops per quarter cycle as shown in Fig-5, the peak magnitude of the harmonic components including the fundamental, are given by Equation:

$$h_1 = \left(4 . \frac{E}{\pi}\right) . [1 - 2\cos\alpha_1 + 2\cos\alpha_2 - 2\cos\alpha_3 \,.....\, 2\cos\alpha_n]$$

$$h_3 = \left(4 . \frac{E}{3\pi}\right) . [1 - 2\cos 3\alpha_1 + 2\cos 3\,\alpha_2 - 2\cos 3\alpha_3 \,.....\, 2\cos 3\alpha_n]$$

. . .

$$h_k = \left(4 . \frac{E}{k\pi}\right) . [1 - 2\cos k\alpha_1 + 2\cos k\alpha_2 - 2\cos k\alpha_3 \,.....\, 2\cos k\alpha_n]$$

Here h_k is the magnitude of the k^{th} harmonic and α_n is the n^{th} primary switching angle. Even harmonics do not show up because of the half-wave symmetry.[4]

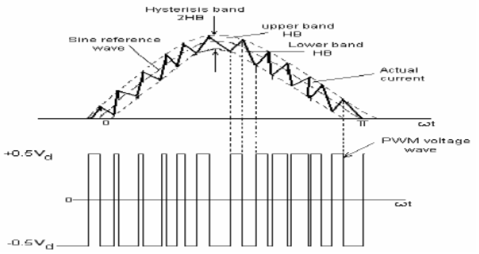

Fig-4: Principle of Hysteresis Band Current Control

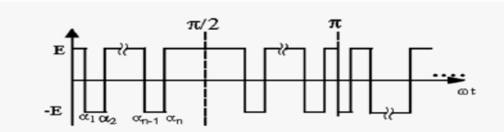

Fig-5: A two-level PWM waveform with odd and half wave symmetry

C. Space Vector PWM

In SVPWM method the output voltage is approximated by using the nearest three output vectors that the nodes of the triangle containing the reference vector in the space vector diagram of the inverter. When the reference vector changes from one region to another, it may induce an output vector abrupt change. In addition we need to calculate the switching sequences and switching time of the states at every change of the reference voltage location. The main advantage of this technique is that it will generate less harmonic distortion in the output voltages and currents. SVPWM is accomplished by rotating a reference vector around the state diagram, which is composed of six basic non-zero vectors forming a hexagon. A circle can be inscribed inside the state map and corresponds to sinusoidal operation. The area inside the inscribed circle is called the linear modulation region or under-modulation region. As seen in Fig-6, the area between the inside circle and outside circle of the hexagon is called the nonlinear modulation region or over-modulation region. The concepts in the operation of linear and nonlinear modulation regions depend on the modulation index, which indirectly reflects on the inverter utilization capability.[2]

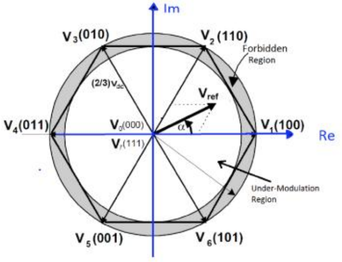

Fig-6: Under-modulation and Over-modulation Regions in Space Vector Representation

2. SIMULATION BASED IMPLEMENTATION

2.1 Implementation of Basic PWM Strategies

A. Single PWM

Single PWM is the basic PWM technique which is rarely used for three phase inverter nowadays. Fig-7 shows implementation of Single PWM on single phase inverter using resistive load (R=1Ω) and DC voltage source of 100V. For the generation of single PWM the logic is explained in the block diagram given in Fig-8 where the amplitude of carrier signal is is kept larger than that of reference signal and the block relational operator gives the switching instants of the respective thyristors. The gating signals produced are shown in Fig-9 with the output voltage waveform.

