Investigation of Various PWM Techniques for Shunt Active Filter

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***Abstract*—**Pulse width modulation (PWM) techniques have been the subject of intensive research for different industrial and power sector applications. A large variety of methods, different in concept and performance, have been newly developed and described. This paper analyzes the comparative merits of Sinusoidal Pulse Width Modulation (SPWM) and Space Vector Pulse Width Modulation (SVPWM) techniques and the suitability of these techniques in a Shunt Active Filter (SAF). The objective is to select the scheme that offers effective utilization of DC bus voltage and also harmonic reduction at the input side. The effectiveness of the PWM techniques is tested in the SAF configuration with a non linear load. The performance of the SAF with the SPWM and (SVPWM) techniques are compared with respect to the THD in source current. The study reveals that in the context of closed loop SAF control with the SVPWM technique there is only a minor improvement in THD. The utilization of the DC bus with SVPWM is also not significant compared to that with SPWM because of the non sinusoidal modulating signal from the controller in SAF configuration.

***Keywords*—**Voltage source inverter, Shunt active filter, SPWM, SVPWM, Matlab/SIMULINK.

I. Introduction

NON-LINEAR loads draw currents that are non-sinusoidal and thus create voltage drops in distribution conductors that are non-sinusoidal. Typical non-linear loads include rectifiers, variable speed drives, any other loads based on solid-state conversion. Transformers and reactors may also exhibit non-linear behaviour in a power system during over voltage conditions. Harmonics create many concerns for utilities and customers alike. Typical phenomena include neutral circuit overloading in three-phase circuits, motor and transformer overheating, metering inaccuracies and control system malfunctions. In order to meet the increasing reactive power demands reactive power compensation has been recognized as an efficient and economic means of increasing power transmission capability. The objective is to achieve effective utilization of DC bus voltage and harmonic reduction in SAF based system. The paper aims to investigate the various PWM techniques and assess the suitability of the technique for SAF with respect to output voltage and THD.

Different PWM techniques and their characteristics have been widely reported in literature [1]. The two most widely used PWM schemes for multilevel inverters are the carrier-based sine-triangle PWM (SPWM) technique and the space vector PWM (SVPWM) technique. These techniques have been extensively studied and compared for their performance in two level inverters [1, 2]. It is shown in these studies that the SVPWM technique inherits several advantages over SPWM such as minimizing THD, effective utilization of DC bus voltage, etc. However, the modulating signal is a pure sinusoidal waveform. The focus of this paper is to investigate various PWM techniques for SAF with non-linear loads where the modulating signal is non-sinusoidal. Performance comparison of various PWM techniques for SAF is not available in the literature. The reference papers [1-4] reveal that with the same Vdc the utilization of the dc bus is better in SVPWM and so the maximum output voltage is 15% greater than that with the SPWM. The results of this study reveal that for the same Vdc magnitude the SVPWM technique exhibits improved performance characteristics compared to SPWM in a general context. However, the improvement is not significant when the techniques are applied to SAF control. Thus a new outlook is provided here with respect to the choice of PWM scheme in the context of control schemes for SAF.

