

THD Analysis of One-Cycle and PWM Controlled Active Power Filters

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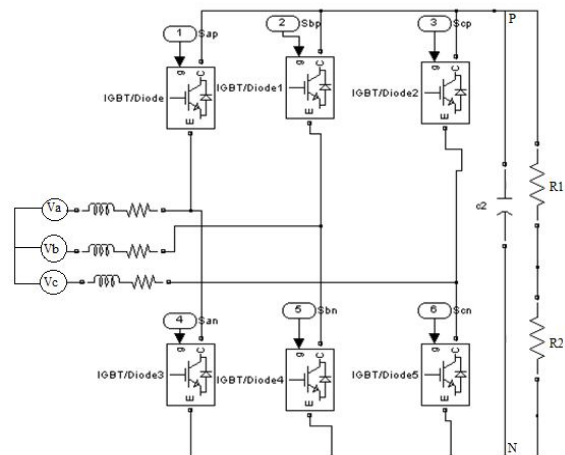
Abstract— Nonlinear loads generate a harmonic and reactive current, which leads to poor power factor and harmful disturbance to other appliances. Active power filters are one of the viable solutions to eliminate the harmonic/reactive currents generated by non linear loads in power lines. In this paper an APF is connected in shunt with the nonlinear loads and functions as compensating current sources to eliminate the harmonic components in the source side so that the current flow into and from the grid is in phase with grid voltage. Here APF power converter is operated in dual boost converter mode with constant switching frequency by using one cycle control method with vector operation and pulse width modulation control. The obtained simulation results were compared through which the best method has been concluded. All features are simulated in the MATLAB/SIMULINK environment.

Keywords—Active powers filter (APF), one-cycle control, pulse width modulation (PWM), power quality control.

I. INTRODUCTION

The harmonics are increased due to the increase in the non linear loads and distributed power sources which are connected to the grid such as Diode/Thyristor rectifiers with R, L, C loads and electronic appliances. As these non linear loads and sources generate the harmonics [1] which cause low power factor and harmful disturbances to the appliances the following are some of the techniques to eliminate the harmonics and improve the power factor, they are PFC technique, passive power filters, active power filters [2-4] which gives the suitable solutions to compensate the

harmonics and improve the power factor. In PFC approach the PFC unit is usually connected in cascade in the power line which processes all the power and corrects the current to unity power factor. This kind of approach is suitable for low power ie., less than 5KVA. The APF can be connected either in series or shunt to the non linear load or sources and generate the harmonics and reactive power component to compensate the harmonics generated by the non-linear loads sources. To overcome the disadvantages due to passive filters, active power filters (APFs) have been presented [5-7] as a current-harmonic compensator for reducing the total harmonic distortion of the current and correcting the power



factor of the input source.

Fig.1. Power stage of the three-phase APF with six-switch bridge voltage-source converter.

These kinds of approaches are applicable for low-power ie., less than 5kVA to high-power applications around 100kVA. The active power filter used in this circuit is comprised with three phase bridge converter with IGBT switches. Most previously reported control approaches need to sense the

load current and calculate its harmonics and reactive components in order to generate the reference for controlling the current of a bridge converter [5, 9, 10, 11, and 15]. One among those approaches of control like PWM control [18] required the real time calculations for which we need to use different components which increase the complexity, cost of the equipment and the stability gets reduced. In this circuit all the switches are operated with switching frequency therefore, the switching losses are high. Reference [16] introduced a promising solution based on one cycle control which eliminates the need of calculations and use of multipliers and voltage sensors in the control loop which makes the circuit simple by introducing three phase APF with six-switch bridge converter with vector operation. It is found that this voltage source converter can be decoupled into a parallel-connected dual-boost converter with two-quadrant operation. Three-phase unity power factor can be achieved by controlling the parallel-connected dual-boost converter using One-Cycle control.

