Space Vector Pulse Width Modulation Technique Applied to Two Level Voltage Source Inverter

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ABSTRACT- Space vector pulse width modulation SVPWM provides a better technique compared to the other pulse width modulation techniques. This paper presents simulation and implementation of SVPWM signal generation for driving three phase two level voltage source inverter VSI, also proposes and analyzes a new switching sequence for generating an SVPWM. Simulation results are obtained using the simulation package PSIM. and the inverter performance is evaluated in terms of total harmonic distortion (THD). The model is experimentally implemented and verified on Arduino Mega Atmega2560 microcontroller.

Keywords: Space vector modulation, Voltage source inverter, two- level inverter

المستخلص– تضمين النبضة المتجهي الفراغي له نتيجة افضل مقارنة بالطرق الاخري لتضمين عرض النبضة. هذه الورقة توضح المحاكاة والتصميم لطريقة تضمين النبضة المتجهي الفراغي لتوليد الاشارات لمغير ثلاثي الطور ذو مصدر الجهد ثنائي المستوى. ايضا تم عرض وتحليل جديد لطريقة تزامن المفاتيح لتوليد تضمين النبضة المتجهي الفراغي. المحاكاة تم تحقيقها باستخدام البرنامج *PSIM*. وتم تقييم الاداء للمغير من حيث تشويش التوافقيات الكلية. النموذج تم بناءة وتحقيقه باستخدام المتحكم الدقيق نوع *Arduino Mega Atmega2560*.

INTRODUCTION

Pulse width modulation is the process that used in sophisticated power electronics systems. which based on generating an analog signal from a digital source by control the duty cycle and frequency through turning the switches on and off at a fast rate. Space vector modulation is one of the most preferred PWM strategies today, because of it's easier digital realization, best DC bus utilization and less THD in output voltages. Inverter means conversion of DC to AC power by using PWM techniques to get AC voltage (or current) output. These output waveforms are desired for many applications, in adjustable speed drives (ASD), uninterruptible power supplies (UPS), active filters, and second generation of flexible AC transmission systems (FACTS) [1-3]. With the development of microprocessors, SVPWM became one of the most important PWM techniques for three-phase inverter [4, 5]. This paper tries to provide all the necessary information required to design and implement practical SVPWM technique on a two-level voltage source inverter in a simplified format. Furthermore, compare the amount of THD for different switching sequences in space vector modulation. Power simulation package PSIM environment is used to implement and simulate the VSI and obtain the results of simulation in form of waves for voltage and current. Furthermore, the results are confirmed by the experimental hardware setup.

VOLTAGE SOURCE INVERTER

There are many sources of the DC voltage for VSI. The source may be a battery's bank, wind turbine energy, and solar photovoltaic cells. Furthermore, AC voltage supply after a rectifier to DC can be qualified as another dc voltage source [6, 7]. Voltage source is called as stiff if the magnitude of source voltage is not depending on the load connected to the source. In VSI voltage supply is considered as stiff at the input [8].

A typical schematic diagram of a two-level voltage source inverter is shown in Figure.1. Six switches (S_1 to S_6) are the power switches that

make the output shape. The upper switches and lower switches are complimentary to each other [9].
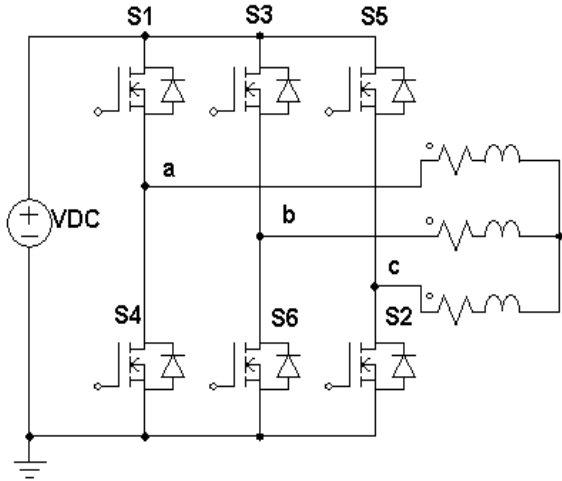