II. Theory of SAF for Non-Linear Load

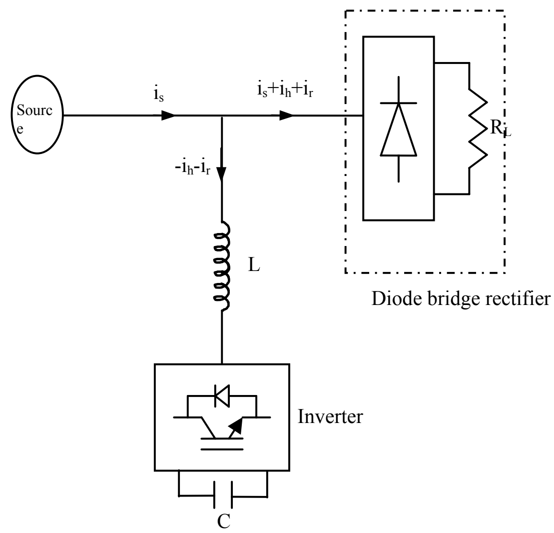

Fig. 1 SAF with Non-linear

One of the most popular active filters used for compensating reactive power and harmonics is the "shunt active filter" [3] shown in Fig. 1. The simple SAF arrangement with non-linear load is considered. The system comprises balanced three-phase voltage sources (VR, VY, VB) feeding a three-phase diode bridge rectifier with resistive load. The SAF is connected to the three-phase line through the inductor L. The converter employed for the SAF is an IGBT based converter, it is a current controlled voltage source inverter which is connected in parallel with the load. This inverter injects an appropriate current into the system to compensate for the undesired components of load current that are responsible for low power factor. The performance of an active filter depends mainly on the technique used to compute the reference current, design of the inverter and the control method used to inject the desired compensation current into the line. The dc side of the converter is connected to a dc storage capacitor, whose voltage can be raised or lowered by controlling the converter. For controlling the inverter output, firing pulses are generated by the control circuit. The input signals of the control circuit are the reactive power demand (i_r) and harmonic component (i_h). For purely reactive compensation, the current injected is in phase quadrature to the respective phase voltage at the point of connection to the power system.

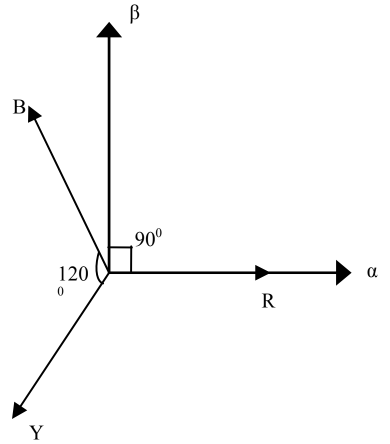

Fig. 2 Frame transformation from abc to α β

The quality problem in rectifier is to draw input current at unity power factor. The control problem in SAF is to provide compensation for the harmonic currents injected by the load. SAF is required for installations where an existing nonlinear load pollutes the line with undesired harmonic currents for which the SAF is supposed to provide a short circuit path. The basic function of SAF is to provide the harmonic current demand locally, so that the input source supplies only the fundamental component of the load current.

III. Control Aspects and Mathematical Model

Reference frame theory based d-q model of SAF is presented in this section. While dealing with instantaneous voltages and currents in three phase circuits mathematically, it is adequate to express their quantities as the instantaneous space vectors. Vector representation of instantaneous three phase quantities R, Y and B which are displaced by an angle 2π/3 from each other is shown in Fig. 2. The instantaneous current and voltage space vectors are expressed in terms of instantaneous voltages and currents as.

$$\mathrm{v} = \left[v_R \; v_Y \; v_B\right]^T \tag{1}$$

$$\mathrm{i} = \left[i_R \;\; i_Y \;\; i_B\right]^T \tag{2}$$

Instantaneous voltages and currents on the RYB coordinates can be transformed into the qudrature α, β coordinates by Clarke Transformation as follows:

$$\begin{bmatrix} v_\alpha \\ v_\beta \\ v_o \end{bmatrix} = T_1 \begin{bmatrix} v_R \\ v_Y \\ v_B \end{bmatrix}$$

$$\begin{bmatrix} i_\alpha \\ i_\beta \\ i_o \end{bmatrix} = T_1 \begin{bmatrix} i_R \\ i_Y \\ i_B \end{bmatrix}$$

where

$$T_1 = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \\ \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \end{bmatrix} \tag{3}$$

Since in a balanced three-phase three-wire system neutral current is zero, the zero sequence current does not exist. Hence the voltages and currents in the α-β reference frame can be expressed as shown in equation 4 & 5.

$$\begin{bmatrix} v_\alpha \\ v_\beta \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & -\frac{\sqrt{3}}{2} & \frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} v_R \\ v_Y \\ v_B \end{bmatrix} \tag{4}$$

These voltages in α-β reference frame can further be transformed into rotating d- q reference frame as

