Comparison of the Performance of Three Level Inverter Based STATCOM with Sinusoidal and Space Vector PWM Techniques

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Abstract

This paper compares the performance of diode clamped three level inverter based STATCOM with sinusoidal and space vector PWM techniques. Space Vector Pulse Width Modulation (SVPWM) technique is the most advantageous technique than the conventional sinusoidal PWM technique for a multilevel inverter. The space vector pulse width modulation technique is an advanced, computation-intensive PWM method and is possibly the best among the all other PWM techniques. Unlike the conventional PWM method the space vector pulse width modulation technique produces lesser amount of harmonics. The total harmonic distortion (THD) of the output waveform is reduced by 47% than the sinusoidal PWM. The switching losses are reduced by 30%. The modelling of complete system is developed in MATLAB- Simulink.

Keywords- STATCOM, SVPWM, PWM, THD, IGBT

Introduction

The output obtained from a two-level inverter is not a pure sinusoidal waveform. It is due to the presence of harmonics in the inverter output voltage which may cause heavy losses and may lead to low efficiency of the induction motors or any other applications which may take the supply from the inverter. So, there is a need for us to reduce these harmonics. The harmonics in a two level inverter is reduced by increasing the switching frequency. But the switching frequency is restricted by the switching losses in high power applications. In such applications multilevel inverters have been widely used in recent years for the advantage of low harmonic output at low switching frequency. At the same time low blocking in the switching devices can be achieved. The more the number of levels of the output voltage the lesser will be the harmonic content. Multi level inverters have advantages of good power quality, good electromagnetic compatibility, low switching losses, high voltage capability. These multi level inverters are used in the active rectifiers and the FACTS applications. The multi level inverters synthesize several voltage levels from the various levels of the DC input. A near sinusoidal voltage waveform can be generated from the various levels of the DC input. They have become attractive in the high power and high voltage applications. By using the multilevel inverters the stress on each device is reduced proportional to the number of the output levels present. With several levels in the output waveform the switching dv/dt stresses are reduced, and hence the lifetime of motor and cables are increased. By using a multilevel inverter the power rating of the equipment can enhanced without any dangerous consequences.

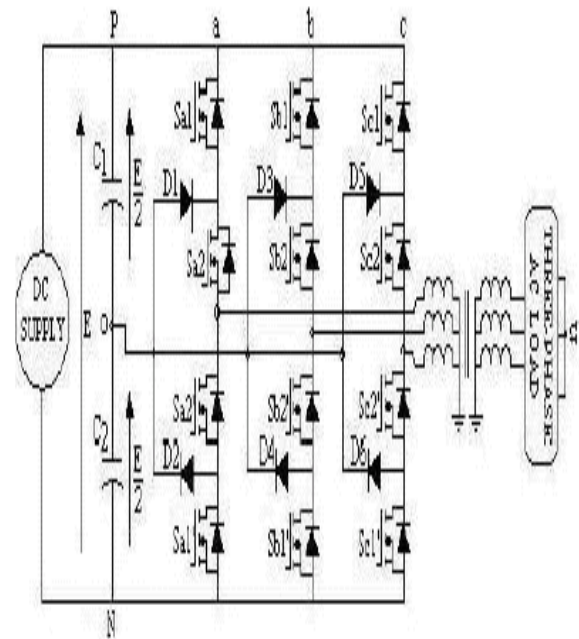## 1. Diode Clamped Three-Level Inverter

Fig. 1 Power Circuit for Three-Phase Three-Level Inverter

Fig. 1 shows the basic circuit for the diode clamped three-level inverter. The circuit employs 12 power switching devices (S_{a1}-S_{a4}) and 6 clamped diodes (D_1-D_6). And the dc-bus voltage is split into three-level by two series-connected bulk capacitors can be defined as the neutral point O. as the result of the diode-clamped the dc-bus voltage $V_{dc}/2$. Thus, the voltage stress of the switching device is greatly reduced. The output voltage V_{ao} has three different states: $+V_{dc}/2$, 0, $-V_{dc}/2$. Here takes phase -A as an example for voltage. For voltage $-V_{dc}/2$, S_{a3} and S_{a4} need to be turned on. We can define these states as 2, 1, and 0, respectively. Then, the switching variable S_a is shown in table1. be similar to three-phase two-level inverter, the switching states of each bridge leg of three-phase three-level inverter is described by using switching variables S_a, S_b and S_c. Whereas the difference is that, in three-level inverter, each bridge leg has three different switching states.