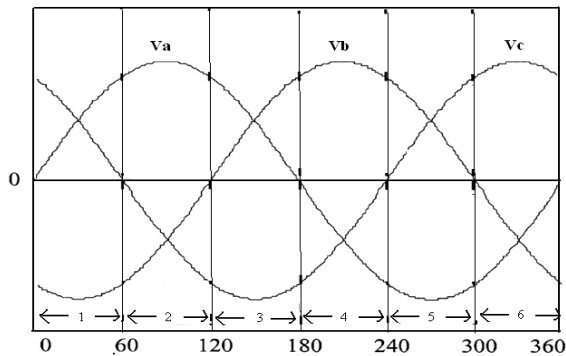


Fig.2. Normalized three-phase grid voltage waveform

II. ONE CYCLE CONTROL

The control is meant to achieve unity power factor at source side, that means source voltage and source current are in phase with each other and to reduce THD (Total Harmonic Distortion) in the line current, by operating APF (Active Power Filter) in the mode of dual boost converter with Vector operation by using One Cycle Control in the form of closed loop control, such that APF would provide compensating currents into the power line.

The overall block diagram of the active power filter is shown in Fig.3. Where V_a, V_b, V_c are the three phase input source voltages, i_a, i_b, i_c are the source currents i_{a1}, i_{b1}, i_{c1} are the nonlinear load currents. Due to load nonlinearity, it

will introduce harmonic currents, so that the current wave form is distorted. Now our APF which is connected in shunt with nonlinear load will inject harmonic current into the AC system, of the same amplitude but reverse in phase to that of the load current harmonics. This will thus result in sinusoidal line currents and unity power factor in the input power system.

This APF is controlled by the gate pulses which are coming from the Vector controlled switching logic circuit, which is mainly controlled by the One-Cycle controller.

III. CONCEPT OF PARALLEL-CONNECTED DUAL-BOOST CONVERTER

The power stage of three phase active power filter is composed of voltage source converter with IGBT switches that is connected in parallel with a non linear load which could be several loads shown in Fig.1. The normalized grid waveform is shown in Fig.2. During the region ($0^\circ \sim 60^\circ$) the voltage V_b is negative dominant. In this case, switch S_{bn} conducts and switch S_{bp} is kept off during the whole 60° region, switches in the other two branches such as $S_{an}, S_{ap}, S_{cn}, S_{cp}$ are controlled complementarily at switching frequency. The voltage source converter can be simplified to reduced convertor with four switches $S_{ap}, S_{an}, S_{cp}, S_{cn}$. This reduced convertor is converted to equivalent parallel-connected dual-boost converter with two grid voltages V_{ab}, V_{cb} . Where V_{ab}, V_{cb} are line to line voltages and E is the dc voltage of energy storage capacitor. The generalized parallel-connected dual-boost converter is of two categories. One is for the regions ($0^\circ \sim 60^\circ$), ($120^\circ \sim 180^\circ$), ($240^\circ \sim 300^\circ$) and the other is for regions ($60^\circ \sim 120^\circ$), ($180^\circ \sim 240^\circ$), ($300^\circ \sim 360^\circ$). Switch pairs T_p, \square_p and T_n, \square_n are controlled complementally. The current through the L_p and L_n increases when switches T_p and T_n are ON and decrease when they are OFF. The complete operation was shown in the Fig.4, Fig.5, Fig.6 and the cross reference of the circuit parameters and symbols between the bridge voltage-source converters are shown in Table.1.