Figure 1: Schematic diagram of two-level VSI

From Figure1, there is a possibility for eight structures of switching status can be configured in the two-level VSI as inserted in Table 1. Status (1) means one of the upper switches is conduct, and status (0) means one of the lower switches is conduct. The three digits in the status correspond to the legs (a, b, & c) in inverter respectively. For example, the switching status [100], means in leg (a) one of the upper switches (S_1) is conduct, and in legs (b & c) there are two of the lower switches (S_6 & S_2) are conducted in the inverter respectively. There are two statuses, [111] and [000] gives zero in the output called zero conditions, and the others are active conditions [10].

SPACE VECTOR MODULATION
The concept of space vector is being derived from the revolving magnetic field of induction machine. Three-phase quantities are transformed to two-phase quantity [11].

The active and zero switching conditions can be represented by active and zero space vectors, respectively. A typical schema of space vector for two-level VSI is shown in Figure 2. The six vectors V_1 to V_6 shapes a symmetric hexagon with similar sectors (1 to 6). Each sector is separated by 60 degrees to each other.

From Figure 2, V_{ref} is the reference voltage vector which used to control the magnitude and frequency of fundamental voltage.

TABLE1: SWITCHING CONDITIONS AND ON-STATUS SWITCHES

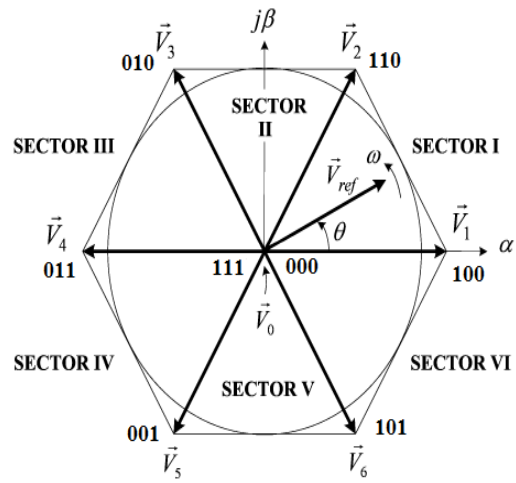| Space Vector		Switching conditions	On-Status Switches
Zero Vector	V_0	111	S_1, S_3, S_5
		000	S_4, S_6, S_2
Active Vector	V_1	100	S_1, S_6, S_2
	V_2	110	S_1, S_3, S_2
	V_3	010	S_4, S_3, S_2
	V_4	011	S_4, S_3, S_5
	V_5	001	S_4, S_6, S_5
	V_6	101	S_1, S_6, S_5

Figure 2: schema of space vector for two-level VSI

SVPWM IMPLEMENTATION
When these 3-phase voltages in equations (1), (2) & (3) are applied to the AC machine, they produce a revolving magnetic flux in the air gap of the machine. This revolving flux component can be represented as a single revolving vector. The magnitude and angle of the revolving vector can be found by {α,β} or Clark's Transformation [12]. The SVPWM is achieved by the next, following steps:

1. Space vector Calculation
Let three-phase sinusoidal voltage quantities be [13].

$$V_{a=}V_m \sin \omega t \qquad (1)$$

$$V_{b=}V_m \sin(\omega t - 2\pi/3) \qquad (2)$$

$$V_{c=}V_m \sin(\omega t - 4\pi/3) \qquad (3)$$

This step determined $\vec{V}_{ref}$ & α through $\{\alpha, \beta\}$ transformation:

$$\vec{V}_{ref} = V_\alpha + jV_\beta$$

$$= \frac{2}{3}\left(V_a + V_b e^{j\frac{2\pi}{3}} + V_c e^{j\frac{4\pi}{3}}\right) \qquad (4)$$

$$|\vec{V}_{ref}| = \sqrt{V_\alpha^2 + V_\beta^2} \qquad (5)$$

$$\alpha = \tan^{-1}\left(\frac{V_\beta}{V_\alpha}\right) \qquad (6)$$

Real and imaginary parts:

$$V_\alpha = \frac{2}{3}\left(V_a + V_b \cos\frac{2\pi}{3} + V_c \cos\frac{2\pi}{3}\right) \qquad (7)$$

$$V_\beta = \frac{2}{3}\left(V_b \sin\frac{2\pi}{3} - V_c \sin\frac{2\pi}{3}\right) \qquad (8)$$