Table 1 Switching Variable of Phase A

V_{ao}	S_{a1}	S_{a2}	S_{a3}	S_{a4}	S_a
$+V_{dc}/2$	ON	ON	OFF	OFF	2
0	OFF	ON	ON	OFF	1
$-V_{dc}/2$	OFF	OFF	ON	ON	0

Using switching variable S_a and DC -bus voltage Vdc, the output phase voltage Vao is obtained as follows:

$$V_{an} = (S_a-1)*V_{dc}/2 \qquad (1)$$

And the output line voltage of phase A and B can be expressed as follows.

$$V_{ab} = V_{ao} - V_{bo} = 1/2*V_{dc} (S_a-S_b) \qquad (2)$$

3. Static Compensator(STATCOM)

The STATCOM has a characteristic similar to the synchronous condenser, but as an electronic device it has no inertia and is superior to the synchronous condenser in several ways, such as better dynamics, a lower investment cost and lower operating and maintenance costs. A STATCOM is build with Thyristors with turn-off capability like GTO or today IGCT or with more and more IGBTs. The static line between the current limitations has a certain steepness determining the control characteristic for the voltage.

The advantage of a STATCOM is that the reactive power provision is independent from the actual voltage on the connection point. This can be seen in the diagram for the maximum currents being independent of the voltage in comparison to the SVC. This means, that even during most severe contingencies, the STATCOM keeps its full capability.
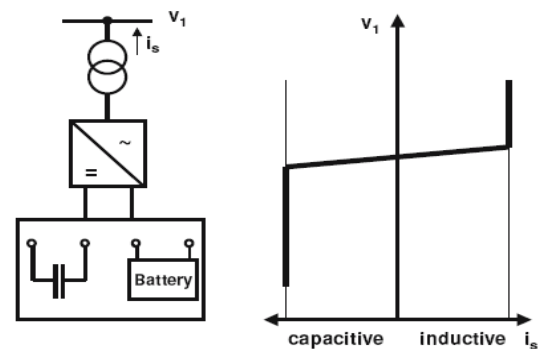

Figure 2. STATCOM structure and voltage / current characteristic

STATCOMs are based on Voltage Sourced Converter (VSC) topology and utilize either Gate-Turn-off Thyristors (GTO) or Isolated Gate Bipolar Transistors (IGBT) devices. The STATCOM is a very fast acting, electronic equivalent of a synchronous condenser. If the STATCOM voltage, Vs, (which is proportional to the dc bus voltage Vc) is larger than bus voltage, Es, then leading or capacitive VARS are produced. If Vs is smaller then Es then lagging or inductive VARS are produced.

4. Controlling Methods for an Inverter

In many industrial applications, it is often required to vary the output voltage of the inverter due to the following reasons:

➤ To compensate for the variations in the input voltage.

➤ To compensate for the regulation of the inverters.

➤ To supply some special loads which need variation of voltage with frequency, such as an induction motor.

The inverter output voltage can be controlled by various following techniques.

- ➢ Single pulse width modulation
- ➢ Multi pulse-width modulation.
- ➢ Minimum ripple current modulation
- ➢ Sinusoidal pulse width modulation (SINE-PWM).
- ➢ Selected harmonic elimination PWM (SHE-PWM).
- ➢ Space vector pulse width modulation (SVPWM).

4.1 Single Pulse Width Modulation

In single-pulse-width-modulation control, there is only one pulse per half cycle and the width of the pulse is varied to control the inverter output voltage. Here the gating signals are generated by comparing a rectangular reference signal of amplitude (A_r) with a triangular carrier wave of amplitude (A_c). The ratio of A_r to A_c is a control variable and is defined as the amplitude modulation index or modulation index M.

4.2 Multi Pulse Width Modulation

The harmonic contents can be reduced by using several pulses in each half-cycle of the output voltage. The generation of gating signals for turning on and off of the switching device is made by comparing a reference signal with a triangular carrier wave. The modulation index controls the output voltage. This type of modulation is also known as uniform pulse-width-modulation (UPWM).

The number of pulses per half cycle is found from p=F_c/2F_o= m_f/2(m_f is the frequency modulation ration or carrier ratio).

4.3 Minimum Ripple Current Modulation

One of the disadvantages of the harmonic injection PWM is that the elimination of lower order harmonics' considerably boosts the next higher level of harmonics. Since the harmonic loss in a machine is dictated by the ripple current, it is this parameter that should be minimized instead of emphasizing the individual harmonics.