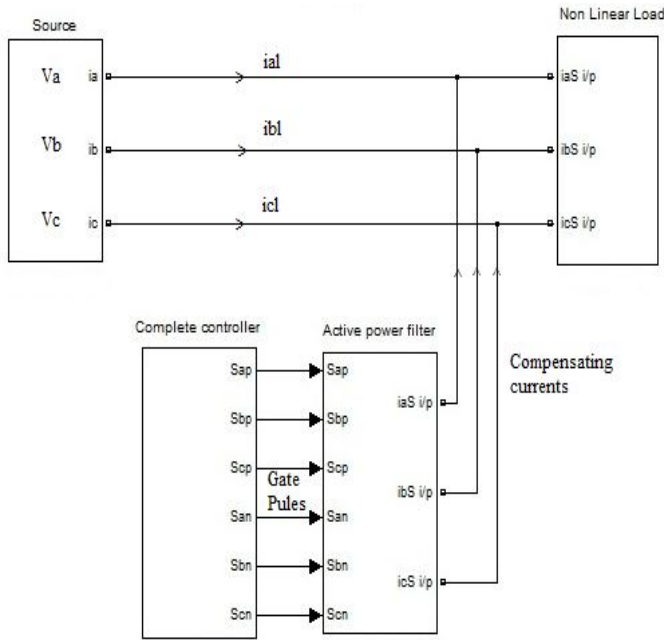


Fig.3. One cycle control of active power filter

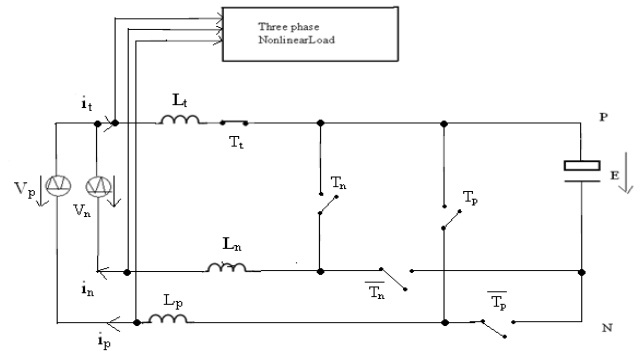


Fig.5. General parallel-connected dual-boost converter with energy bidirectional flowing for regions (0~60), (120~180), and (240~300).

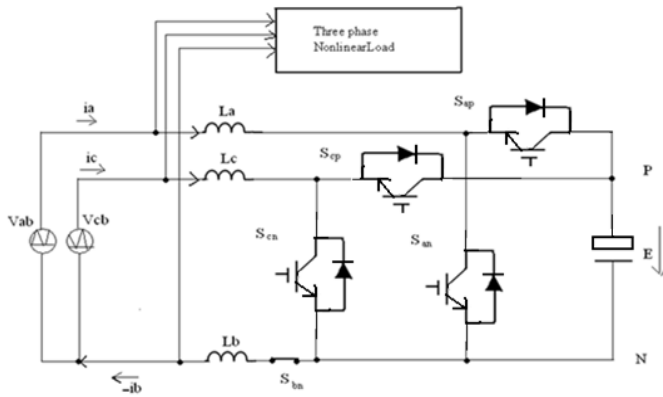


Fig.4. Power stage of the three-phase APF during 0_60°region

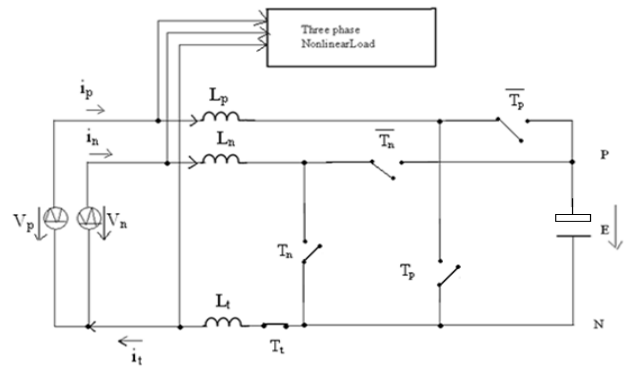


Fig.6. General parallel-connected dual-boost converter with energy bidirectional flowing for regions (60~120), (180~240), and (300~360).

TABLE I

CROSS REFERENCE OF THE CIRCUIT PARAMETERS AND SYMBOLS BETWEEN THE BRIDGE VOLTAGE-SOURCE CONVERTER AND THE DUAL BOOST

Region	V _p	V _n	i _p	i _n	L _p	L _n	L _t	T _p	T _n	□ _p	□ _n	T _t
0~60	V _a	V _c	i _a	i _c	L _a	L _c	L _b	S _a	S _c	□ _a	□ _c	S _b
60~120	V _a	V _b	-i _b	-i _c	L _b	L _c	L _a	S _b	S _c	□ _b	□ _c	S _a
120~180	V _b	V _a	i _b	i _a	L _b	L _a	L _c	S _b	S _a	□ _b	□ _a	S _c
180~240	V _b	V _c	-i _c	-i _a	L _c	L _a	L _b	S _c	S _a	□ _c	□ _a	S _b
240~300	V _c	V _b	i _c	i _b	L _c	L _b	L _a	S _c	S _b	□ _c	□ _b	S _a
300~360	V _c	V _a	-i _a	-i _b	L _a	L _b	L _c	S _a	S _b	□ _a	□ _b	S _c

CONVERTER.