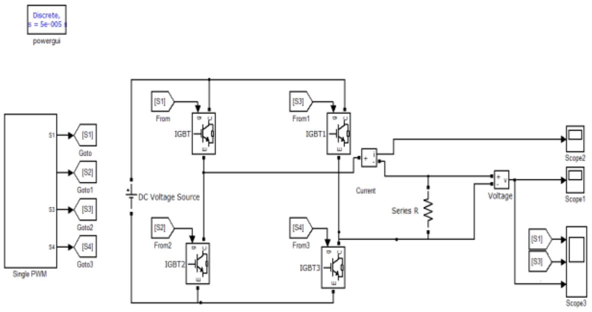

Fig-7: Single PWM implemented on single phase inverter

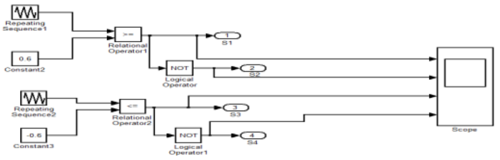

Fig-8: Block diagram of Single PWM generation

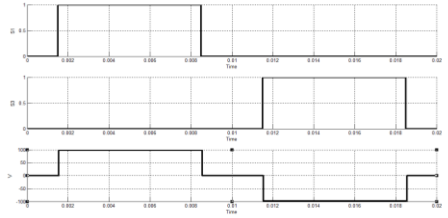

Fig-9: Output Waveforms for Single PWM technique

B. Multiple PWM

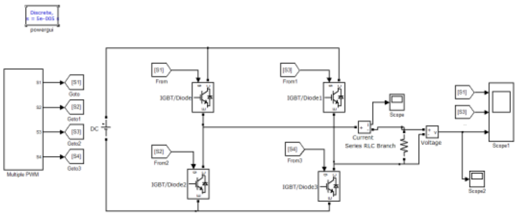

Fig-10: Multiple PWM implemented on single phase inverter

Multiple PWM is the basic PWM technique which is rarely used for three phase inverter nowadays. Fig-10 shows implementation of Multiple PWM on single phase inverter using resistive load (R=1Ω) and DC voltage source of 100V. For the generation of Multiple PWM the logic is explained in the block diagram given in Fig-11 where the amplitude of carrier signal is is kept larger than that of reference signal and the block relational operator gives the switching instants of the respective thyristors. The gating signals produced are shown in Fig-12 with the output voltage waveform.

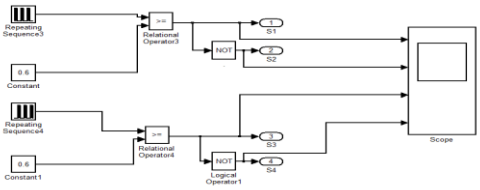

Fig-11: Block diagram of Multiple PWM generation

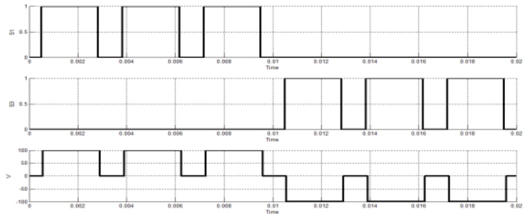

Fig-12: Output Waveforms for Multiple PWM

C. Sinusoidal PWM

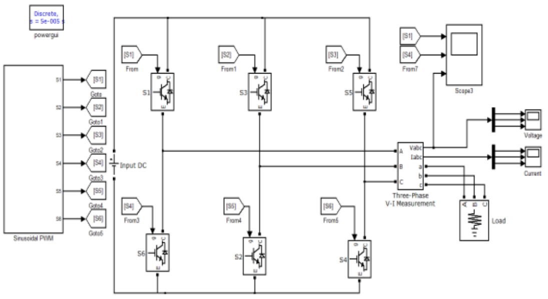

Fig-13: Sinusoidal PWM implemented on three phase inverter

Fig-13 shows the implementation of Sinusoidal PWM on three phase inverter with resistive load (R=1Ω) and DC source of 350V. As shown in Fig-14 block diagram of sinusoidal PWM generation is given where a low-frequency sinusoidal modulating waveform is compared with a high-frequency triangular waveform, which is called the carrier waveform. The switching state is changed when the sine waveform intersects the triangular waveform. The crossing positions determine the variable switching times between states. In three-phase SPWM, a triangular voltage waveform (V_T) is compared with three sinusoidal control voltages (V_a, V_b, and V_c), which are 120° out of phase with each other and the relative levels of the waveforms are used to control the switching of the devices in each phase leg of the inverter as shown in Fig-16. A six-step inverter is composed of six switches S1 through S6 with each phase output connected to the middle of each inverter leg as shown in Fig-13. The output of the logical operator in Fig-14 form the control signals for the three legs of the inverter. Two switches in each phase make up one leg and open and close in a complementary fashion. That is, when one switch is open, the other is closed and vice-versa. The switches are controlled in pairs ((S1; S4), (S3; S6), and (S5; S2)) and the logic for the switch control signals is:

S1 is ON when $V_a>V_T$ S4 is ON when $V_a<V_T$
S3 is ON when $V_b>V_T$ S6 is ON when $V_b<V_T$
S5 is ON when $V_c>V_T$ S2 is ON when $V_c<V_T$

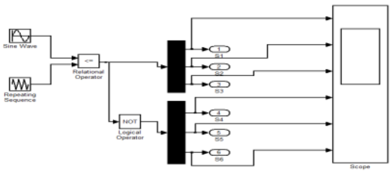

Fig-14: Block diagram of Sinusoidal PWM generation

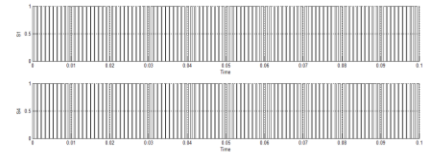

Fig-15: Gate Signals of SPWM

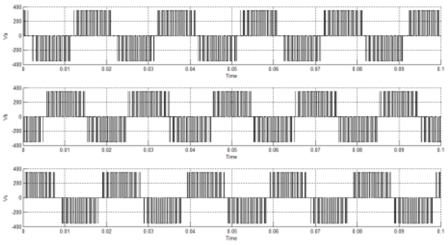

Fig-16: Voltage Output of SPWM

2.2 Implementation of Advanced PWM Strategies

A. Hysteresis Band Current Control PWM

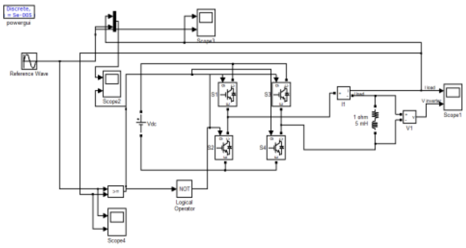

Fig-17: Hysteresis Band Current Control PWM implemented on single phase inverter

One of the simplest current control PWM techniques is the hysteresis band (HB) control shown in this Fig-18. Basically, it is an instantaneous feedback current control method in which the actual current continuously tracks the command current within a pre assigned hysteresis band as shown in Fig-17. As indicated in the Fig-19, if the actual current exceeds the HB, the upper device of the half-bridge is turned off and the lower device is turned on. As the current decays and crosses the lower band, the lower device is turned off and the upper device is turned on. If the HB is reduced, the harmonic quality of the wave will improve, but the switching frequency will increase, which will in turn cause higher switching losses.

