

Sampled Reference Frame Algorithm Based on Space Vector Pulse Width Modulation for Five Level Cascaded H-Bridge Inverter

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Abstract

In This paper the Sampled Reference Frame Algorithm for Five Level Cascaded H-Bridge Inverter is presented. This simple method is less computation method than Sector Identification. This SVPWM can drive any Multilevel Inverter with good DC utilization, less switching stress. This is used for high voltage and high power applications. By using Sampled Reference Frame Algorithm, there is no use of look up tables, sector selection, no need of reference voltage and angle information, 3ϕ to 2ϕ transformation. The inverter's structure of these inverters is developed by using MATLAB SIMULINK software.

Keywords: Space vector pulse width modulation. (SVPWM). Sinusoidal pulse width modulation (SPWM), Multilevel Inverter (MLI), Sector Identification Method, Sample Reference Frame Algorithm

1. Introduction

Decades the multi level inverter acts an important role in industries because of high voltage /high power application. To control the multi level inverter the pulse width modulation is suggested [2]. Conventional Sinusoidal Pulse Width Modulation (SPWM) disadvantages are overcome by the SVPWM. The SVPWM has better dc utilization, less switching stress and low THD [6]. The Sector Identification can be done by 3ϕ to 2ϕ transformation. Then, the looks up tables are used to determine the switching vectors in better switching sequence. Finding the duration of switching vectors can be simplified by mapping the sector of multilevel inverter that considered to two level inverter. Then the Sampled Reference Frame Algorithm is the less computational method. By this sampled reference frame algorithm, switching times determined from the sampled reference phase voltages. After getting modulating wave, this compare with carrier wave. That is followed by carrier based pulse width modulation. There are 2 types, 1) Phase Shifted Multicarrier Modulation and 2) Level Shifted Multi Carrier Modulation [4]. The level shifted multi carrier modulation is classified into 3, they are, In-Phase Disposition (IPD), Alternative Phase Opposite Disposition (APOD), Phase Opposite Disposition (POD). In this paper the in phase disposition method is used. Then that pulses are given to the Cascaded Five Level H-Bridge Inverter. That has been developed in the MATLAB SIMULINK software.

2. Multi Level Inverter

Multi Level Inverter is used to boost the voltage level with low THD. There are three types of Multi Level Inverter, They are, Diode Clamped Multi Level Inverter, Capacitor Clamped Multi Level Inverter, Cascaded H-Bridge Multi Level Inverter.

Cascaded H-Bridge Multi Level Inverter

In this cascaded H-bridge multi level inverter, the cascaded full bridge with separate DC sources, number of devices are less used [1].

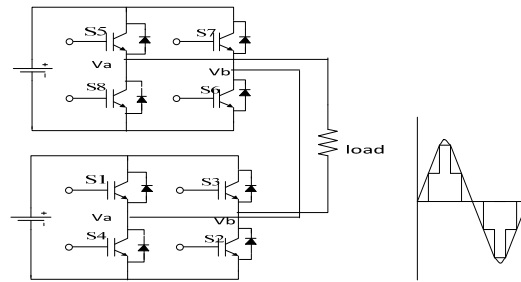


Figure 1. Five level cascaded H-bridge inverter.

Using of H- bridges including in this multilevel inverter increases the voltage level of the inverter. The Figure 1 shows the five level cascaded H-bridge inverter. This having 8 switches, two DC sources and load. This requires less no of components, same amount of components are sufficient in every voltage level. For different voltage level the operation of switching sequence will be following in the table 1, when the battery has $2V_{dc}$ voltage.

Table 1. Operating Switches with Different Voltage Level.

Sl.No	Voltage Level	Operating Switches
1	0	$S_1 S_5 S_7 S_3$
2	V_{dc}	$S_1 S_6 S_8 S_2$
3	$2V_{dc}$	$S_1 S_6 S_5 S_2$
4	$-2V_{dc}$	$S_3 S_8 S_7 S_4$
5	$-V_{dc}$	$S_4 S_6 S_5 S_2$

3. Basic Principle of SVPWM

The SVPWM have the constant switching time calculations for each state. This SVPWM can easily be changed to higher levels. SVPWM have good utilization of the DC link voltage, low current ripple and relative easy hardware implementation [3]. Compared to the SPWM, the SVPWM has a 15% higher utilization ratio of the voltage. As the number of level increases, the redundant switching states increases and also the complexity of selection of the switching states [5].