4.4 Sinusoidal Pulse Width Modulation

Sinusoidal Pulse width modulation (PWM) techniques are effective means to control the output voltage frequency and magnitude. It has been the subject of intensive research during the last few decades. Especially, the space-vector PWM is used for three-phase converter applications. Here we mainly consider the carrier based PWM approaches that are often applied to the single phase applications.

Figure 3 is a general scheme of PWM modulation. In order to produce a sinusoidal voltage at desired frequency, say f_1, a sinusoidal control signal $V_{control}$ at the desired frequency (f_1) is compared with a triangular waveform $V_{carrier}$ as shown in Fig. 3(a), at each compare match point, a transition in PWM waveform is generated as shown in Fig. 3(b). When $V_{control}$ is greater than $V_{carrier}$, the PWM output is positive and When $V_{control}$ is smaller than $V_{carrier}$, the PWM waveform is negative.
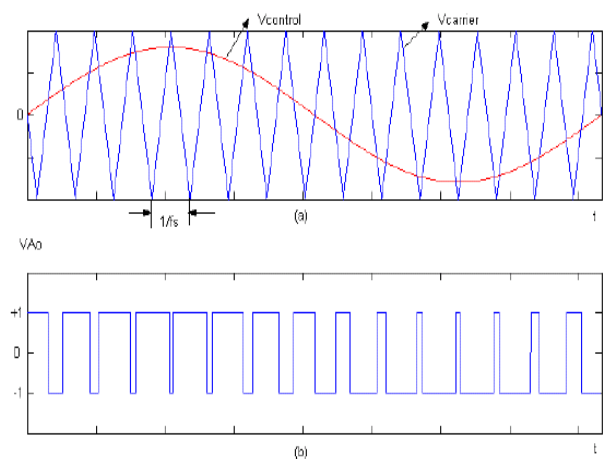

Fig. 3(a) Reference and carrier wave
Fig. 3(b) Pulses generated on comparison

The frequency of triangle waveform $V_{carrier}$ establishes the inverter's switching frequency f_s. We define the modulation index m_i as follows:

$$m_i = V_{control} / V_{tri} \tag{3}$$

where $V_{control}$ is the peak amplitude of the control signal and V_{tri} is the peak amplitude of the triangle signal (carrier). Also the frequency modulation ratio is defined as

$$m_f = f_s / f_1 \tag{4}$$

m_f is the ratio between the carrier and control frequency. The fundamental component $(V_{out})_1$ of the H bridge output voltage $(V_{out})_1$ has the property as depicted in equation below in a linear modulation region:

$$(V_{out})_1 = m_i * V_d \qquad m_i \leq 1.0 \qquad (5)$$

The equation (3) shows that the amplitude of the fundamental component of the output voltage varies linearly with the modulation index. The m_i value from zero to one is defined as the linear control range of sinusoidal carrier PWM.

4.5 Selected Harmonic Elimination PWM (SHE-PWM)

In the selected harmonic elimination PWM method the undesirable lower order harmonics of a square wave can be eliminated and the fundamental voltage can be controlled .

4.6 Space Vector Pulse Width Modulation

Space Vector Pulse Width Modulation (SVPWM) technique is the most advantageous technique than the conventional sinusoidal PWM technique for a multilevel inverter. The space vector pulse width modulation technique is an advanced, computation-intensive PWM method and is possibly the best among the all other PWM techniques. Unlike the conventional PWM method the space vector pulse width modulation technique produces lesser amount of harmonics. The total harmonic distortion (THD) of the output waveform is reduced by 47% than the sinusoidal PWM. The switching losses are reduced by 30%. The output crest voltage is increased by 1.115 times than that of the conventional sine-PWM method. If the inverter is used for the drives then this method gives higher torque and higher efficiency for the motors. It gives 15% better utilization of the DC bus voltage. It also reduces the switching as well as the commutation losses. It gives the maximum output voltage at the rated frequency. It also limits the duty cycle to the two thirds than the sine-PWM. On the whole it improves the inverter efficiency. The maximum phase-to-center voltage by sinusoidal and space vector PWM are respectively;

$V_{max} = V_{dc}/2$ for Sinusoidal PWM

$V_{max} = V_{dc}/\sqrt{3}$ for Space Vector PWM

where Vdc is DC-Link voltage.