The objective of three phases APF is to control three phase grid currents to follow the three phase grid voltages, respectively. This can be achieved by controlling the equivalent parallel-connected dual-boost converter. This is obtained by doing interpolation i.e., for (0°~60°) Phase currents i_a, i_b replaced by i_p, i_n and phase voltages V_a, V_c replaced by V_p, V_n where V_p=V_{ab} and V_n=V_{cb}. The control goal is given using ohms law V=IR.

IV. SWITCHING STATES OF PARALLEL CONNECTED DUAL-BOOST CONVERTER

We have totally four switches in the equivalent circuit for every cycle. So we get four combinations as follows, switch state-I (T_p-ON, T_n-OFF, □_p-OFF, □_n-OFF) likewise we frame other four switch states.

TABLE II

SWITCHING STATES AND INDUCTOR VOLTAGES FOR PARALLEL-CONNECTED DUAL-BOOST CONVERTER.

State	T _p	T _n	□ _p	□ _n	V _{Lp}	V _{Ln}	V _{Lt}
I	ON	ON	OFF	OFF	V _p *	V _n *	V _t *
II	ON	OFF	OFF	ON	V _p *+1/3E	V _n *-2/3E	V _t *-1/3E
III	OFF	ON	ON	OFF	V _p *-2/3E	V _n *+1/3E	V _t *-1/3E
IV	OFF	OFF	ON	ON	V _p *-1/3E	V _n *-1/3E	V _t *-2/3E

Considering switching state-I for fig.5 and by applying super position theorem and current division rule we obtain the voltages V_{lp}, V_{ln}, V_{lt} which was given in the below table. For a three phase APF with a constant switching frequency, only two switching sequences are possible, i.e., I,II,IV (condition d_p>d_n where d_p, d_n are the duty ratios of switches T_p, T_n, respectively) or I,III,IV is the other sequence which is possible. Based on the assumption that switching frequency is much higher than the line frequency, the inductor voltage-second balance is approximately valid, that is

$$\begin{aligned}
 V_p^* d_n + \left(V_p^* + \frac{1}{3} E \right) * (d_p - d_n) + \left(V_p^* - \frac{1}{3} E \right) * (1 - d_p) &= 0 \\
 V_t^* d_n + \left(V_t^* - \frac{1}{3} E \right) * (d_p - d_n) + \left(V_t^* - \frac{2}{3} E \right) * (1 - d_p) &= 0 \\
 V_n^* d_n + \left(V_n^* - \frac{2}{3} E \right) * (d_p - d_n) + \left(V_n^* - \frac{1}{3} E \right) * (1 - d_p) &= 0
 \end{aligned}
 \tag{1}$$

The following equation is true for a symmetrical three-phase system:

$$V_p^* + V_n^* - V_t^* = 0
 \tag{2}$$

From the above two equations (1) and (2) we obtain

$$\begin{bmatrix} (1 - d_p) \\ (1 - d_n) \end{bmatrix} = \begin{bmatrix} 2 & 1 \\ 1 & 2 \end{bmatrix} * \begin{bmatrix} \frac{V_p^*}{E} \\ \frac{V_n^*}{E} \end{bmatrix}
 \tag{3}$$

This equation gives a relationship between the duty cycle and the input, output voltage for the parallel-connected dual-boost converter. For the unity-power-factor three-phase APF, the control goal is to force the grid line current in each phase to follow the correspondent sinusoidal phase voltage, i.e.,

$$\begin{aligned} V_a &= R_e * I_a \\ V_b &= R_e * I_b \\ V_c &= R_e * I_c \end{aligned} \quad (4)$$

Where R_e is the emulated resistance that reflects the real power of the load and the control goal of three-phase APF can be rewritten as follows

$$V_p^* = R_e * i_p \quad (5)$$

$$V_n^* = R_e * i_n \quad (6)$$

Substituting equations (5) and (6) into the equation (2) and considering the switch is ON for the entire 60° region, it is obtained as

$$\begin{bmatrix} (1 - d_p) \\ (1 - d_n) \end{bmatrix} = \frac{R_e}{ER_s} * R_s * \begin{bmatrix} 2 & 1 \\ 1 & 2 \end{bmatrix} * \begin{bmatrix} i_p \\ i_n \end{bmatrix}_{d_i=1} \quad (7)$$

The control key equation obtained by substituting $V_m = ER_s/R_e$ in equation (7).

$$V_m * \begin{bmatrix} (1 - d_p) \\ (1 - d_n) \end{bmatrix} = R_s * \begin{bmatrix} 2 & 1 \\ 1 & 2 \end{bmatrix} * \begin{bmatrix} i_p \\ i_n \end{bmatrix}_{d_i=1} \quad (8)$$

By using the above equation (8) we design the one cycle controller as shown in the below Fig.5.