Reference Vector

The reference vector is represented in a $\alpha\beta$ -plane. The switches being ON or OFF are determined by the location of the reference vector on this $\alpha\beta$ -plane.

Table 2. Eight Switching States of the Inverter

Zero State	000
Active State	001
Active State	010
Active State	011
Active State	100
Active State	101
Active State	110
Zero State	111

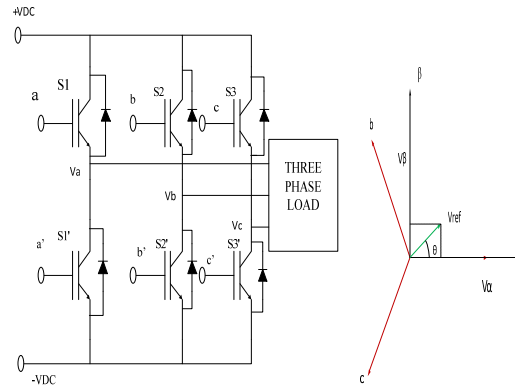


Figure 2. (a) Three phase inverter, (b) diagram of reference vector in abc and αβ axis

The switches ON means 1, OFF means 0. The switches 1, 3, 5 are the upper switches and if these are 1 it turns the upper inverter leg ON and the terminal voltage (V_a , V_b , and V_c) is positive. If the upper switches are zero, then the terminal voltage is 0. 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 [9]. These are represented by active (V_1 - V_6) and zero (V_0) vectors. The zero vectors are placed in the axis origin.

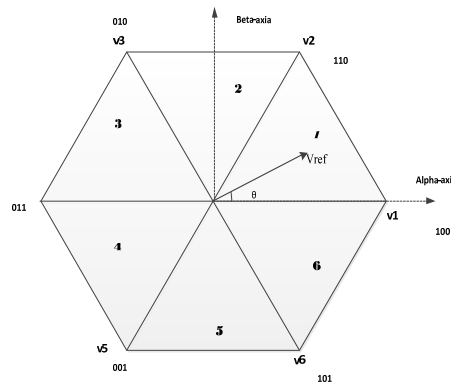


Figure 3. Space Vector Diagram of Two Level Inverter.

It is assumed that the three-phase system is balanced:

$$V_{a0} + V_{b0} + V_{c0} = 0 \quad (1)$$

These are the instantaneous phase voltages:

$$V_a = V \sin(\theta t) \quad (2)$$

$$V_b = V \sin\left(\theta t + \frac{2\pi}{3}\right) \quad (3)$$

$$V_c = V \sin\left(\theta t + \frac{4\pi}{3}\right) \quad (4)$$

When the three phase voltages are applied to a AC machine a rotating flux is created. This flux is represented as one rotating voltage vector. The magnitude and angle of this vector can be calculated with Clark's Transformation:

$$V_{ref} = V_{\alpha} + jV_{\beta} \quad (5)$$

The magnitude and angle of the reference vector is:

$$|V_{ref}| = \sqrt{V_{\alpha}^2 + V_{\beta}^2} \quad \theta = \tan^{-1} \left(\frac{V_{\beta}}{V_{\alpha}} \right)$$

The reference voltage can then be expresses as:

$$V_{\alpha} + jV_{\beta} = \frac{2}{3} \left(V_a + e^{j\frac{2\pi}{3}} V_b + e^{-j\frac{2\pi}{3}} V_c \right) \quad (6)$$

Inserting the phase sfted values for V_a , V_b and V_c gives:

$$V_{\alpha} + jV_{\beta} = \frac{2}{3} \left(V_a + \cos\left(\frac{2\pi}{3}\right) V_b + \cos\left(\frac{2\pi}{3}\right) V_c \right) + j \frac{2}{3} \left(\sin\left(\frac{2\pi}{3}\right) V_b - \sin\left(\frac{2\pi}{3}\right) V_c \right) \quad (7)$$