This means that Space Vector PWM can produce about 15 percent higher than Sinusoidal PWM in output voltage. The Figure 2 shows the variation of the output voltage with sine-PWM and SVPWM techniques.
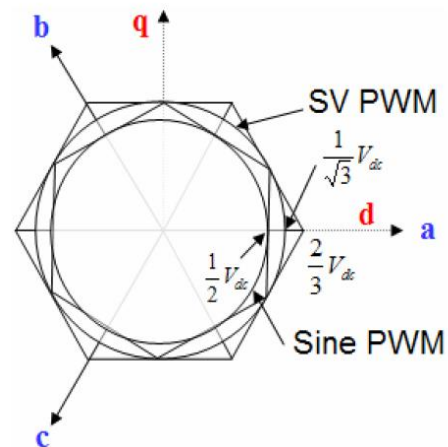

Fig. 4 Comparison of Sine-PWM and SVPWM

The basic principle of SVPWM depends on synthesizing the reference voltage vector by time averaging of the three nearest vector produced by the inverter. The reference voltage vector is the required command voltage which should be given to the application as required. The state of the inverter is nothing but a condition of the devices of the inverter which are whether on/off. Space vector pulse width modulation technique is based on the approximation of a rotating reference voltage space vector. The rotating reference voltage space vector in question represents the spatial vector sum of the three-phase voltage.

The implementation of the SVPWM technique involves many steps. They are mainly

- Transformation of 3-phase to 2-phase.
- Calculating the space vector voltage.
- Identifying the three nearest vectors
- Calculation of the dwelling times on the three nearest vectors.
- Determination of the switching instants.
- Giving the pulses to the inverter devices.

5. Sinusoidal PWM For a Three-Level Inverter

If the fundamental output voltage and corresponding power level of the PWM inverter are to be increased to a high value, the dc link voltage Vdc must be increased and the devices must be connected in series. By using matched devices in series, static voltage sharing may be somewhat easy, but dynamic voltage sharing during switching is always difficult. The problem may be solved by using a multi-level inverter or neutral point clamped (NPC), inverter..

Since the operation of all the phase groups is essentially identical, consider only the operation of the half-bridge for phase A. A pair of devices with bypass diodes is connected in series with an additional diode connected between the neutral point and the center of the pair as shown. The devices Sa1 and Sa2 function as main devices(like a two-level inverter), the Sa2 and Sa3 function as auxiliary devices which help to clamp the output potential to the neutral point with the help of clamping diodes D1 and D2. All the PWM techniques discussed so far can be applied to this inverter. The main devices (Sa1 and Sa4) generate the Va0 wave, whereas the auxiliary devices (Sa3 and Sa2) are driven complementary to the respective main devices. With such control, each output potential is clamped to the neutral potential in the off periods of the PWM control. Evidently, the positive phase current $+i_a$ will be carried by devices D1 and Sa2 at the neutral clamping condition. On the other hand, negative phase current $-i_a$ will be carried by D1 and D2 when Vao is positive, by Sa3 and Sa4 when Vao is negative, and by Sa3 and diode at the neutral clamping condition. This operation mode gives three voltage levels (+0.5Vdc, 0, and -0.5Vdc) at the Vao wave as shown in the figure of phase voltage below. Like wise the wave forms for all the other phases are generated and the resultant line-line voltages are obtained.

The implementation of a three-level inverter by sine-PWM is carried out by the same principle as that of a two-level inverter. Here we have two carrier waves are these two carrier waves are compared with the single sinusoidal wave and corresponding pulses are generated which are to be supplied to the inverter gate devices. And for the other phases the sinusoidal wave is displaced by an angle 2Π/3 and 4Π/3.

6. Space Vector Pulse Width Modulation For

Three-Level Inverter

There are altogether 27 switching states in a diode-clamped three-level inverter. They correspond to 19

voltage vectors (V_0 to V_{18}) whose positions are fixed. These space voltage vectors can be classified into 4 groups: large voltage vectors (V_{13}, V_{14}, etc...), medium voltage vectors (V_7, V_8, etc..) small voltage vectors (V_1, V_2, etc..), and zero voltage vectors (V_0).
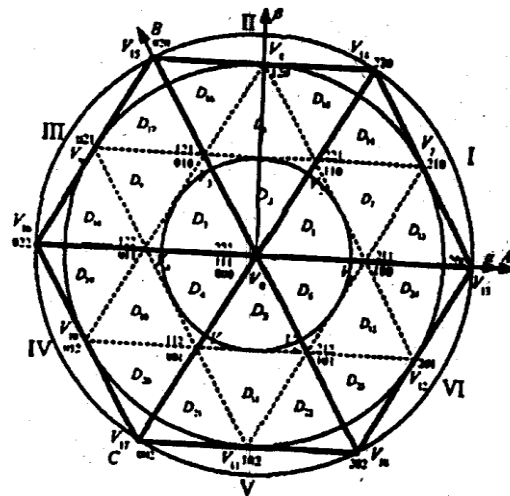