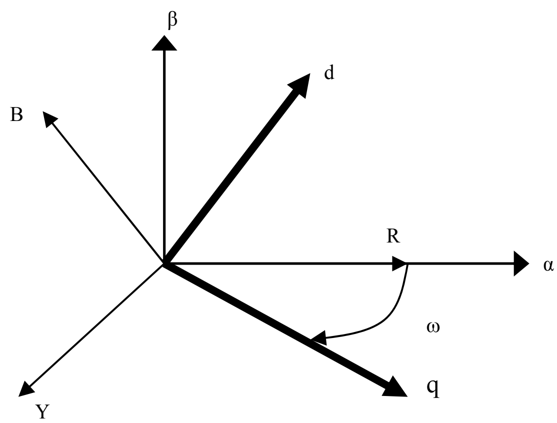

Fig 3 α β to dq transformation

$$\begin{bmatrix} v_d \\ v_q \end{bmatrix} = T_2 \begin{bmatrix} v_\alpha \\ v_\beta \end{bmatrix} \tag{5}$$

where $T_2 = \begin{bmatrix} \cos\omega_r & -\sin\omega_r \\ \sin\omega_r & \cos\omega_r \end{bmatrix}$

where ωr is the angular velocity of the d- q reference frame (Fig. 3). The current components in the d- q reference frame can be similarly obtained using the α-β to d-q transformation matrix T2. The unit vector required for this transformation is generated using the stepped down grid voltages as described in [6].

IV. Modelling of STATCOM

A simple arrangement of STATCOM as SAF with non-linear load is considered. The source voltages (V_R, V_Y, V_B) and the inverter output voltages (V_{R1}, V_{Y1}, V_{B1})as shown in Fig. 4. The inverter output is connected through the inductor L and resistor R to the source side. The source voltage can be expressed as follows

$$v_R = i_1 R + L\, di_1/dt + v_{R1} \quad (6)$$

$$v_Y = i_2 R + L\, di_2/dt + v_{Y1} \quad (7)$$

$$v_B = i_3 R + L\, di_3/dt + v_{B1} \quad (8)$$

The equations (6, 7, 8) are transformed in terms of the d-q variables using the reference frame transformation given by equations 3, 4 and 5 as follows.

$$L\, d_{id}/dt = -i_d R + (v_{Rd} - v_{R1d}) - \omega L\, i_q \quad (9)$$

$$L\, d_{iq}/dt = -iqR + (v_{Rq} - v_{R1q}) + \omega L\, i_d \quad (10)$$

$L\, d_{id}/dt = -i_d R + v_d$
$L\, d_{iq}/dt = -iqR + v_q$
where

$$v_d = (v_{Rd} - v_{R1d}) - \omega L\, i_q \quad (11)$$

$$v_q = (v_{Rq} - v_{R1q}) + \omega L\, i_d \quad (12)$$

From the above equations the system model and the current controllers are derived as shown in Figs. 5 and 6.