The voltage vectors on the alpha and beta axis can then be described as:

$$\begin{pmatrix} V_{\alpha} \\ V_{\beta} \end{pmatrix} = \frac{2}{3} \begin{pmatrix} 1 & \cos\left(\frac{2\pi}{3}\right) & \cos\left(\frac{2\pi}{3}\right) \\ 0 & \sin\left(\frac{2\pi}{3}\right) & -\sin\left(\frac{2\pi}{3}\right) \end{pmatrix} \begin{pmatrix} V_a \\ V_b \\ V_c \end{pmatrix} \quad (8)$$

$$= \frac{2}{3} \begin{pmatrix} 1 & -\frac{1}{2} & \frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{pmatrix} * \begin{pmatrix} V_a \\ V_b \\ V_c \end{pmatrix} \quad (9)$$

$$V_{\alpha} = \frac{2}{3} \left(V_a - \frac{1}{2} V_b - \frac{1}{2} V_c \right) \quad (10)$$

$$V_{\beta} = \frac{2}{3} \left(\frac{\sqrt{3}}{2} V_b - \frac{\sqrt{3}}{2} V_c \right) \quad (11)$$

Having calculated V_{α} , V_{β} , V_{ref} and the reference angle, the first step is taken. The next step is to calculate the duration time for each vector V1-V6.

Time Duration

Along α -axis:

$$V_1 + V_2 \cos 60 T_2 = V_{ref} T_S \cos \theta \quad (12)$$

Along β -axis:

$$V_2 \sin 60 T_2 = V_{ref} T_S \sin \theta \quad (13)$$

$$T_2 = \frac{V_{ref} T_S \sin \theta}{V_2 \sin 60} \quad (14)$$

Substitute α -axis equation, we get
For sector 1,

$$T_1 = \frac{2 * V_{ref} T_S \sin(60 - \theta)}{\sqrt{3} V_{DC}} \quad (15)$$

$$T_2 = \frac{2*V_{ref}T_S \sin \theta}{\sqrt{3}V_{DC}} \quad (16)$$

We know, $\cos \theta = \frac{V_\alpha}{V_{ref}}$

$$\text{So, } V_\alpha = V_{ref} * \cos \theta \quad (17)$$

$$\sin \theta = \frac{V_\beta}{V_{ref}}$$

So,

$$V_\beta = V_{ref} * \sin \theta \quad (18)$$

Then T_1, T_2 becomes,
For sector 1,

$$T_1 = \frac{T_S}{V_{DC}} (V_\alpha - \frac{1}{\sqrt{3}} V_\beta) \quad (19)$$

$$T_2 = \frac{T_S}{V_{DC}} \frac{2}{\sqrt{3}} V_\beta \quad (20)$$

For sector 2,

$$T_1 = \frac{T_S}{V_{DC}} (V_\alpha + \frac{1}{\sqrt{3}} V_\beta) \quad (21)$$

$$T_2 = \frac{T_S}{V_{DC}} (-V_\alpha + \frac{1}{\sqrt{3}} V_\beta) \quad (22)$$

For sector 3,

$$T_1 = \frac{T_S}{\sqrt{3}V_{DC}} (2V_\beta) \quad (23)$$

$$T_2 = \frac{-T_S}{V_{DC}} (V_\alpha + \frac{1}{\sqrt{3}} V_\beta) \quad (24)$$

For sector 4,

$$T_1 = -\frac{T_S}{V_{DC}} (V_\alpha - \frac{1}{\sqrt{3}} V_\beta) \quad (25)$$

$$T_2 = -\frac{T_S}{V_{DC}} \frac{2}{\sqrt{3}} V_\beta \quad (26)$$

For sector 5,

$$T_1 = -\frac{T_S}{V_{DC}} (V_\alpha + \frac{1}{\sqrt{3}} V_\beta) \quad (27)$$

$$T_2 = -\frac{T_S}{V_{DC}} (-V_\alpha + \frac{1}{\sqrt{3}} V_\beta) \quad (28)$$

For sector 6,

$$T_1 = -\frac{T_S}{\sqrt{3}V_{DC}} (2V_\beta) \quad (29)$$

$$T_2 = \frac{T_S}{V_{DC}} (V_\alpha + \frac{1}{\sqrt{3}} V_\beta) \quad (30)$$

Total time is

$$T_S = T_1 + T_2 + T_0 \quad (31)$$

Switching Time

Duty Cycle:

Each sector having 7 switching states for each cycle. It starts and ends with a zero vector. The uneven numbers travel counter clockwise in each sector and the even sectors travel clockwise. The table3 shows the duty cycle of three phases that's are, T_A , T_B , and T_C for six sectors.

