Power Quality Improvement using PWM based Active Front End Converter

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Abstract

The AC-DC power converters are widely used in various applications like power equipment, dc motor drives, front-end converters in adjustable-speed ac drives, slip power recovery of induction motors, HVDC transmission, SMPSs etc... The AC-DC conversion is accomplished by an uncontrollable diode bridge rectifier and phase controlled rectifier. These converters have simple structure and they offer high consistency [1]. But their major drawback is the discontinuity in supply current. This leads to presence of harmonics in higher proportion, poor power factor at supply side and reduction in average output voltage. To overcome these problems, the use of PWM techniques for controlling the state of active switches is becoming wide. The converter using such techniques is widely known as Active Front End Converter. This paper presents the power quality comparison of diode bridge rectifier, phase control rectifier & active front end converter operated by SPWM and SVPWM control techniques. The simulation results of the presented techniques have been demonstrated, compared with hardware and then conclusion is drawn from the comparison.

Keywords:*AFE, SPWM, SVPWM,*

INTRODUCTION

The continuous development of the power and microelectronics devices sustains repeated development in design and awareness of modern adjustable speed drives & DC link converter. The interest of researchers is in the realization of advanced AC/DC line-side converters called active front end converter (AFE converter).These active front-end rectifiers due to their properties systematically displace the diode & SCR bridges by becoming an important part of the modern frequency converters for the intelligent motion control applications [2].Phase control and commutation of semiconducting devices impact the phase displacement between the first harmonics of the consumed current and the first harmonics of the supply voltage. This displacement leads to poor power quality like power factor degradation and current harmonics which cause non-sinusoidal voltage drops on the supply network impedances and lead to supply voltage deformation. This may cause malfunctions of other devices that are sensible to the sinusoidal shape of the supply voltage [3].The power factor can also be controlled by this technique and there are minimal effects on the supply network. The size of filter required by the PWM converters is generally small under balanced supply voltage.

I. ACTIVE FRONT END (AFE) CONVERTER

Active Front End Converter refers to the power converter system consisting of the line-side converter with active switches such as IGBTs, MOSFETs GTOs and the dc link capacitor bank as shown in Fig. 1. The AFE converter normally functions as a rectifier. But, during regeneration it can also be operated as an inverter, feeding power back to the line. The line-side converter is popularly referred to as a PWM rectifier in the literature. This is due to the fact that, with active switches, the rectifier can be switched using a suitable pulse width modulation technique[4].

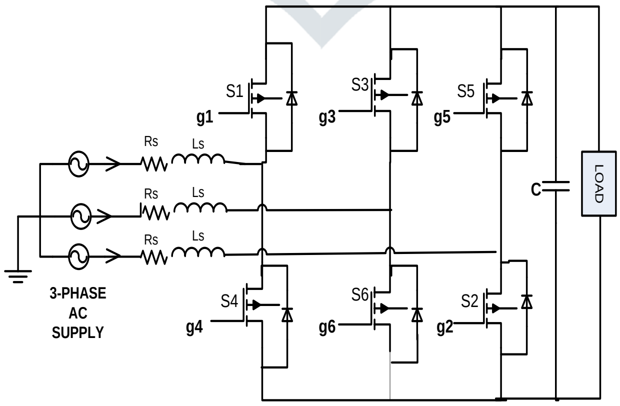

Fig. 1: *3-phase Active Front End (AFE) Converter*

II. PWM TECHNIQUES FOR AFE CONVERTER

The main aim of the PWM techniques used in the AC/DC line-side converters is to control the amplitudes of harmonics of converter input PWM three-phase voltages. Also,to correct the shape of the line current harmonic spectrum. Many PWM techniques have been developed depending on the necessities. The choice of the particular PWM technique arises from the desired performance of the synchronous rectifiers. Generally PWM techniques for frequency converters may be classified as follows: Sinusoidal PWM, Hysteresis-Band PWM, Space Vector PWM, Selected Harmonic Elimination PWM, Minimum Current Ripple PWM, Sinusoidal PWM with Instantaneous Current Control and Random PWM. This paper presents basic assumptions and applications of selected, most frequently used modulation techniques applied to PWM rectifiers. For the comparative analysis of the Active Front End, line-side converter has been chosen to examine the proposed modulation methods. Here we have considered two PWM techniques:

1. Sinusoidal Pulse-Width Modulation (SPWM)
2. Space Vector PWM (SVPWM)

III. SINUSOIDAL PULSE-WIDTH MODULATION

Sinusoidal Pulse-Width Modulation is based on the comparison of the converter voltage reference sine signals having frequency of 50 Hz with the carrier signal of the triangular shape having frequency in thousands of Hertz. When the amplitude of reference wave is higher than the amplitude of carrier wave, gate pulses are obtained. The width of each pulse is varied in proportion to the amplitude of a reference sine signal. The realization of the Sinusoidal Pulse-Width Modulation is shown in Fig. 2.