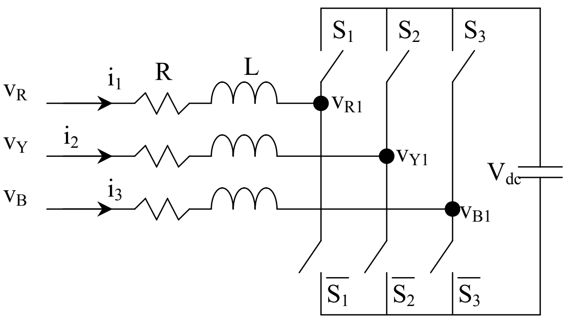

Fig. 4 Schematic of SAF

V. DC Bus Voltage Control

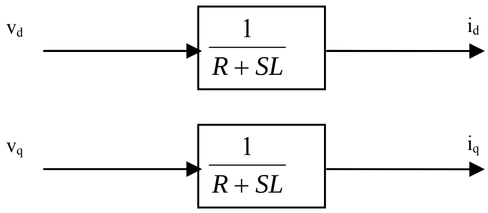

Fig. 5 System model

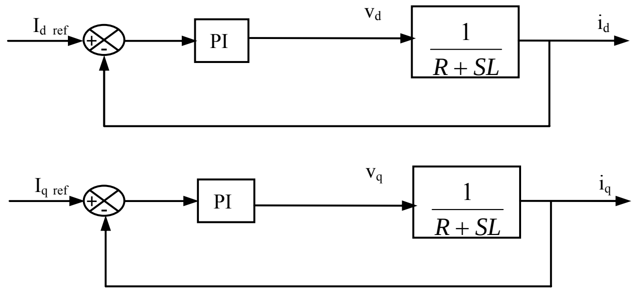

Fig. 6 Current controller

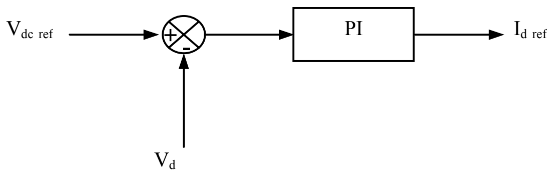

Fig. 7 Voltage controller

The output voltage of active filter denoted as in Fig. 4 is generated to reduce the source reactive power. The voltages VR1, VY1 and VB1 are controlled by changing the switching pulses. This causes a flow of instantaneous power into the inverter which charges/discharges the inverter dc bus capacitor. Despite the resultant dc bus voltage fluctuations, its average value remains constant in a lossless active filter. However, the converter losses and active power exchange causes the capacitor voltage to vary dynamically.

Regulation of this voltage for proper operation of active filter requires balancing by active power exchange at the fundamental frequency. The inverter is controlled to generate a fundamental frequency current signal in phase with the fundamental frequency voltage at the active filter terminals to regulate the dc bus voltage and for the active power balancing of the inverter. The voltage controller block diagram is shown in Fig. 7.

The overall control strategy is shown in Fig. 8. The load currents, inverter output currents and the DC bus voltage form the input signals to the inverter. The sine and cosine references are calculated from the source voltage waveform. Secondly the d-q components of load and inverter output currents are computed. Further using this control scheme is implemented from the derived mathematical model. The controller output acts as a modulating signal for the inverter

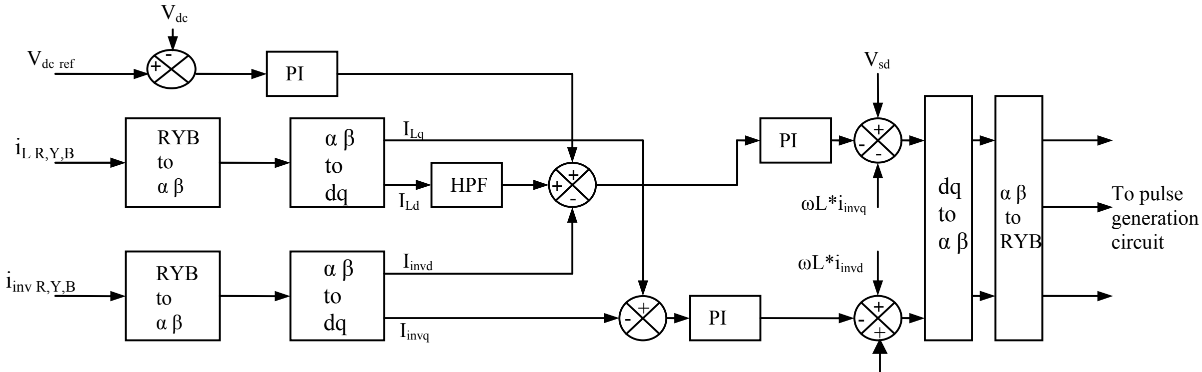

Fig 8 SAF Controller block diagram

and hence it will accordingly change the switching pattern of the inverter.

VI. Results and Discussion

In order to verify the performance of the shunt active filter using the SPWM and SVPWM schemes the test system is simulated using MATLAB/SIMULINK. Simulation studies are carried out using the system parameters given in Table I.

TABLE I
SYSTEM PARAMETERS

Sending end voltage (line-to-neutral)	230 ∠ 0^0 v(rms)
System frequency	50 Hz
DC link capacitor	1750μF
Inductor	10mh
Resistive load of (Three phase diode bridge rectifier)	50 Ω

Simulations are carried out for two different cases. In each case the reference dc voltage is varied and the optimum value of required dc reference to improve the source current close to a sinusoidal and to reduce the harmonic content as per the IEEE standard 519 is found. The Fig. 9a and 9b show the non-linear load current and its harmonic spectrum which is the load situation common to both SPWM and SVPWM schemes. The THD of the load current is 26.1%. By using the SAF control when the DC reference voltage is 700 V, the source current THD is 13.32% and 14.27% respectively for SVPWM and SPWM. The source current waveform, harmonic