Table 3. Switching Time of Six Sector

Sector no	T_A	T_B	T_C
1	$T_1+T_2+T_0/2$	$T_0/2+T_2$	$T_0/2$
2	$T_2+T_0/2$	$T_1+T_2+T_0/2$	$T_0/2$
3	$T_0/2$	$T_1+T_2+T_0/2$	$T_2+T_0/2$
4	$T_0/2$	$T_2+T_0/2$	$T_1+T_2+T_0/2$
5	$T_2+T_0/2$	$T_0/2$	$T_1+T_2+T_0/2$
6	$T_1+T_2+T_0/2$	$T_0/2$	$T_2+T_0/2$

4. Sampled Reference Frame Algorithm

By using sampled reference frame algorithm, the space vector wave (like third harmonic content wave) will be produced directly from the reference phase amplitude. In SPWM, each reference phase amplitude compared with carrier and then V_{offset} is added to the reference phase amplitude for generating maximum voltage of fundamental phase voltages. The V_{offset} will be,

$$V_{offset} = -(V_{max} + V_{min})/2 \quad (32)$$

V_{max} is the maximum magnitude from sampled reference voltages. V_{min} is the minimum magnitude from the sampled reference phase voltages. Adding V_{offset} at the sampling time will be active vectors being in sampling time, making SPWM equivalent to SVPWM. From that sampled reference phase amplitude, the minimum magnitude is first crosses the carrier wave, that creates first switching transition, the maximum magnitude cross triangular carrier wave creates last switching transition for two level inverter [10]. This can implemented to five level inverter. The following are the steps of algorithms consisting in the sampled reference frame algorithm.

Step 1:

Find the sampled values for reference phase voltages

$$V_{as} = \sin \theta \quad (33)$$

$$V_{bs} = \sin(\theta + 120) \quad (34)$$

$$V_{cs} = \sin(\theta + 240) \quad (35)$$

Step 2:

Find the time equivalent of each voltage

$$T_{as} = V_{as} * \left(\frac{T_S}{V_{DC}} \right) \quad (36)$$

$$T_{bs} = V_{bs} * \left(\frac{T_s}{V_{DC}} \right) \quad (37)$$

$$T_{cs} = V_{cs} * \left(\frac{T_s}{V_{DC}} \right) \quad (38)$$

Where T_s is the sampling time period and V_{DC} is the dc input voltage to the multi level inverter.

Step 3:

$$\max(T_{as}, T_{bs}, T_{cs}) \quad (39)$$

$$\min(T_{as}, T_{bs}, T_{cs}) \quad (40)$$

Step 4:

Find offset time period

$$T_{offset} = -(T_{max} + T_{min})/2 \quad (41)$$

Step 5:

Find the time period for inverter leg switches,

$$T_{ga} = T_{as} + T_{offset} \quad (42)$$

$$T_{gb} = T_{bs} + T_{offset} \quad (43)$$

$$T_{gc} = T_{cs} + T_{offset} \quad (44)$$

5. Simulation and Results

The simulation results of the SPWM and SVPWM in five level cascaded H-bridge inverter circuits by using MATLAB is following below and wave forms are in works space model.

Sector Identification of SVPWM:

The three phase sine waves with 120 degree phase shift are converted to two phase $\alpha\beta$. that transformation circuit is developed in the following mat lab software.

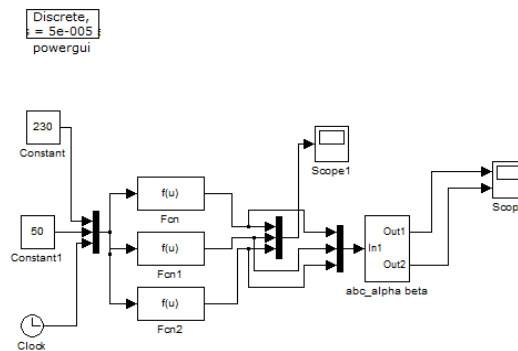


Figure 3. 3 ϕ to 2 ϕ transformation.