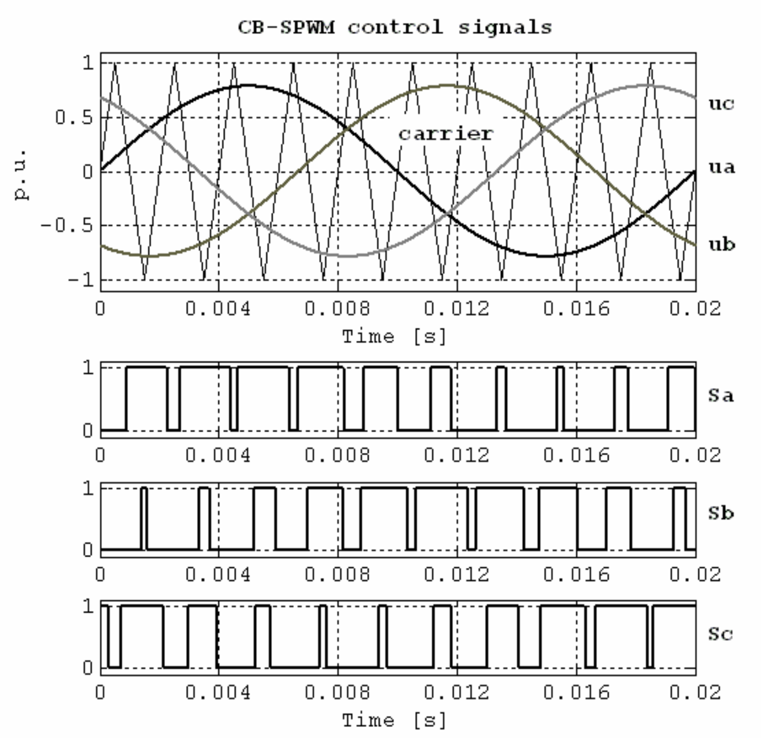

Fig. 2*: Sine Pulse Width Modulation (SPWM)*

IV. SPACE VECTOR PWM (SVPWM)

To understand the Space vector modulation theory, the concept of a rotating space vector is very important.

The idea of space vectors is derived from the rotating field of AC machine. In this modulation technique the three phase quantities can be transformed to their equivalent 2-phase quantity either in synchronously rotating frame or stationary frame. From this 2-phase component the reference vector magnitude can be found and used for modulating the control signals. The process for obtaining the rotating space vector is explained in the following section, considering the stationary reference frame

For example, if the three-phase sinusoidal and balanced signal is given by equation

$$Va=Vm sin\omega t \quad (1)$$

$$Vb=Vm \sin(\omega t-2\pi/3) \quad (2)$$

$$Vc=Vm sin(\omega t+2\pi/3) \quad (3)$$

$$Vref=2/3[Van+\alpha Vbn+\alpha^2 Vcn] \quad (4)$$

Where, $\alpha = e^{j\frac{2\pi}{3}}$

They generate a rotating flux in the air gap of the AC machine. This rotating flux element can be represented as a single rotating voltage vector. The magnitude and angle of the rotating vector can be found by the mean of Clark's Transformation. The representation of rotating vector in complex plane is shown in Fig. 3.

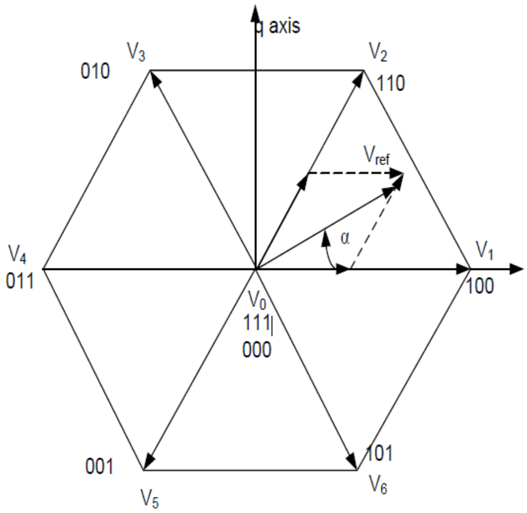

Fig. 3: *Space vector diagram*

From equation (4), it can be seen that the space vector *Vref*with magnitude *Vm*rotatesin a circular orbit at angular velocity *ω,* where the direction of rotation depends on the phase sequence of voltages. With the sinusoidal three phase command voltages, the composite PWM fabrication at the converter input should be such that the averagevoltage follows these command voltage with minimum amount of harmonic distortion [5].