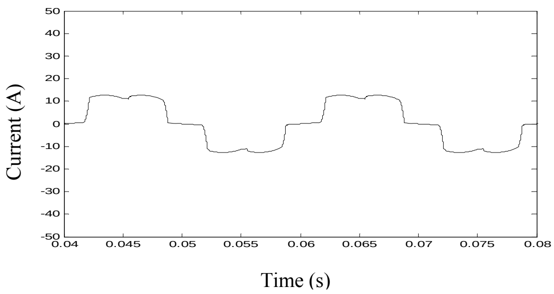

Fig. 9 (a) Load current waveform

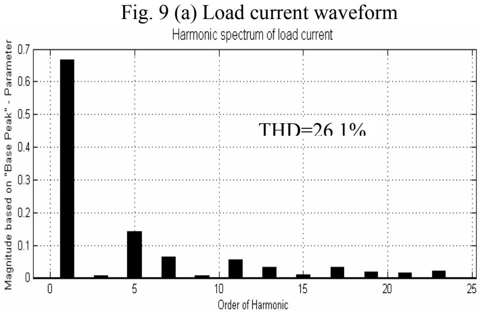

Fig 9(b) Harmonic spectrum of load current

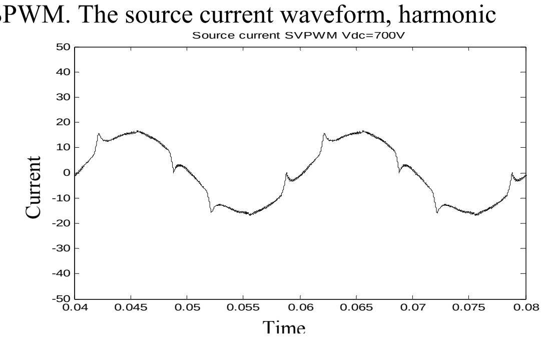

Fig.10.a. Source current wave form (SVPWM) V_{dc} ref = 700V

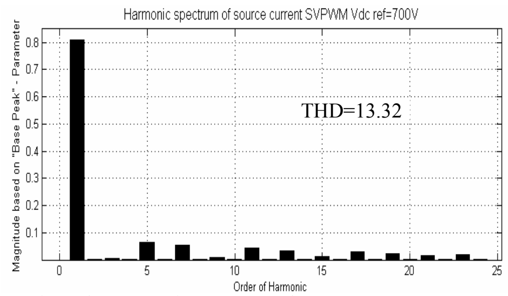

Fig.10.b. Harmonic spectrum of source current (SVPWM) V_{dc} ref = 700V

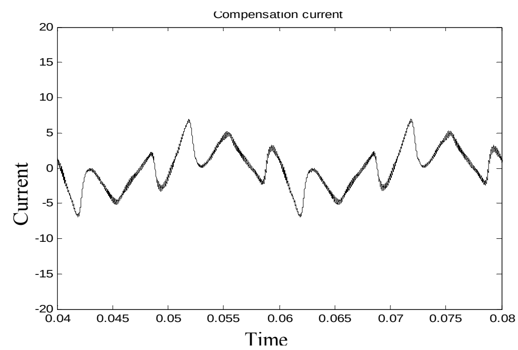

Fig.10.c. Compensation current waveform (SVPWM) V_{dc} ref = 700V

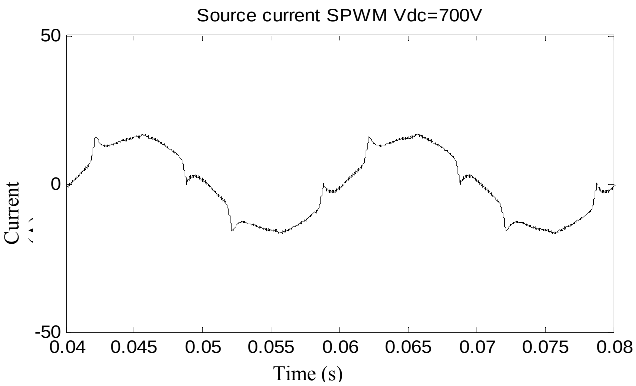

Fig.11.a. Source current wave form (SPWM) V_{dc} ref = 700V

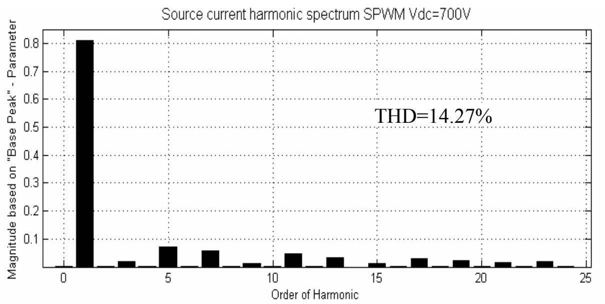

Fig.11.b. Harmonic spectrum of source current (SPWM) V_{dc} ref = 700V

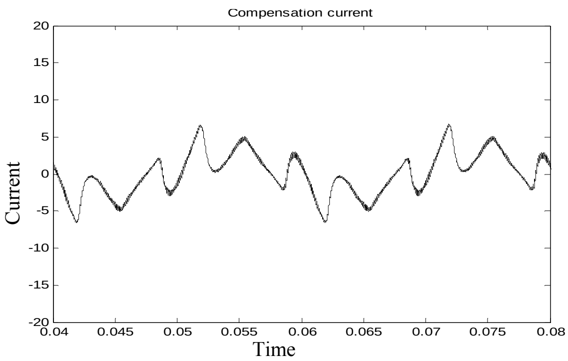

Fig.11.c compensation current waveform (SPWM) V_{dc} ref = 700V

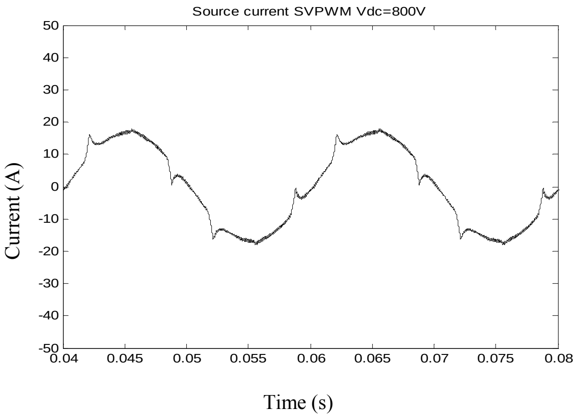

Fig.12.a. Source current waveform (SVPWM) V_{dc} ref = 800V

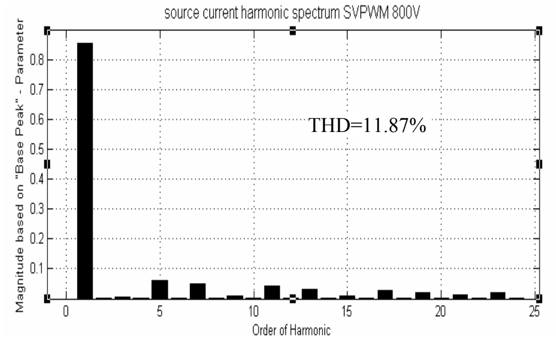

Fig.12.b. Harmonic spectrum of source current (SVPWM) V_{dc} ref = 800V