The reference vector moving around all sectors that create an angle θ , that compare with each sectors having 60 degree angle [8]. That Simulink model is following below.

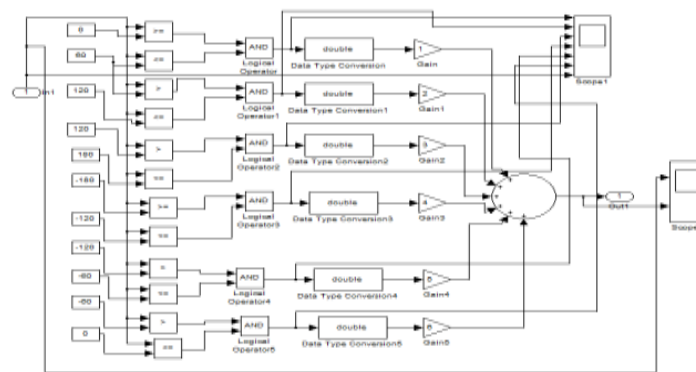


Figure 4. Sector Selection model.

The overall Simulink model of sector identification SVPWM method with three phase five level cascade h-bridge inverter is proceeded below.

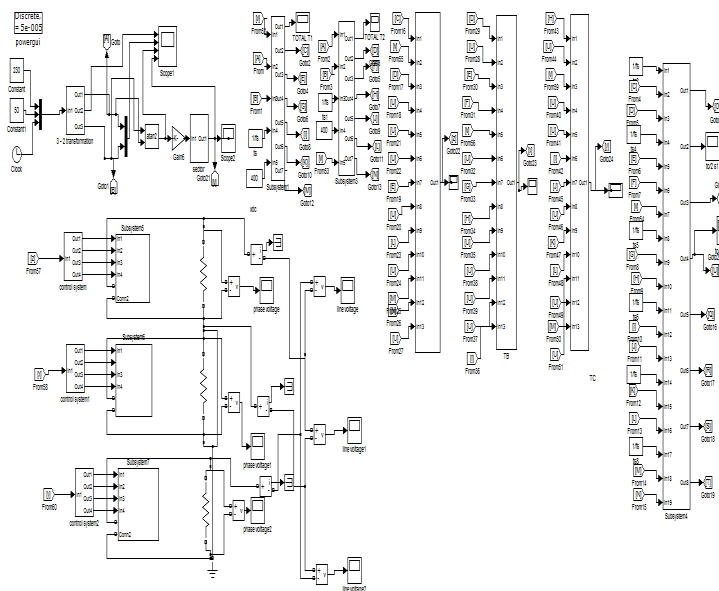
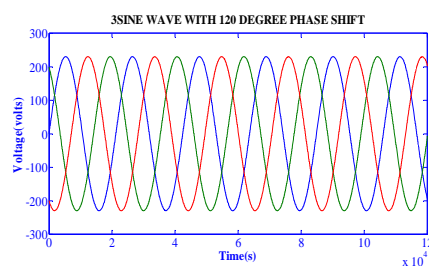


Figure 5. The overall Simulink model of sector identification SVPWM method.

The V_a, V_b, V_c sine wave with 120 degree phase shift is converted to two phase wave form ($\alpha\beta$) that is 90 degree phase shift each other when α is 0 degree β is 90°.

Figure 6. 3 ϕ sine waves with 120° phase shift

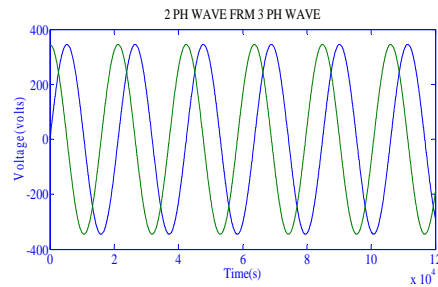


Figure 7. 2ϕ sine waves with 90° phase shift.

The angle θ wave form will be triangular wave. The sector selection wave is 6 step wave that is given below.