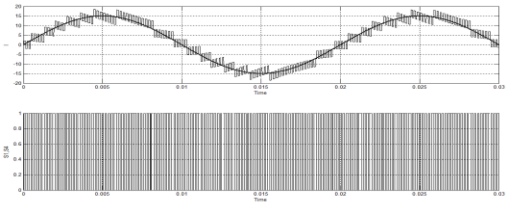

Fig-18: Gate Signal Generation of hysteresis band current control PWM

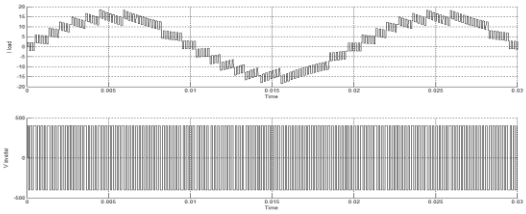

Fig-19: Output Waveforms of Hysteresis Band Current control PWM

B. *Selected Harmonic Elimination PWM*

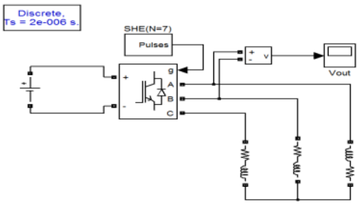

Fig-20: Selected Harmonic Elimination PWM

The model Fig-20 shows the simulation for Six Harmonic Removal Pulses (i.e., N=7). Selected Harmonics made zero are: 5th, 7th, 11th, 13th, 17th and 19th (i.e., N=7 means six (i.e., N-1) dominant harmonics are made zero). In this simulation the dominant harmonics will be: (3N+2) and (3N+4) i.e., 23rd and 25th Harmonics. Selected harmonics could be eliminated from the inverter output voltage by introducing notches at suitable time instants (angles) in the pole voltage waveform. To eliminate more number of unwanted harmonics from the output one needs to have more notches per output cycle. Same logic is applied for each phase as shown in Fig-21.For the required magnitude of output voltage and frequency and the inverter's dc bus voltage, these notch angles need to be calculated off-line using digital computer and later used for generating the switching sequence. The notch angle information for all three phases taken together can be converted into a matrix of switching word for the inverter. The consecutive switching word information at short and regular time interval (in time steps of, say, 10 microseconds) is stored for a full output cycle in consecutive locations of a memory device, like, EPROM. To output the proper switching signal these stored values are output sequentially by sequentially incrementing the address word of the EPROM. The time rate at which the address changes should be identical to the time rate at which the information was stored. The switching word information is then converted into gate control signals for the inverter switches. As the inverter's input and output parameters change, the switching matrix changes too. For an inverter producing variable voltage, variable frequency output the total requirement of memory size becomes large. However the cost of memory chips is coming down and hence the scheme is one of the preferred PWM schemes.

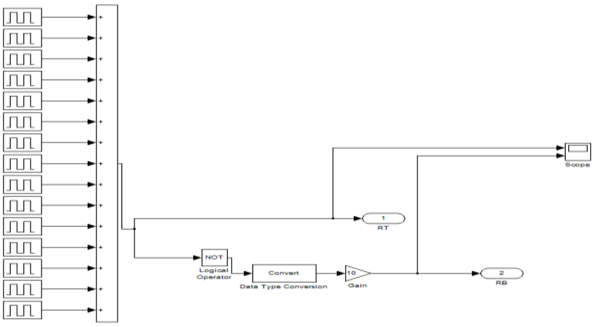

Fig-21: Block diagram of SHE PWM

signal generation (Phase-R)

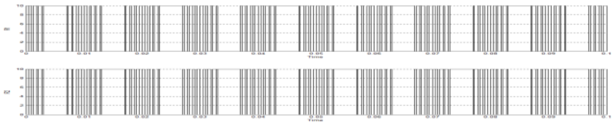

Fig-22: Gate signals of SHE PWM (R Phase)

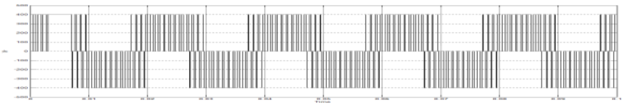

Fig-23: Voltage Output of SHE PWM

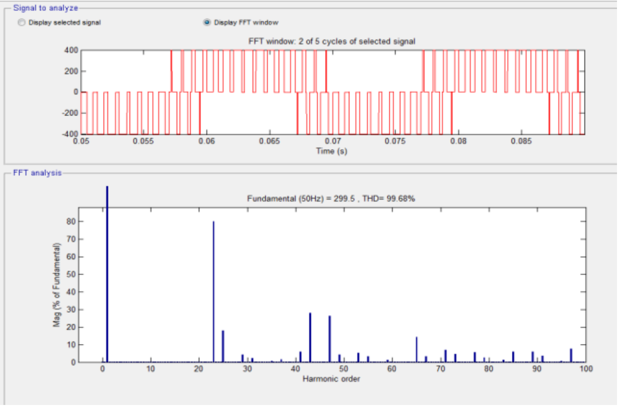

Fig-24: FFT Analysis of SHE PWM

C. *Space Vector PWM*

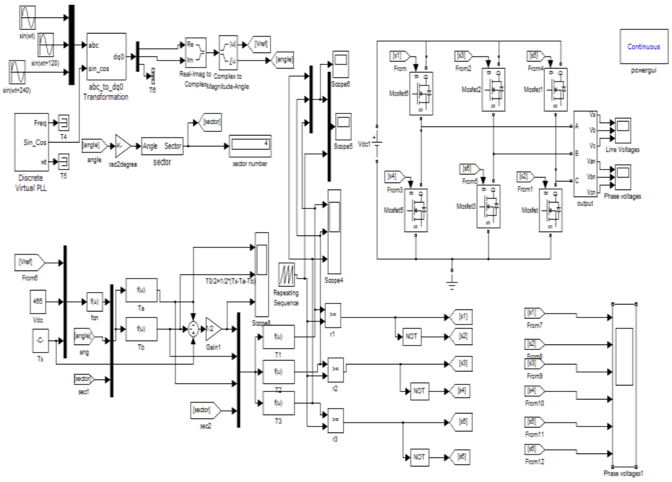

Fig-25: Space Vector implemented on three phase inverter

To generate a rotating space vector with constant amplitude, the reference voltage vector must be limited to the inscribed circle inside the hexagon. The simulation model used to verify SVPWM scheme is shown in Fig-25 and it has seven steps, which are shown in detail in same figure.