Fig. 5 Space vector hexagon for three-level inverter

The plane can be divided into 6 major triangular sectors (1-6) enclosed by solid lines by the large voltage vectors and zero voltage vector. Each major section represents pi/3 of the fundamental cycle. Within each major sector, there are 4 minor triangular sectors (enclosed by the dotted lines). There are totally 24 minor sectors in the plane. And the vertices of these sectors represent the voltage vectors. Notice table 2, each small voltage vector and zero voltage vector have 2 and 3 redundant switching states, respectively. This will be analyzed in the later section.

In three-phase three-level inverter, when the rotating voltage vector falls into one certain sector,

Table 2. 27 states for a three-level inverter

SWITCHING STATES	S_a	S_b	S_c	VOLTAGE VECTORS

S_1	0	0	0	V_0
S_2	1	1	1	V_0
S_3	2	2	2	V_0
S_4	1	0	0	V_1
S_5	1	1	0	V_2
S_6	0	1	0	V_3
S_7	0	1	1	V_4
S_8	0	0	1	V_5
S_9	1	0	1	V_6
S_{10}	2	1	1	V_1
S_{11}	2	2	1	V_2
S_{12}	1	2	1	V_3
S_{13}	1	2	2	V_4
S_{14}	1	1	2	V_5
S_{15}	2	1	2	V_6
S_{16}	2	1	0	V_7
S_{17}	1	2	0	V_8
S_{18}	0	2	1	V_9
S_{19}	0	1	2	V_{10}
S_{20}	1	0	2	V_{11}
S_{21}	2	0	1	V_{12}
S_{22}	2	0	0	V_{13}
S_{23}	2	2	0	V_{14}
S_{24}	0	2	0	V_{15}
S_{25}	0	2	2	V_{16}
S_{26}	0	0	2	V_{17}

S_{27}	2	0	2	V_{18}

adjacent voltage vectors are selected to synthesize the desired rotating voltage vector based on the vector synthesis principle, resulting in three-phase PWM waveforms. By the examination of the phase angle and the magnitude of a rotating reference voltage vector V*, the sector wherein V* resides can be easily located.

8. Simulation Results

Fig. 6 shows the simulink diagram of considered system without STATCOM. Three phase source is connected Fixed R-L Load through three phase V-I measurement block. Three phase fault is created during the time interval 0.1 to 0.2 sec.
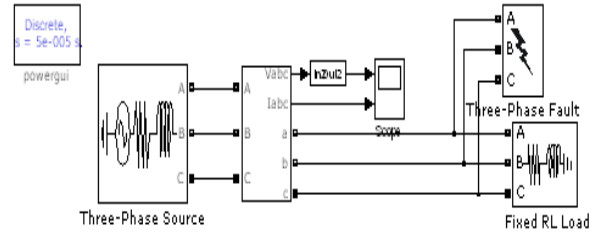