V. SVPWM IMPLEMENTATION

The space vector PWM can be implemented by the following steps:

Step1. Determine Vd, Vq, Vref, and angle (α)

Step2. Determine time duration T1, T2, T0

Step3. Determine the switching time of each switches

Step1. Determine Vd, Vq, Vref, & angle (α)

Fig. 4 shows the conversion of 3-phase to 2-phase quantity

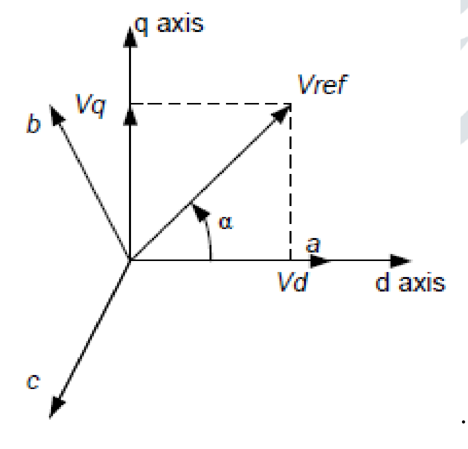

Fig. 4*: Voltage Space Vector and its d, q axis*

$$Vd = Van - Vbn*\cos 60 - Vcn * \cos 60$$

$$= Van - \ Vbn - \ Vcn \qquad (5)$$

$$Vq = Vbn * \cos 30 - Vcn * \cos 30$$

$$= \ Vbn - \ Vcn \qquad (6)$$

Therefore,

$$\begin{bmatrix} V_d \\ V_q \end{bmatrix} = \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & -\frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} V_{cn} \\ V_{bn} \\ V_{cn} \end{bmatrix} \qquad (7)$$

$$\left| V_{ref} \right| = \sqrt{V_d^{\ 2} + V_q^{\ 2}} \qquad (8)$$

$$\alpha=\tan^{(-1)}\left(\frac{V_d}{V_q}\right)=2\omega fst=\omega_s t \qquad (9)$$

Where f_s is Fundamental frequency

The voltage *Vd*, *Vq*, *Vref*, and angle α are calculated by using the above equations (7-9).

Step 2: Determine time duration T1, T2, T0

The principle of SVPWM method is that the command voltage vector is approximately calculated by using three adjacent vectors. The duration of each voltage vectors is obtained by using voltage time equation (10) of vector calculation:

$$T_1V_1 + T_2V_2 + T_oV_o = T_sV_{ref} \qquad (10)$$

$$T_1 + T_2 + T_0 = Ts \qquad (11)$$

Where V_1, V_2 and V_0 are vectors that define the triangle region in which Vref is located. T1, T2 and T0 are the corresponding vector durations and Ts is the sampling time. The magnitude of voltage vector is,

$V_1=V_2=V_3=V_4=V_5=V_6=$ Vdc

Switching time duration calculation in sector 1 is : In sector 1 Vref between three nearest voltage vector V_0 V_1, and V_2. The Magnitude and angle of adjustment voltages are:

$$V_0=0, \qquad V_1=\frac{2}{3}V_{dc}\times e^{j0}, \qquad V_2=\frac{2}{3}V_{dc}\times e^{j\frac{\Pi}{3}}$$

So voltage equation is,

$$T_1\left(\frac{2}{3}V_{dc}*e^{j0}\right)+T_2\left(\frac{2}{3}V_{dc}*e^{j\frac{P}{3}}\right)+T_0(0)=TsV_{ref}*e^{ja} \qquad (12)$$

Therefore,

$$\text{Re:}\ T_1\left(\frac{2}{3}V_{dc}*\cos 0\right)+T_2\left(\frac{2}{3}V_{dc}*\cos\frac{\pi}{3}\right)=TsV_{ref}*\cos\alpha \qquad (13)$$

$$\text{Im;}\ T_1\left(\frac{2}{3}V_{dc}*\sin 0\right)+T_2\left(\frac{2}{3}V_{dc}*\sin\frac{\pi}{3}\right)=TsV_{ref}*\sin\alpha \qquad (14)$$

and,

$$T_1+T_2+T_3=Ts \qquad (15)$$

Solving equations (13), (14) and (15) we get,

$$T_1=Ts*\left(\frac{|V_{ref}|}{\frac{2}{3}V_{dc}}\right)*\left(\frac{\sin\left(\frac{\pi}{3}-\alpha\right)}{\sin\frac{\pi}{3}}\right) \qquad (16)$$

$$T_2=Ts*\left(\frac{|V_{ref}|}{\frac{2}{3}V_{dc}}\right)*\left(\frac{\sin\alpha}{\sin\frac{\pi}{3}}\right) \qquad (17)$$

and,

$$T_0=T_S-T_1-T_2$$

Similarly, by doing switching time duration calculation for all sectors, the reference signal is generated.

Step 3: Determine the switching time of each switches

For a switching of AFE converter switches, different switching pattern like symmetrical & asymmetrical switching pattern are possible. Here, we have used symmetrical switching pattern. Figure 5 shows symmetrical switching patterns for each sector.