From equation (7) and (8) we can get the transformation

$$\begin{bmatrix} V_\alpha \\ V_\beta \end{bmatrix} = \frac{2}{3}\begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix}\begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} \qquad (9)$$

2. Switching Time Durations

Switching time durations, T_0, T_1 and T_2 are calculated for sector 1 by the Volt-Sec method as:

$$V_{ref}\, T_s = V_1 T_1 + V_2 T_2 + V_0 T_0 \qquad (10)$$

$$T_1 = T_s\, a\, \sin\left(\frac{\pi}{3} - \theta\right) \qquad (11)$$

$$T_2 = T_s\, a\, \sin\theta \qquad (12)$$

where $a = \frac{\sqrt{3}\, V_{ref}}{Vd}$ is the modulation index

$$T_0 = T_s - T_1 - T_2 \qquad (13)$$

Generally switching time durations for all sectors can be determined by the following equations:

$$T_1 = T_s\, a\, \left[\sin\left(\frac{n}{3}\pi - \theta\right)\right] \qquad (14)$$

$$T_2 = T_s\, a\, \sin\left(\theta - \frac{n-1}{3}\pi\right) \qquad (15)$$

$where\ n = 1\ to\ 6$

3. Switching Sequences

After calculations of space vectors and the switching time durations, the next step is determining prospective switching sequences for a given, V_{ref}.

I.First Switching Sequence

Different groups of switches will be turned on or off if V_{ref} pass into sectors one by one, Figure 3 shows Space vector diagram for V_{ref} passes through all sectors. This sequence begins and ends with Zero Vector [000] as indicate in Table 2.
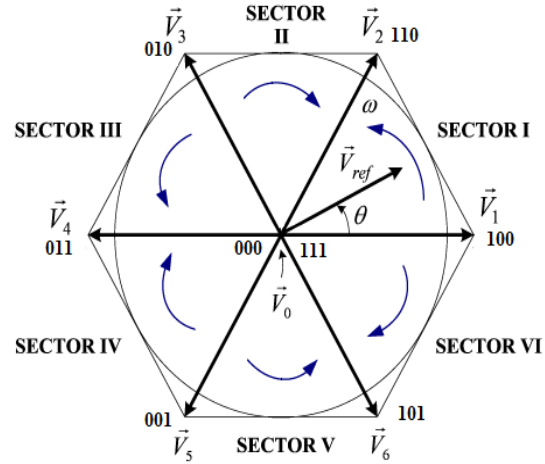

Figure 3: Space vector diagram for First sequence

TABLE 2: SWITCHING SEGMENT FOR FIRST SEQUENCE

sec	Switching segment						
1	V_0 000	V_1 100	V_2 110	V_0 111	V_2 110	V_1 100	V_0 000
2	V_0 000	V_3 010	V_2 110	V_0 111	V_2 110	V_3 010	V_0 000
3	V_0 000	V_3 010	V_4 011	V_0 111	V_4 011	V_3 010	V_0 000
4	V_0 000	V_5 001	V_4 011	V_0 111	V_4 011	V_5 001	V_0 000
5	V_0 000	V_5 001	V_6 101	V_0 111	V_6 101	V_5 001	V_0 000
6	V_0 000	V_1 100	V_6 101	V_0 111	V_6 101	V_1 100	V_0 000

II.Second Switching Sequence

The inverter output voltage will change everyone cycles over time when V_{ref} revolves around every rotation in space, This switching sequence begins and ends with switching status [111] instead of [000] as shown in Figure 4.

III. Third Switching Sequence

The conduction of the lower switches in inverter legs will be longer than that of the upper switches if used the First sequence the same thing happens in the upper switches if used the second sequence.