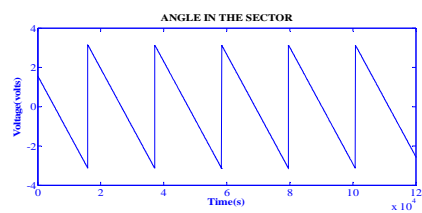


Figure 8. The triangle wave of an angle.

Then after sector selection, the T_A, T_B, T_C values are getting like a modulating waveform. That compared with the four carrier wave. That is given to the five level cascaded inverter.

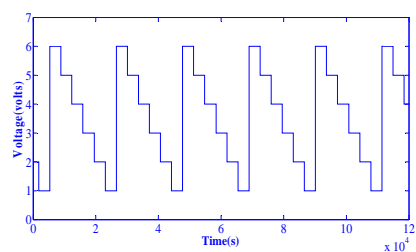


Figure 9. Stepped wave of the sectors.

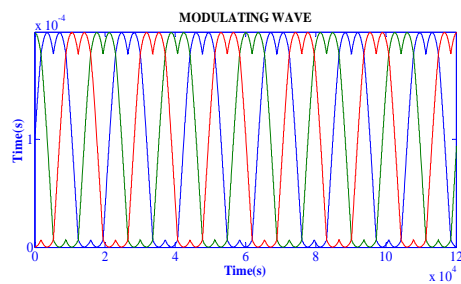


Figure 10. 3ϕ modulating SV wave.

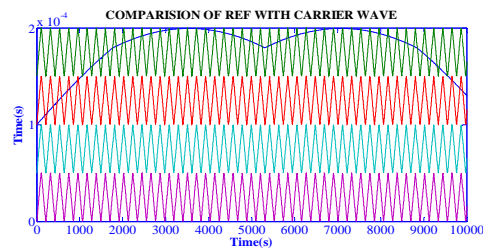


Figure 11. Triangular with ref wave.

The combined 3 phase wave forms are following Figure 12 is the phase voltage and Figure 13 is the line voltage.

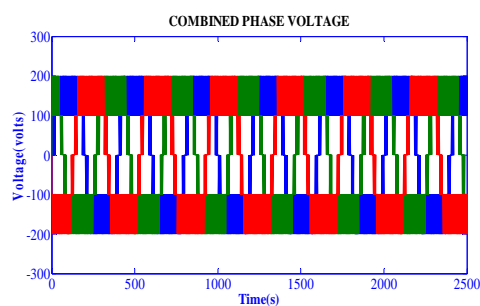


Figure 12. Phase voltage for 5level inverter

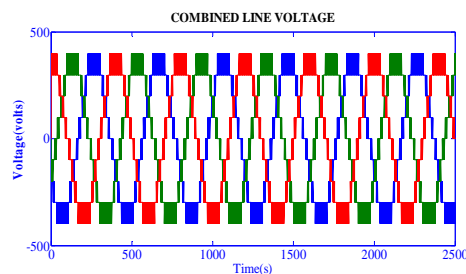


Figure 13. Line voltage for five level inverter.

Sampled Reference Frame Algorithm

The three phase V_a, V_b, V_c converted to T_{as}, T_{bs}, T_{cs} [7]. From that the maximum and minimum values of T_{as}, T_{bs}, T_{cs} are used to find the T_{offset} . that model is following below.