1. The first step Fig-25 generation of three-phase sinusoidal input voltages with variable frequency, amplitude, direction, and DC bus voltage is done. The three signals are delayed by 120° from each other.
2. The three-phase abc voltages are then converted to two-phase ab voltages given in the Fig-25 as:

$$\begin{aligned} V_\alpha &= \frac{2}{3}V_a - \frac{1}{3}V_b - \frac{1}{3}V_c \\ V_\beta &= \frac{1}{\sqrt{3}}V_b - \frac{1}{\sqrt{3}}V_c. \end{aligned}$$

It is necessary to know in which sector the reference output is in order to determine the switching time. The reference voltages Va and Vb are utilized to determine the sector of the vectors from 1 to 6. These values are the inputs to the third step.

3. Equations in the third step calculates the phase angle, it can be used to identify the sector of the reference voltage. The modulation index is entered in the first step. It is the ratio of the amplitude of the output sinusoidal voltage to the maximum fundamental voltage.

$$\theta = \tan^{-1}\left(\frac{V_\beta}{V_\alpha}\right)$$
$$\theta \in [0, 2\pi]$$

4. In the fourth step, the switching time calculator is used to calculate the timing of the reference voltage vector. The inputs are the sector in which the voltage vector lies, the modulation index, the sampling time period of switching frequency, and coswt, and sinwt. The duration time of the active and zero vectors are then calculated using

$$\begin{bmatrix} T_a \\ T_b \end{bmatrix} = \frac{MI\sqrt{3}T_s}{\pi} \begin{bmatrix} \sin\frac{k\pi}{3} & -\cos\frac{k\pi}{3} \\ -\sin\frac{(k-1)\pi}{3} & \cos\frac{(k-1)\pi}{3} \end{bmatrix} \begin{bmatrix} \cos n\omega T_s \\ \sin n\omega T_s \end{bmatrix}.$$

In the same step (Fig-25), we also have Sample & Hold blocks after sector Ta and Tb. The purpose of these blocks is to hold the values of Ta and Tb fixed during each TPWM period.

5. In fifth step triangular generator is used to produce a unit triangular waveform at the PWM switching frequency.
6. The gate timing signals from the fourth step are compared with the triangular generator of fifth step, producing the outputs for the six switches of the inverter.
7. In seventh step block is built to simulate a inverter. Fig-26 and 27 shows the output voltage waveforms obtained from the SVPWM strategy.

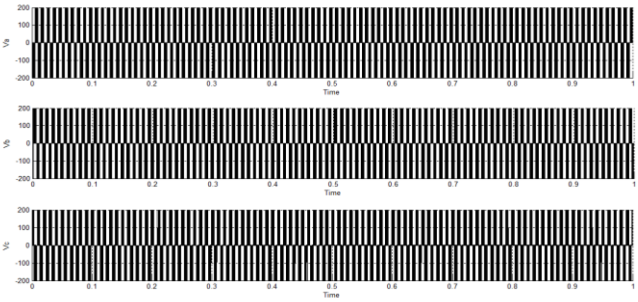

Fig-26: Line Voltages

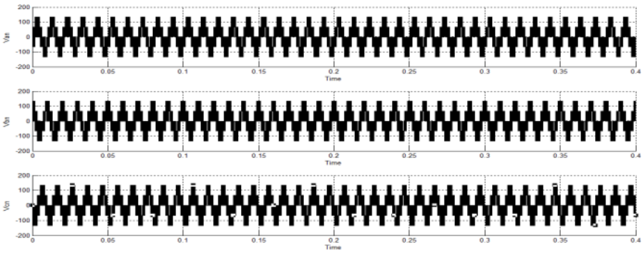

Fig-27: Neutral Voltages

3. CONCLUSIONS

This paper has evaluated six different PWM techniques namely Single PWM, Multiple PWM, Sinusoidal PWM, Selected harmonic Elimination PWM, Hysteresis Band current control PWM and Space Vector PWM . The paper has provided a thorough review of the each technique with a special focus on the operation of single and three phase inverter which will be implemented digitally in Phase-II. In this paper, Simulink models for all six techniques have been developed and tested in the MATLAB/Simulink environment. The report discusses the advantages and drawbacks of each technique.

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BIOGRAPHIES

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