Fig. 6 Simulink Diagram of Considered System

Three phase output voltages and currents at source and harmonic analysis of currents are shown in Fig. 7 and Fig. 8 respectively.
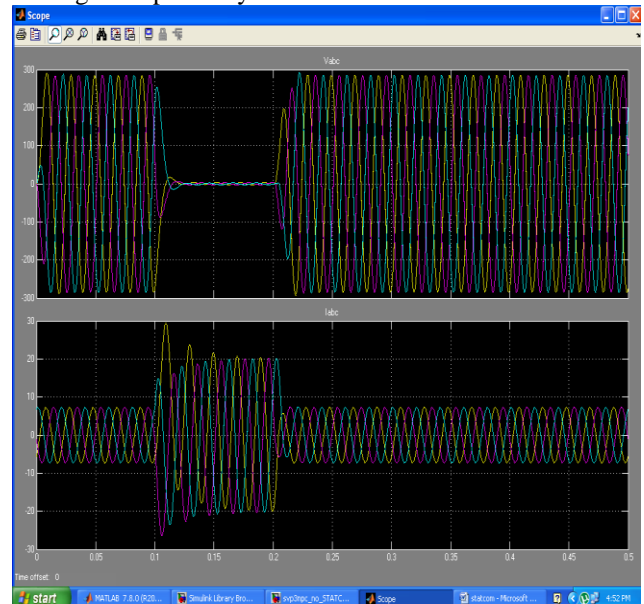
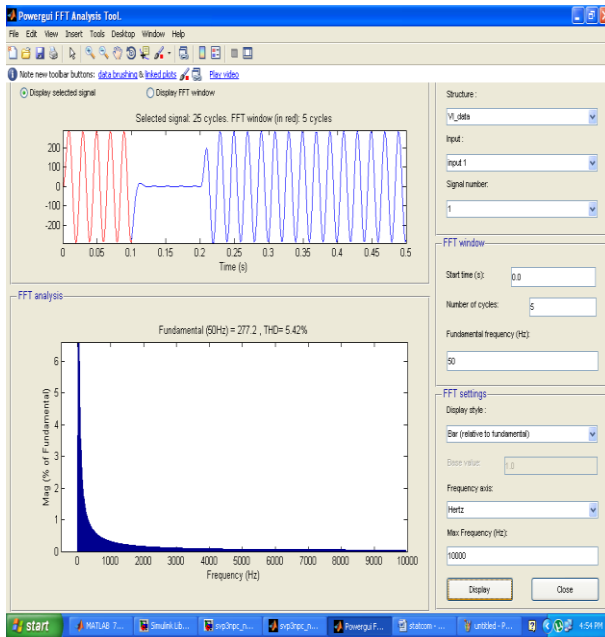**Fig. 7 Three phase voltages and currents at source**

Fig. 8 Harmonic analysis of sourece three phase currents

Three phase output voltages and currents at source and at STATCOM and harmonic analysis of currents with sinusoidal pulse width modulation are shown in Fig. 9 , Fig. 10 and Fig. 11 respectively.
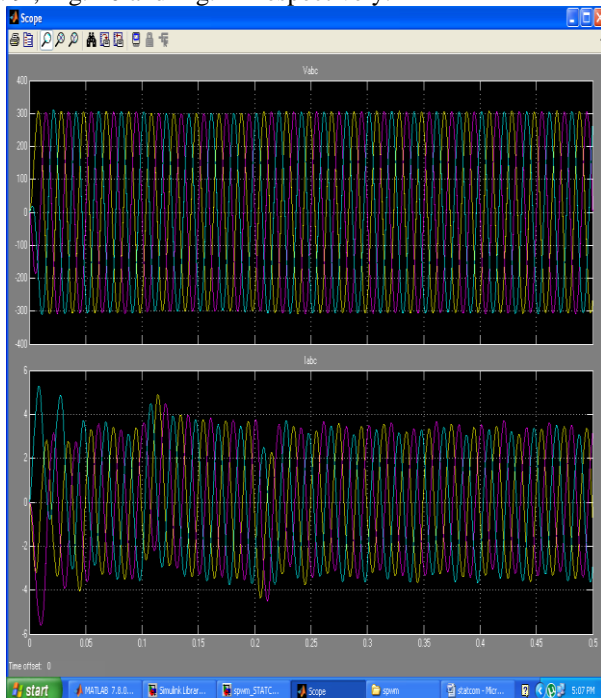