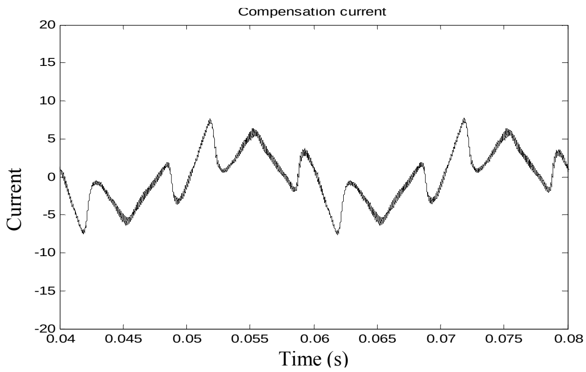

Fig12.c. Compensation current waveform (SVPWM) V_{dc} ref = 800V

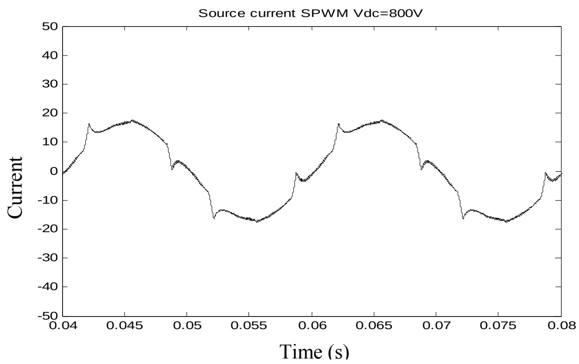

Fig13.a. Source current waveform (SPWM)V_{dc} ref = 800V

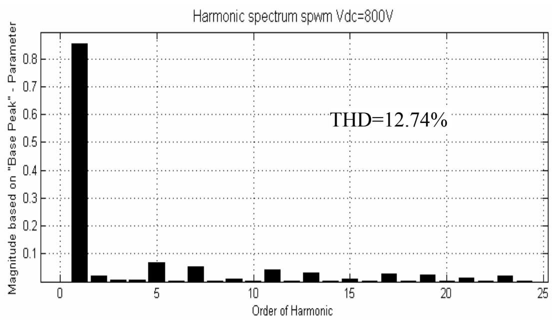

Fig.13.b. Harmonic spectrum of source current (SPWM) V_{dc} ref = 800V

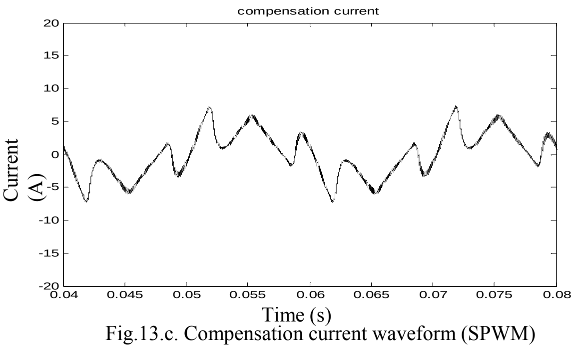

Fig.13.c. Compensation current waveform (SPWM)
V_{dc} ref = 800V

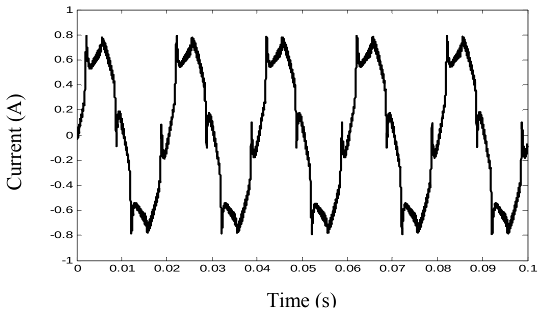

Fig. 14 Modulating signal

spectrum and compensation current waveforms are shown in Figs. (10-11). For further improvement in the THD the DC reference voltage is increased to 800V. With this the THD is 11.87% and 12.74% for SVPWM and SPWM respectively. The improved source current waveforms and THD are shown in Figs (12-13) respectively.

VII. Performance Comparison

An attempt is also made here to examine the aspect of effective utilization of dc bus voltage in the case of SVPWM compared to that with SPWM. For this purpose, three different preset values of dc bus voltage Vdc are considered. For a given Vdc, firstly the THD in source current with SPWM scheme is computed. Secondly the THD in source current with SVPWM is computed for the same Vdc and also for reduced values of Vdc at 85%,90% and 95%. These results are tabulated (as shown in Table II). Similarly for the second set a different preset dc voltage is considered and the THD in source current is computed for SPWM scheme. Further for the SVPWM, the THD in source current is computed with different reduced values of dc voltages with 85%, 90%, 95% and 100% respectively. These results are shown in Tables III and 4 for Vdc=800V and 900V respectively.

Earlier the reference papers [2-4] had noted that using the SVPWM technique the effective utilization of the DC bus voltage is $2/\sqrt{3}$times of that of the SPWM. However the present results show that the utilization is much smaller and the maximum value is 1.744.