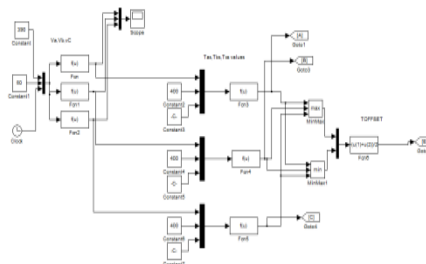


Figure 14. Circuit of Finding Offset Value

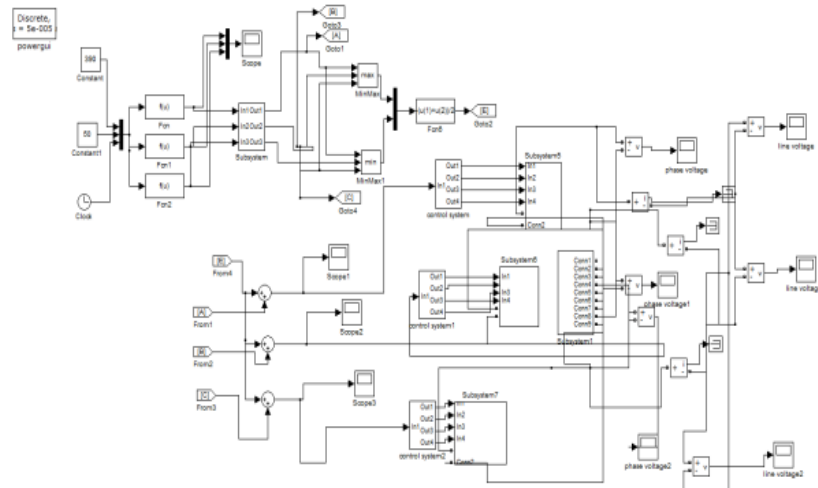
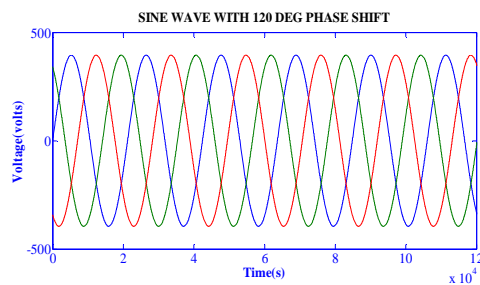
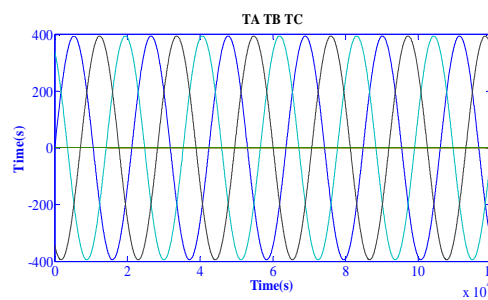


Figure 15. The overall circuit model of sampled reference

The overall circuit model of sampled reference frame is given above. The modulating wave is compared to the carrier. Then that is given to five level inverter the three phase V_a, V_b, V_c and T_{as}, T_{bs}, T_{cs} are shown by Figure16 and Figure17.

Figure 16. 3 ϕ sine wave with 120° phase shift.Figure 17. T_{as}, T_{bs}, T_{cs} Wave with 120° phase shift.

Then, the T_{\max} and T_{\min} from T_{as}, T_{bs}, T_{cs} is given. The T_{offset} wave is like a triangular wave form, is converted to modulating wave. That shown in Figure 18, Figure 19, and Figure 20.

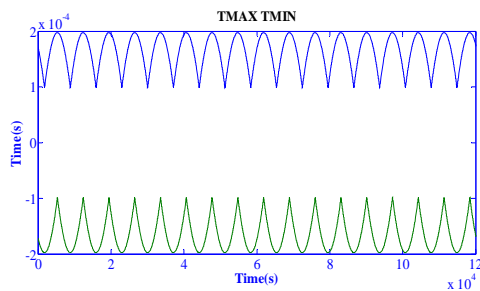
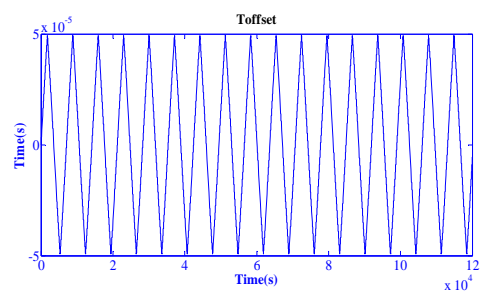
Figure 18. T_{\max} And T_{\min} wave.

Figure 19. Triangular wave of offset.