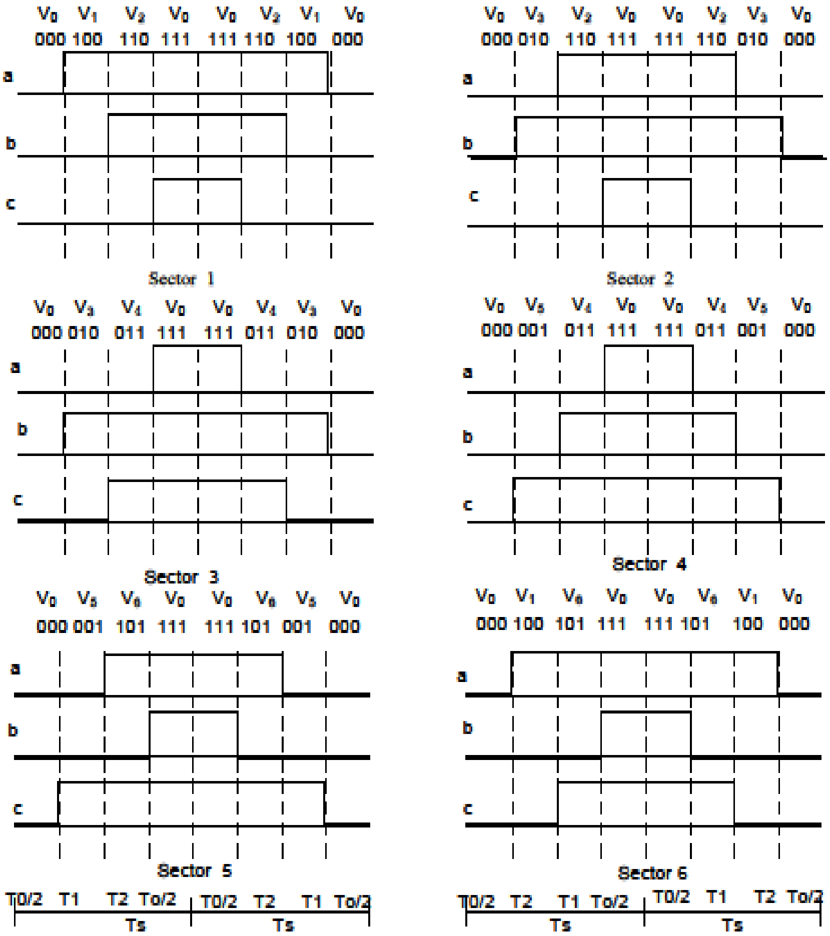

Fig. 5: *SVPWM switching patterns at each sector*

Based on **Fig. 5**, the switching time at each sector is summarized in Table 1, and it will be built in SIMULINK model to implement SVPWM

Table 1:*Switching Time Calculation at each sector*

Sector	Upper Switches(S1, S3, S5)	Lower Switches(S4, S6, S2)
1	$S1 = T_1 + T_2 + T_0/2$ $S3 = T_2 + T_0/2$ $S5 = T_0/2$	$S4 = T_0/2$ $S6 = T_1 + T_0/2$ $S2 = T_1 + T_2 + T_0/2$
2	$S1 = T_1 + T_0/2$ $S3 = T_1 + T_2 + T_0/2$ $S5 = T_0/2$	$S4 = T_2 + T_0/2$ $S6 = T_0/2$ $S2 = T_1 + T_2 + T_0/2$
3	$S1 = T_0/2$ $S3 = T_1 + T_2 + T_0/2$ $S5 = T_2 + T_0/2$	$S4 = T_1 + T_2 + T_0/2$ $S6 = T_0/2$ $S2 = T_2 + T_0/2$
4	$S1 = T_0/2$ $S3 = T_1 + T_0/2$ $S5 = T_1 + T_2 + T_0/2$	$S4 = T_1 + T_2 + T_0/2$ $S6 = T_2 + T_0/2$ $S2 = T_0/2$
5	$S1 = T_2 + T_0/2$ $S3 = T_0/2$ $S5 = T_1 + T_2 + T_0/2$	$S4 = T_2 + T_0/2$ $S6 = T_1 + T_2 + T_0/2$ $S2 = T_0/2$
6	$S1 = T_1 + T_2 + T_0/2$ $S3 = T_0/2$ $S5 = T_1 + T_0/2$	$S4 = T_0/2$ $S6 = T_1 + T_2 + T_0/2$ $S2 = T_1 + T_0/2$

VI. SVPWM BASED SWITCHING STATES

The circuit model of a typical three-phase AFE converter is shown in Fig. 6, S1 to S6 are the six power switches that shape the input current, which are controlled by the switching variables g1, g2, g3, g4, g5 and g6. When an upper switch is switched on, i.e., when g1, g3 or g5 is 1, the corresponding lower switch is switched off, i.e., the corresponding g4, g6 or g2 is 0.Therefore, the on and off states of the upper switches S1, S3 and S5 can be used to determine the output voltage. Switching states are indicated in Table 2.