This will cause unbalanced in power and heating. The problem can be solved by used the two types of the switching sequences alternatively, as shown in Figure 5.
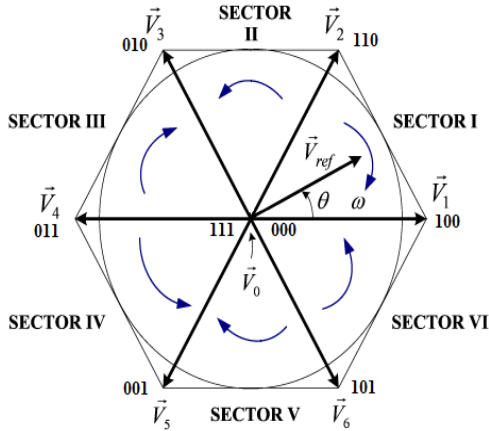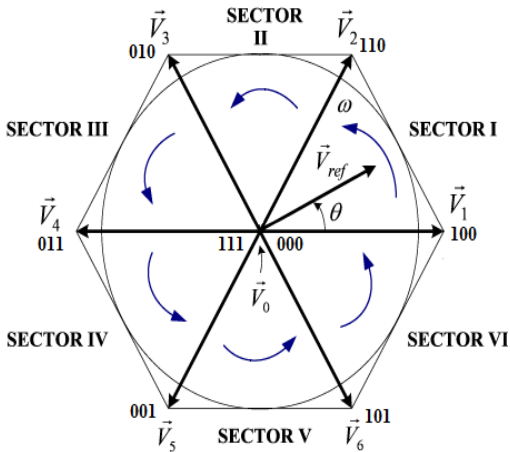

Figure 4: Space vector diagram for Second Sequence

Figure 5: Space vector diagram for Third sequence

TABLE 3: SEVEN-SEGMENT FOR MODIFIED SWITCHING SEQUENCE

sec	Switching segment						
1	V_1 100	V_2 110	V_0 111	V_1 100	V_0 111	V_2 110	V_1 100
2	V_2 110	V_3 010	V_0 000	V_2 110	V_0 000	V_3 010	V_2 110
3	V_3 010	V_4 011	V_0 111	V_3 010	V_0 111	V_4 011	V_3 010
4	V_4 011	V_5 001	V_0 000	V_4 011	V_0 000	V_5 001	V_4 011
5	V_5 001	V_6 101	V_0 111	V_5 001	V_0 111	V_6 101	V_5 001
6	V_6 101	V_1 100	V_0 000	V_6 101	V_0 000	V_1 100	V_6 101

IV Modified Switching Sequence

The output of the inverter is adjusted by modulate the magnitude & revolving speed of reference voltage. The design of switching sequence for a given reference voltage is not unparalleled. This proposed switching sequence is different from other sequences, for example, in a sector 1 starts and ends with vector V_1.and in a sector 2 starts and ends with vector V_2 and so on in other sectors as shown in Table 3.

SIMULATION of SVPWM

Simulation used SVPWM technique based on space vector theory & using Power Simulation package PSIM environment to obtaining the results. First block in the model as shown in Figure 6 calculates space vector by determines V_α, V_β by convert three phase sinusoidal voltage into two-phase equivalent using Clark's transformation through Equations (7), (8) & (9), and then determines V_{ref}, and angle (α) using Equations (5) & (6). As shown in Figure 7, the second block is used to determine vector location which determines V_{ref} position in various sectors.
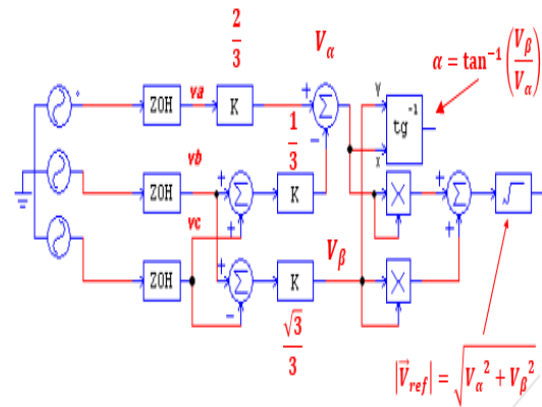

Figure 6: Space Vector Calculation

Next step the model calculates switching time duration (T_0, T_1 and T_2) using Volt-Sec method through Equations (11), (12) & (13).as shown in Figure 8.