The Figs. (15.a, b, c) show the performance comparison with Vdc reference of 800V for the SPWM scheme wherein the THD is 12.76%.For the SVPWM, different Vdc voltages,

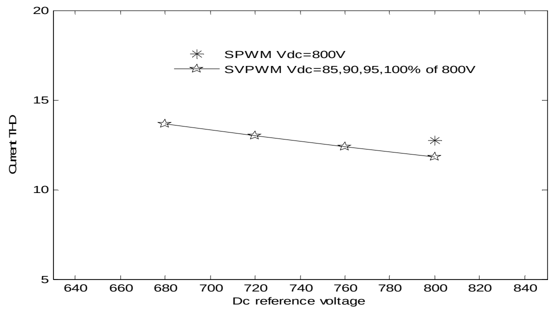

Fig.15 (a) THD performance comparison of SPWM (vdc=800V) and SVPWM

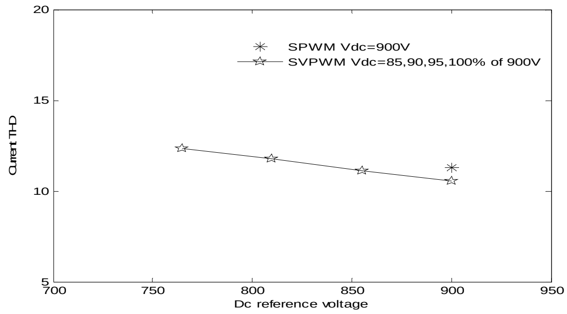

Fig.15 (b) THD performance comparison of SPWM(vdc=900V) and SVPWM

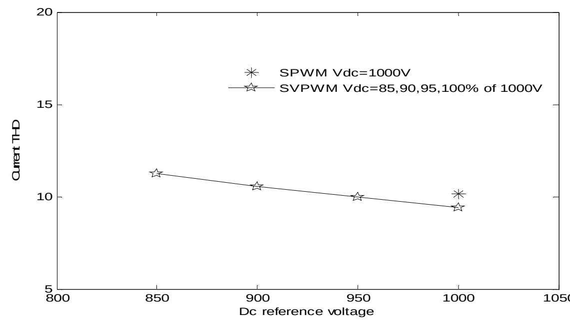

Fig.15(c) THD performance comparison of SPWM (vdc=1000V) and SVPWM

viz, 85%, 90%, 95% and 100% are considered and the corresponding THD is computed. The Table (II-IV) shows that by reducing the Vdc reference to 85%, the reduction of THD in SVPWM is negative compared to SPWM. It means that actually the THD is greater in SVPWM .Similarly for 90% of Vdc reference is also negative. For 95% and 100% of Vdc reference there is a slight improvement in THD but it is less than 1%. Thus the utilization of DC bus voltage and the harmonic improvement is not significant in the context of employing the computationally intensive SVPWM as the control strategy for SAF application. This may be due to the fact that the modulating signal of the inverter from the controller is not purely sinusoidal it is shown in Fig. 14.

TABLE II
PERFORMANCE COMPARISON OF SVPWM WITH SPWM(V_{DC}=800V,THD=12.76%)

S.NO	% of 800V Vdc		THD in %	% of THD reduction With SVPWM
	%	Vdc		
1	85	680	13.68	-0.92
2	90	720	13.02	-0.26
3	95	760	12.41	0.35
4	100	800	11.84	0.92

TABLE III
PERFORMANCE COMPARISON OF SVPWM WITH SPWM (V_{DC}=900V,THD=11.3%)

S.NO	% of 900V Vdc		THD in %	% of THD reduction With SVPWM
	%	Vdc		
1	85	765	12.33	-1.03
2	90	810	11.76	-0.46
3	95	855	11.14	0.16
4	100	900	10.57	0.73

TABLE IV
PERFORMANCE COMPARISON OF SVPWM WITH SPWMV_{DC}=1000V,THD=11.15%

S.NO	% of 1000V Vdc		THD in %	% of THD reduction With SVPWM
	%	Vdc		
1	85	850	11.27	-0.12
2	90	900	10.57	0.58
3	95	950	9.976	1.174
4	100	1000	9.406	1.744

VIII. CONCLUSION

In this paper the results of investigation of an SAF with SPWM and conventional SVPWM performance are reported with respect to source current THD and DC bus utilization. There is only a slight improvement in THD with SVPWM but it is not much significant compared to that of the SPWM when applied to SAF closed loop control strategy. The utilization of the DC bus is also not significant when applied to SAF because of the non sinusoidal modulating signal from the controller.

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