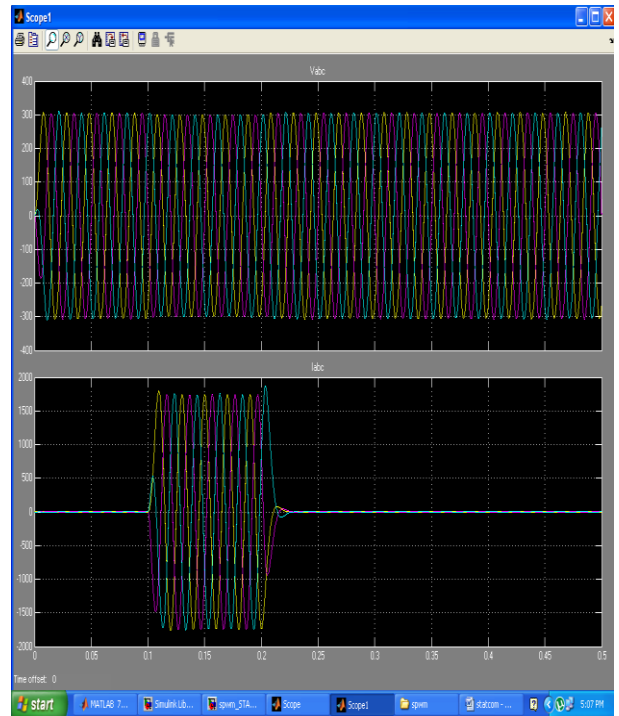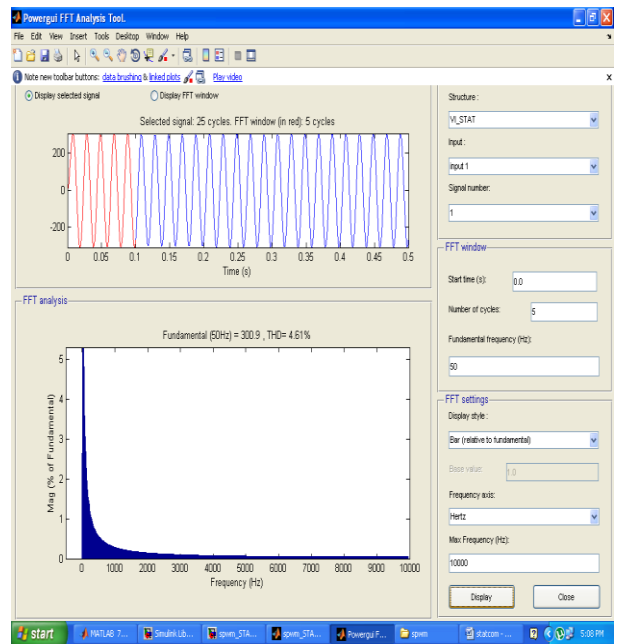**Fig. 9 Three phase voltages and currents at source**

Fig. 10 Three phase voltages and currents at STATCOM

Fig. 11 Harmonic analysis of sourece three phase currents

Three phase output voltages and currents at source and at STATCOM and harmonic analysis of currents

with sinusoidal pulse width modulation are shown in Fig. 12 , Fig. 13 and Fig. 14 respectively.
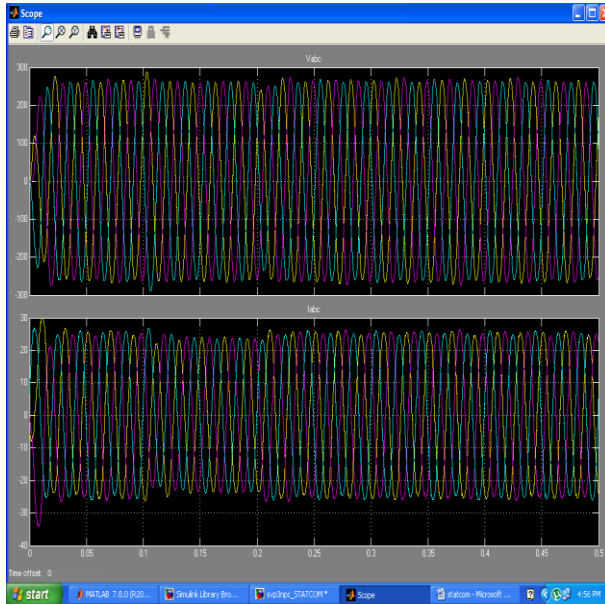

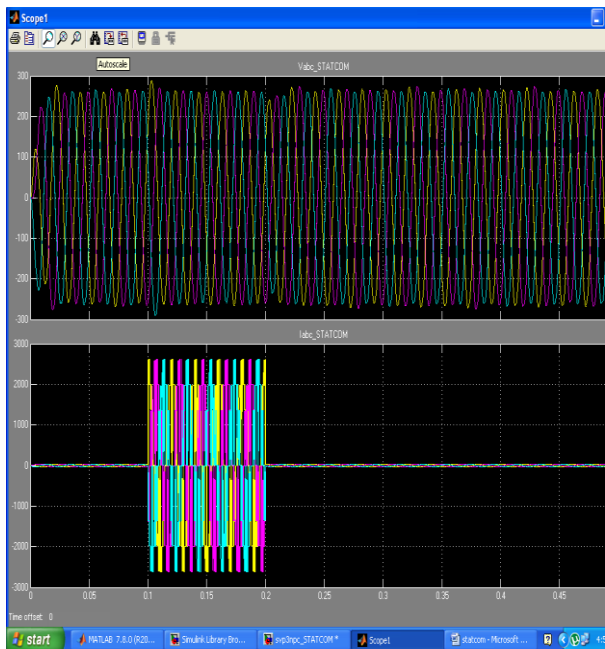**Fig. 12 Three phase voltages and currents at source**