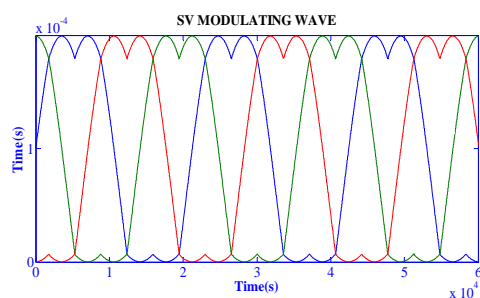
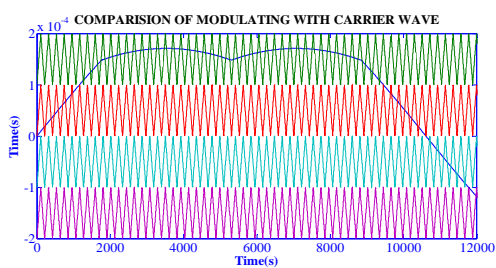
Figure 20. 3 ϕ modulating SV wave

Figure 21. Triangular wave with reference wave.

The following is the combined three phase wave of phase and line voltage of Five Level Inverter. That is given in Figure 22 and Figure 23.

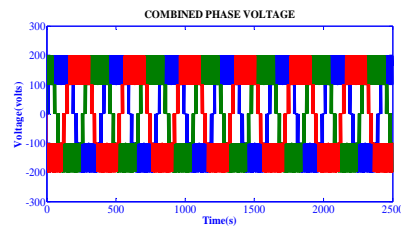


Figure 22. Phase voltage for five level inverter

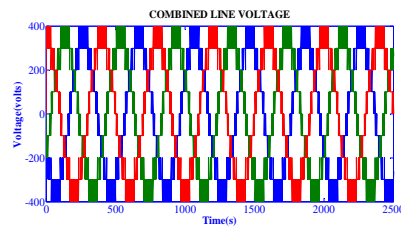


Figure 23. Line voltage for five level inverter.

Compared to sector identification the sampled reference frame SVPWM having low THD level that will be given in the following.

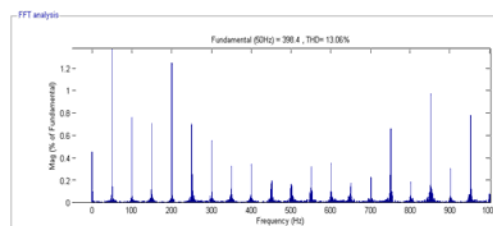


Figure 24. THD LEVEL for line voltage (sector identification)

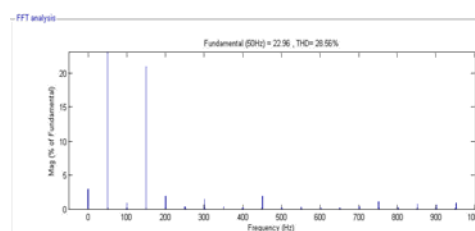


Figure 25. THD LEVEL for line current (sector identification)

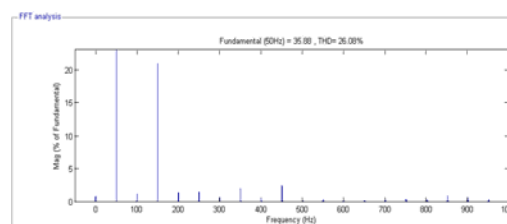


Figure 26. THD LEVEL for line voltage (sampled reference frame)

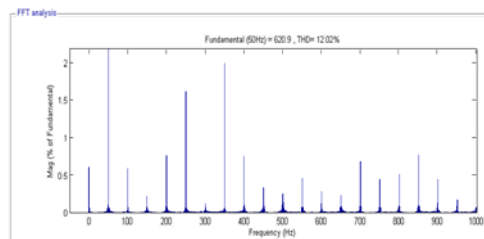


Figure 27. THD LEVEL for line current (sampled reference frame)

The sector identification line current THD is 28.56%.and line voltage THD is 13.06%.and then the sampled reference frame line current THD is 26.08 and line voltage THD is 12.02% without filter

6. Conclusion

A space vector pulse width modulation with sector identification and sampled reference frame algorithm was presented. The SVPWM can drive the inverter gating signal from the sampled amplitudes of the reference phase voltages. In this project the five level cascade h-bridge inverter has been used. This has no look up tables and less computation method and hence reduces the implementation time compared to sector identification method. Because it have no sector identification method, and also V_{ref} and angle $\alpha\beta$ information is not needed. This results show good performance and less computation time was presented using MATLAB SIMULINK model.

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