The last step the model used lookup tables(Q1-Q6) which derived from switching sequence tables to generate space vector pulses required to drive the VSI as shown in Figure 9.

RESULTS

Simulation results have been taken for various switching sequences feeding a passive load for

R=2Ω and L=8mH. Switching frequency of 5 kHz was used in the model. DC link voltage of the two-level inverter was taken as 220V.

Figures 10 to 13 shows inverter output waveforms produced by SVM scheme. The first sequence in Figure 10 shows line-line and phase voltages output waveforms. It furthermore, shows sinusoidal output current waveform for the inverter with THD (13%) for fundamental frequency 60Hz. As can be seen the output voltage waveform has two levels. The second sequence output waveforms illustrated in Figure 11 as can be seen the output waveforms are plotted for voltages and also for current with THD (14%). Figure 12 illustrate the third sequence output waveforms.
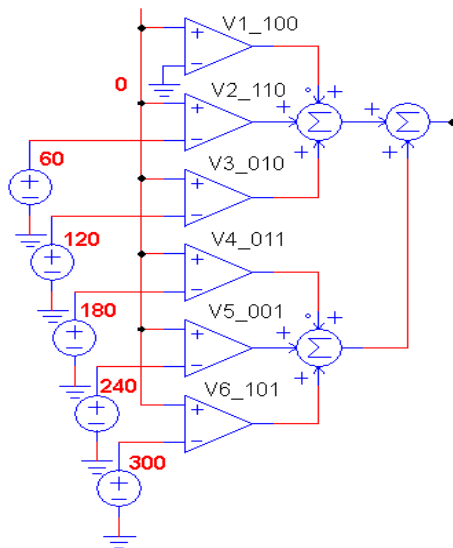
Figure 7: Vector location determination
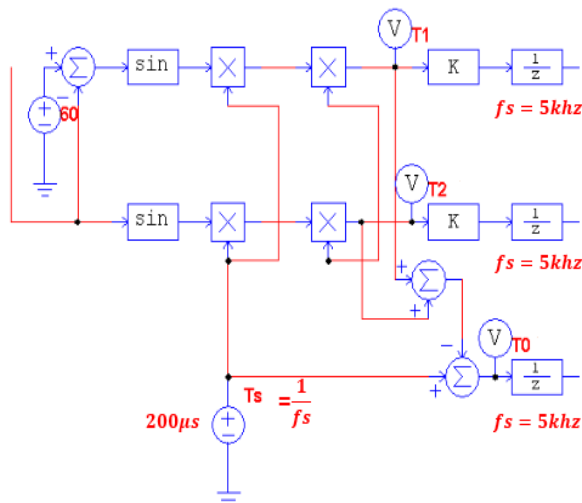
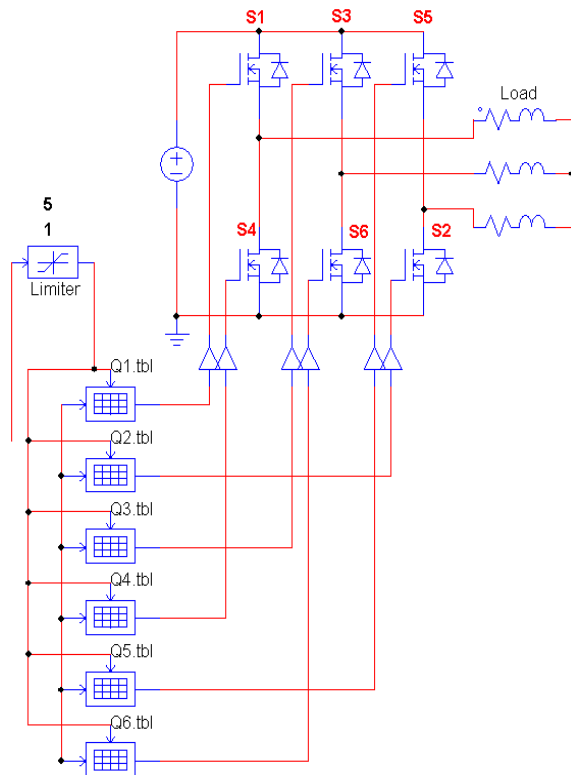**Figure 8: switching time duration calculation**