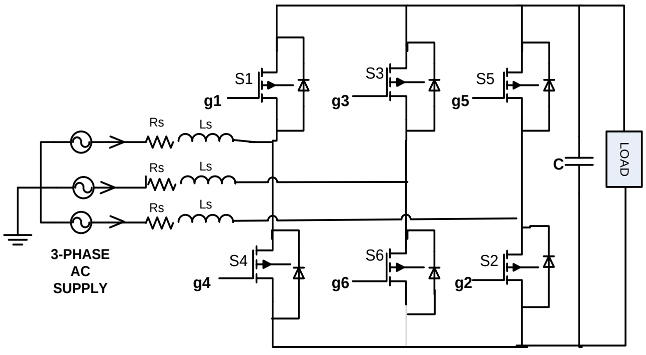

Fig. 6: *3-φ Active Front End Converter*

Table 2: *Definition of Switching States*

Switching State	Leg A		Leg B		Leg C	
	S1	**S4**	**S3**	**S6**	**S5**	**S2**
1	On	Off	On	Off	On	Off
0	Off	On	Off	On	Off	On

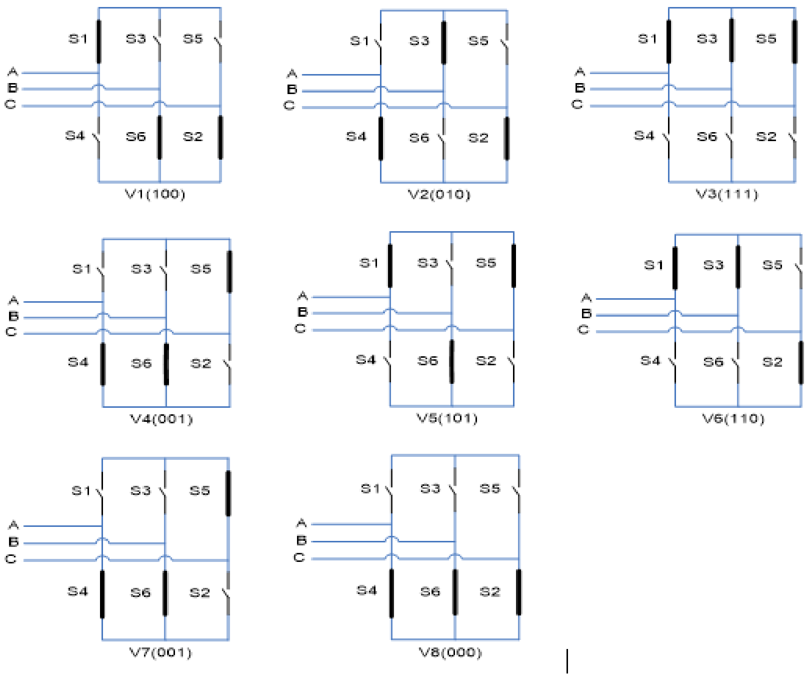

Fig. 7*: Switching States for SVPWM*

Table 3 gives summary of switching states and corresponding phase-to-neutral voltages of an isolated neutral machine

Table 3: *Summary of switching states*

State	**ON Devices**	***Van***	***Vbn***	***Vcn***	**Space voltage vector**
0	S4 S6 S2	0	0	0	$V0$ = (000)
1	S1 S6 S2	(2/3)Vdc	-(1/3)Vdc	-(1/3)Vdc	$V1$ = (100)
2	S1 S3 S2	(1/3)Vdc	(1/3)Vdc	-(2/3)Vdc	$V2$ = (110)
3	S4 S3 S2	-(1/3)Vdc	(2/3)Vdc	-(1/3)Vdc	$V3$ = (010)
4	S4 S3 S5	-(2/3)Vdc	(1/3)Vdc	(1/3)Vdc	$V4$ = (011)
5	S4 S6 S5	-(1/3)Vdc	-(1/3)Vdc	(2/3)Vdc	$V5$ = (001)
6	S1 S6 S5	(1/3)Vdc	-(2/3)Vdc	(1/3)Vdc	$V6$ = (101)
7	S1 S3 S5	0	0	0	$V7$ = (111)

VII. AFE IMPLEMENTATION

Fig. 8 shows the block diagram of AFE converter implementaion. AFE converter controlled using either SPWM or SVPWM techniques.