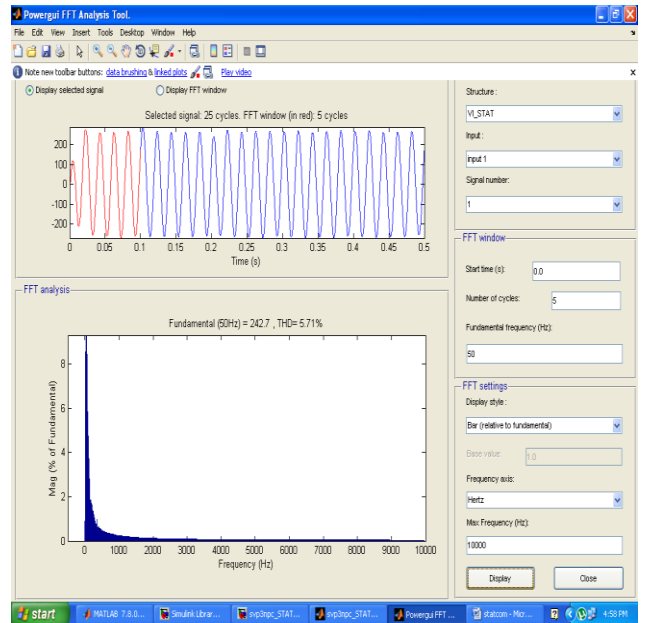**Fig. 13 Three phase voltages and currents at STATCOM**

Fig. 14 Harmonic analysis of sourece three phase currents

6. Conclusions

The space vector pulse width modulation technique is an advanced, computation-intensive PWM method and is possibly the best among the all other PWM techniques. Unlike the conventional PWM method the space vector pulse width modulation technique produces lesser amount of harmonics. The total harmonic distortion (THD) of the output waveform is reduced by 47% than the sinusoidal PWM. The switching losses are reduced by 30%.Without FACTS DEVICES, the line-line voltages drooped from 300Vph-ph to nearly 5Vph-ph and current reached from about 10A to 20A. With FACTS DEVICES, the line-line voltages maintained 300Vph-ph. Excess current and voltage generated and absorbed by STATCOM.

7.References

[1] Acha, V.G. Agelidis, O. Anaya-Lara and T.J.E. Miller, *Power Electronic Control in Electrical Systems,* England, Newnes, 2002.

[2] Ghosh and G.Ledwich, *Power quality enhancement using custom power devices*, London, Kluwer Academic Publishers, 2002.

[3] V.R. Dinavahi, M.R. Iravani and R. Bonert, "Real-time digital simulation and experimental verification of a D-STATCOM interfaced with a digital controller," *International Journal of Electrical Power & Energy Systems*,Vol. 26, No. 9, Nov. 2004, pp. 703-713.

[4] Akagi, Y. Kanazawa and A. Nabae, "Generalized theory of the instantaneous reactive power in three-phase circuits," *in Proc. of IEEE IPEC,* 1983, pp. 821-827.

[5] D.M. Divan, S. Bhattacharya and B. Banerjee, "Synchronous Frame Harmonic Isolator using Active Series Filter," in *Proc. of European Power Electronic Conference*, 1991, pp. 3030-3035.

[6] G.D. Marques, "A comparison of active power filter control methods in unbalanced and non-sinusoidal conditions," in *Proc. of IEEE IECON*, Vol. 1, 1998, pp. 444 – 449.

[7] V. Soares, P. Verdelho and G. D. Marques, "Active Power Filter Control Circuit Based on Instantaneous Active and Reactive Current id-iq Method," in *Proc. of IEEE PESC*, 1997, pp. 106-1101.

[8] P. K. Dash, D.P. Swain, A.C. Liew and S. Rahman, "An adaptive linear combiner for on-line tracking of power system harmonic," *IEEE Trans. on Power Systems*, January 1996, pp. 21-25.

[9] N. Pecharanin, "An application of neural network to harmonic detection in active filter," *in Proc. of WCCI-ICNN'94,* 1994, Vol. 6, No 684, pp. 3756.

[10] Pechanranin, H Uitsui and M. Sone, "Harmonic detection by using neural network," in *Proc. of IEEE International Conference on Neural Network,* 1995, Vol. 2, pp. 923-926.

[11] B.N. Singh, A. Chandra and K. Al-Haddad, "DSP-based indirect-current controlled STATCOM. I. Evaluation of current control techniques," *IEE Proceedings Electric Power Applications*, Vol. 147, no 2, March 2000, pp.107 - 112.