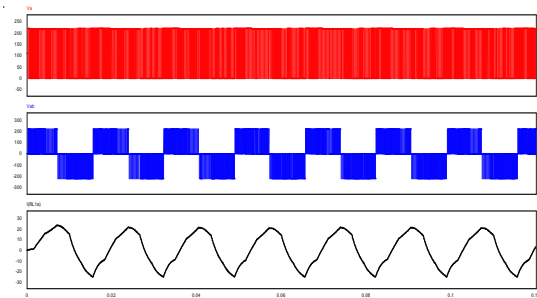**Figure 9: Switching sequences generation.**

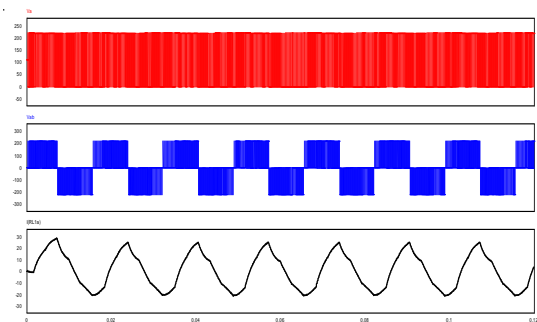**Figure 10: Inverter output waveform for First sequence**

Figure 11: Inverter output waveform for Second sequence

Comparing with previous sequences (First and Second) it can be seen the THD is decreased to (10%). Figure 13shows proposed switching sequence output waveforms.as we can see the results shows less harmonics distortion in the output waveform. Also it can be observed that the THD is decreased to (4%) comparing with the other switching sequences. Table 4 shows comparative results statement of all four switching sequences.
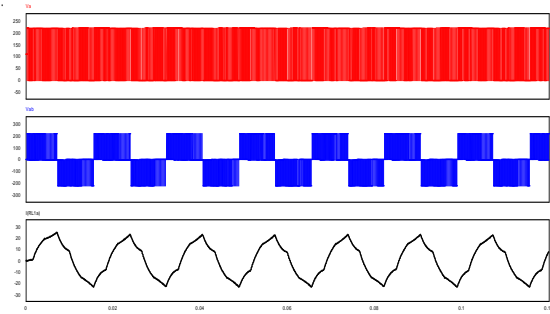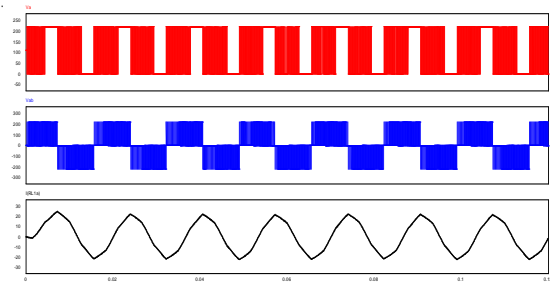

Figure 12: Inverter output for Third sequence

Figure 13: Inverter output for modified sequence

EXPERIMENTAL SETUP

The model of SVPWM for two levels VSI in (section 5) is implemented on Arduino Mega board Atmega2560 microcontroller and the experimental results are presented for two-level inverter before and after LC filter. Figure 14 shows the experimental circuit design for two level (VSI). The circuit is consisted of Arduino Mega board with ATmega2560 microcontroller.

This microcontroller generates space vector pulses from code written by (IDE) software. Furthermore, circuit contains 6 switches type N-channel MOSFET(IRF450) and high & low side transistor drivers' type (IR2112). Figures 15 & 16 illustrate real phase voltage wave forms measured by oscilloscope, generated by space vector

modulation for two level VSI before and after LC filter .and its same as waveforms that we get from previous simulation model.