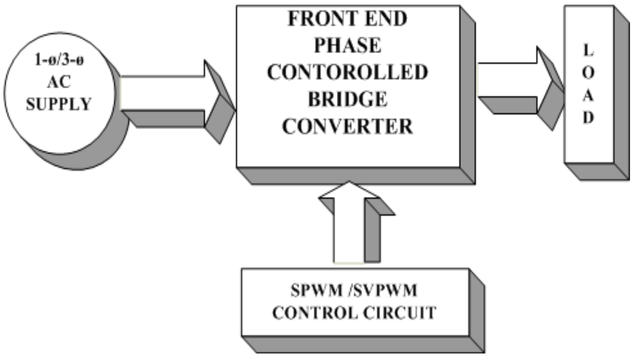

Fig. 8: *Block diagram of AFE converter*

VIII. SIMULATION RESULTS

We have done the simulation of AFE converter in PSIM software and the results obtained are shown below. We have obtained the results for diode bridge rectifier for solely for comparison. Simulation and Hardware parameters are specified in Table 4.

Table 4. *Simulation Parameter*

Parameter	Value
Supply Voltage Vs	440V
Source Resistance Rs	1 to 1.5 ohm
Source Inductance Ls	0.2mH
Filter Capacitor Cf	470uF
Load Resistance R_L	5 ohm
Switching Frequency Fs	1500 to 5000 Hz
Modulation Index MI	0.88

Results of Uncontrolled front end converter:

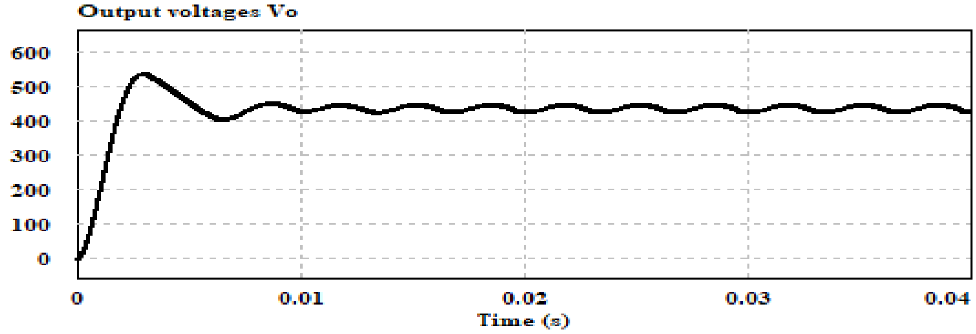

Fig. 9: *Output Voltage of uncontrolled converter*

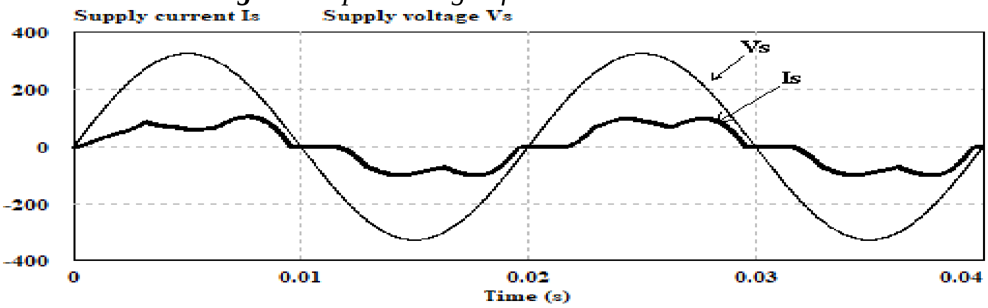

Fig. 10*: Supply voltage and Current of converter*

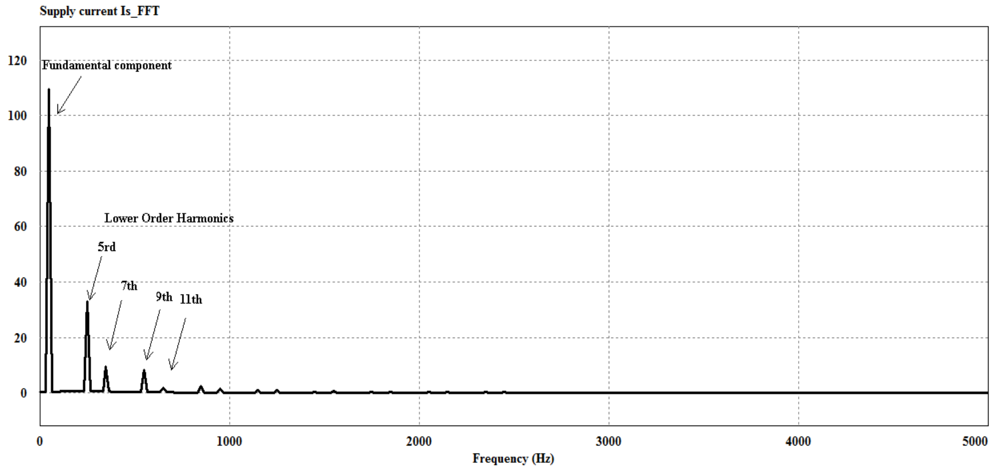

***Fig. 11**: FFT Analysis of Supply Current*

Results of Acive Front End (AFE) using Sine PWM :