Figure 17 shows the Real image for experimental circuit setup.

TABLE 4 . COMPARATIVE RESULTS BETWEEN FOUR SEQUENCES

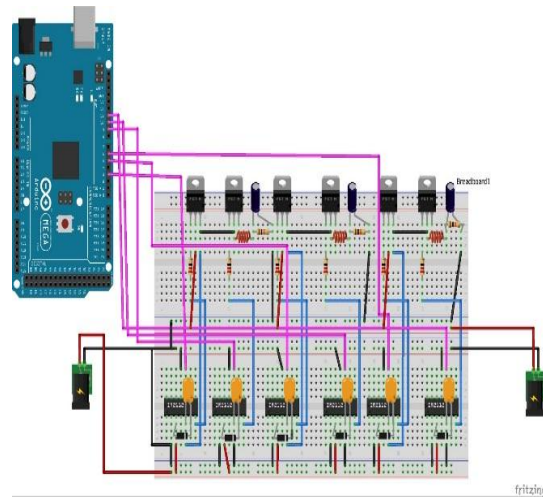| No	Performance Parameters	First	Second	Third	Modified Sequence
1	Phase voltage THD	288%	264%	286%	280%
2	Line voltage THD	117%	117%	123%	113%
3	Line current THD	13%	14%	10%	4%

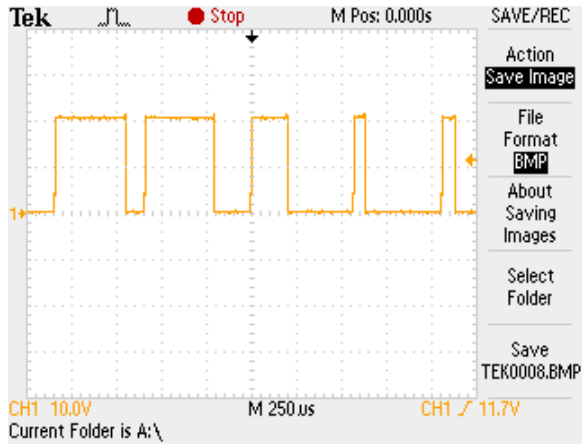**Figure 14: Experimental circuit design for two- level VSI**

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Figure 15: Measured voltage waveforms for two level VSI before filter

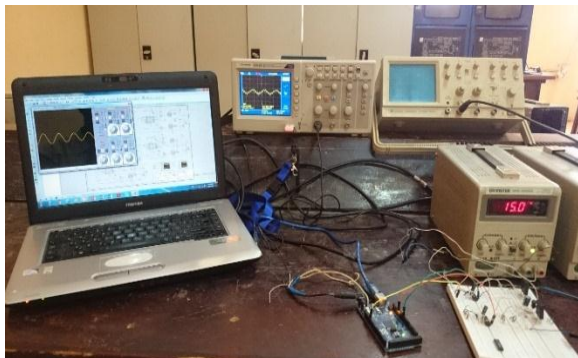**Figure 16: Measured voltage waveforms for two level VSI after filter**

Figure 17: Real image for experimental circuit setup

CONCLUSION

The simulation study of a two-level inverter is implemented using SVPWM because it's more efficiently, generates less harmonic distortion and simple digital realization. In this paper, a two-level inverter has been modeled and simulated using the PSIM package program. Simulation results have been given for various switching sequences using 5kHz switching frequency and a passive load. 220v is used for DC voltage supply of a two-level inverter. Comparative is made between four switching sequences and the proposed one is the best choice to drive the inverter because it has less THD comparison with other switching sequences. Implementation is confirmed by generating SVPWM waveforms from code written in cheap microcontroller and results are matching with the simulation very well. Further studies should be done for more than two-level SVPWM to get higher level for voltages. In the future, studies may be available for implementing the same switching sequences that we realize but in the three level or four level. Definitely, the performance will be different comparing with switching sequences in two- level inverter.

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