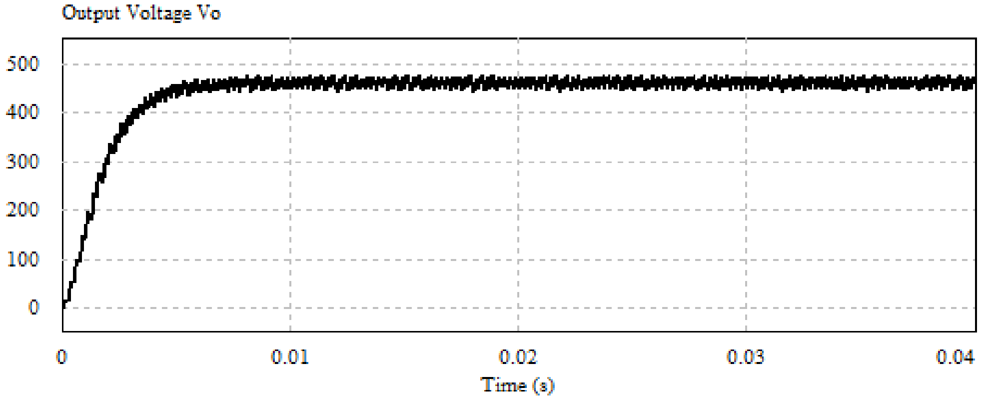

***Fig. 12:** Output Voltage of AFE using SPWM*

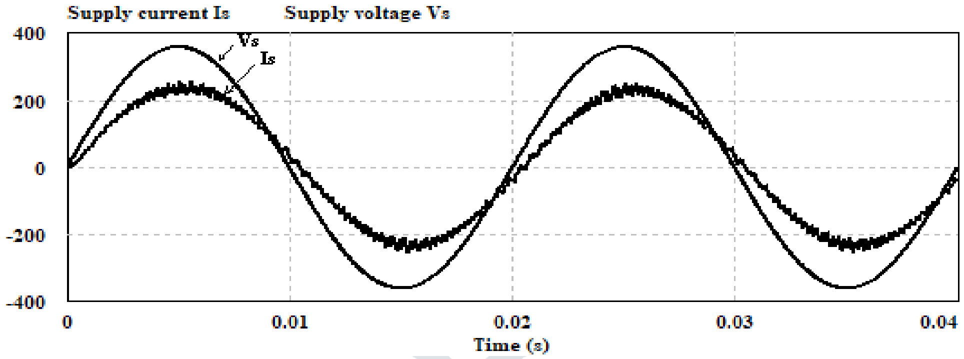

***Fig. 13:**Supply Voltage and Current of AFE Converter*

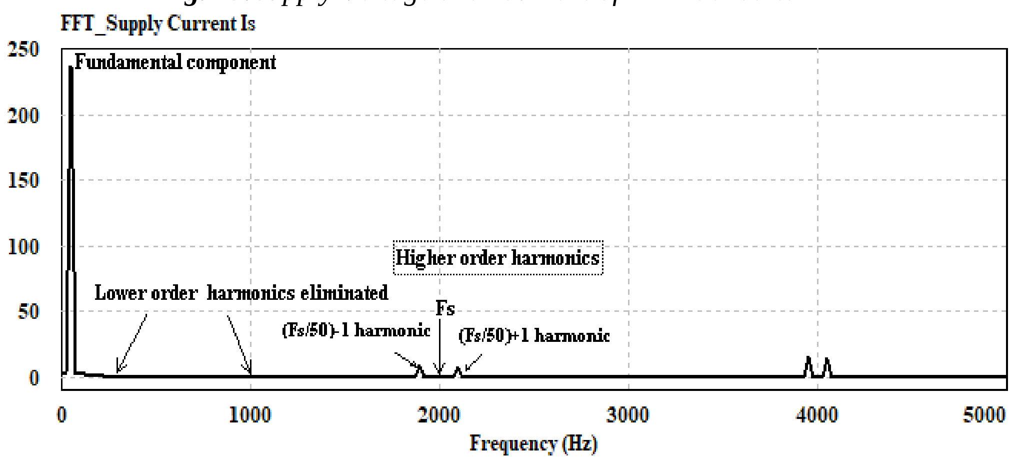

***Fig. 14:**FFT Analysis of Supply Current*

Results of Acive Front End (AFE) using SVPWM

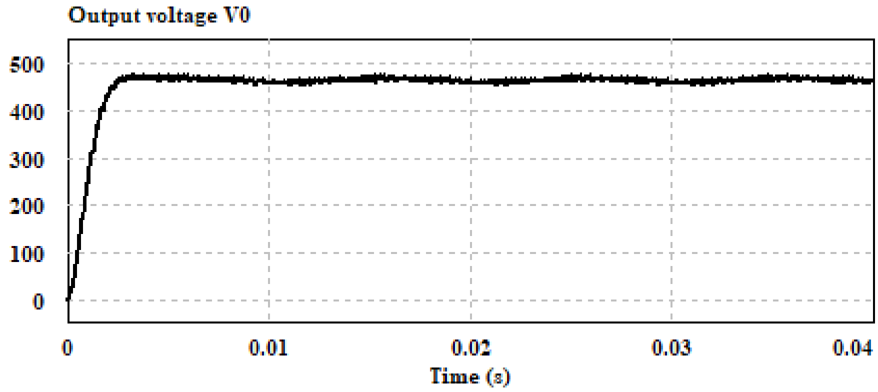

Fig. 15:*Output Voltage of AFE using SVPWM*

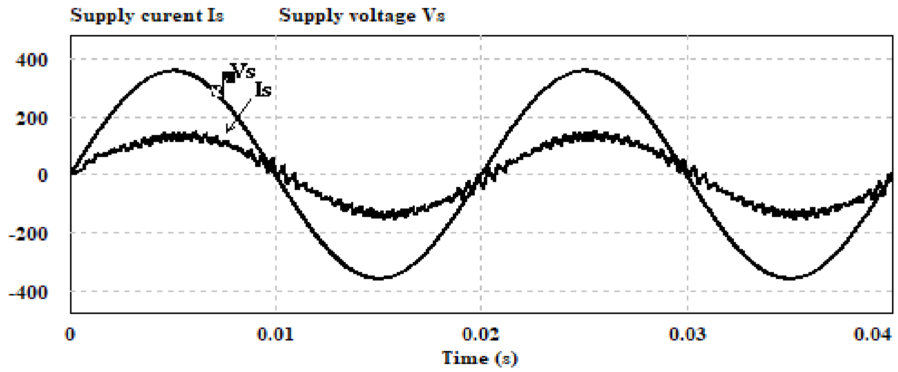

Fig. 16:*Supply Voltage and Current of AFE Converter*

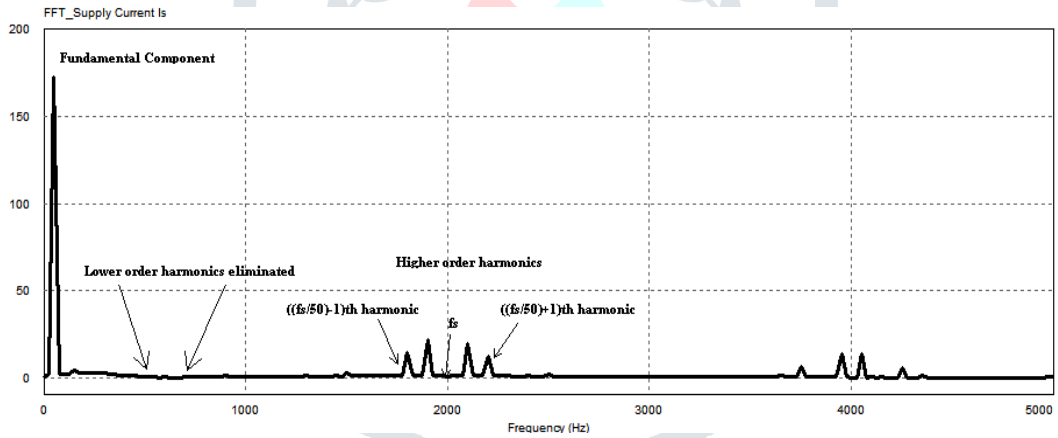

Fig. 17:*FFT Analysis of Supply Current*

IX. RESULTS EVALUATION SUMMARY

The results for Uncontrolled front end converter &Active Front End converter using SPWM / SVPWM are summarised in Table 5.

Table 5: *Result Evalution of front end converter*

Sr. No	Front End converter Topology	Lower order Harmonics	Supply current THD	Output voltage Vo
1	Uncontrolled front end converter	5^{th} , 7^{th} …….	0.243	430V
2	AFE converter using SPWM	fs$\pm$1,2fs …	0.124	456V
3	AFE converter using SVPWM	fs$\pm$1,2fs …	0.262	465V

CONCLUSIONS

The performance analysis of AFE converter & uncontrolled front end converter is done in PSIM software. From the simulation results and evalution **Table 5**, it can be concluded that using PWM based AFE converter, supply current lower order harmonicswhich are present in uncontrolled front end converter, can be eliminated, also supply power factor, supply current and supply voltage power quality and output voltage can be improved using AFE converter with the help of SPWM/ SVPWM techniques. Also, by using SVPWM AFE converter, average output voltage is higher as compared to SPWM AFE converter.

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