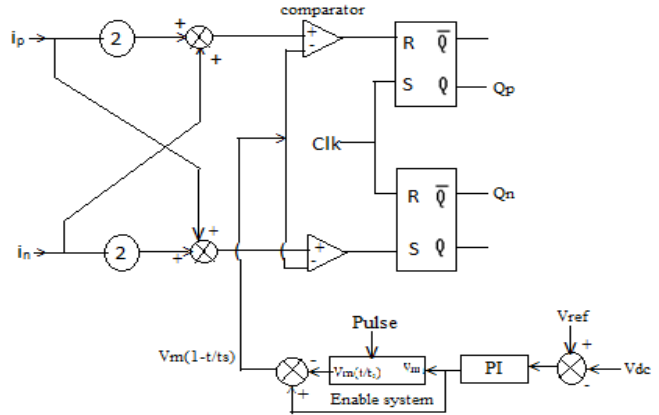


Fig.7. Extended one cycle control core.

Fig.7 illustrates that $R_s(2i_p+i_n)$ is compared with $V_m(1-t/\pi)$ and when this two signals meet the comparator changes its state which resets the corresponding flip-flop's as a result the switch is turned OFF. From the above controller we obtain four outputs $Q_p, \bar{Q}_p, Q_n, \bar{Q}_n$. So now according to the operation of the dual boost converter the switching logic is being designed. For each switch of APF among six there will be six regions ($0 \sim 60^\circ$) to ($300^\circ \sim 360^\circ$). The control algorithm for the APF is as follows in the following table.

TABLE III
CONTROL ALGORITHM FOR THE APF

Region	i_p	i_n	d_p	d_n	d_t	Q_{ap}	Q_{an}	Q_{bp}	Q_{bn}	Q_{cp}	Q_{cn}
$0^\circ \sim 60^\circ$		i_c	d_a	d_n	d_b	\bar{Q}_p	Q_p	OF	ON	\bar{Q}_n	Q_n
	i_a		d_n	d_p				F			
$60^\circ \sim 120^\circ$		i_c	d_b	d_n	d_{ap}	ON	F	Q_p	\bar{Q}_p	Q_n	\bar{Q}_n
	i_b		d_p	d_n							
$120^\circ \sim 180^\circ$		i_c	d_b	d_n	d_{cn}	\bar{Q}_n	Q_n	\bar{Q}_p	Q_p	OF	ON
	i_b		d_n	d_p						F	
$180^\circ \sim 240^\circ$		i_c	d_c	d_n	d_b	Q_n	\bar{Q}_n	ON	F	Q_p	\bar{Q}_p
	i_c		d_p	d_n							
$240^\circ \sim 300^\circ$		i_b	d_c	d_n	d_{an}	OF	ON	\bar{Q}_n	Q_n	\bar{Q}_p	Q_p
	i_c		d_n	d_p		F					
$300^\circ \sim 360^\circ$		i_b	d_a	d_n	d_{cp}	Q_p	\bar{Q}_p	Q_n	\bar{Q}_n	ON	OF
	i_a		d_p	d_n						F	

So, now according to this order we need to frame the logic block for switching the dual boost converter and inject the current in opposite direction to compensate the harmonics the source side.

V. PULSE WIDTH MODULATION CONTROL

As like in one cycle control the harmonics that are produced due to the non linear loads can be even compensated by using PWM controller [18]. PWM is a modulation technique that conforms the width of three pulse, formally the pulse duration, based on modulator signal information. Main features of PWM are the reference frame transformation and a digital low pass filter are used to compute the harmonic of the nonlinear load current, the voltage decouplers and pole zero cancellation methods are used in the current controllers of the APF to provide fast current harmonic compensation. In Fig.8 i_{al}, i_{bl} ,

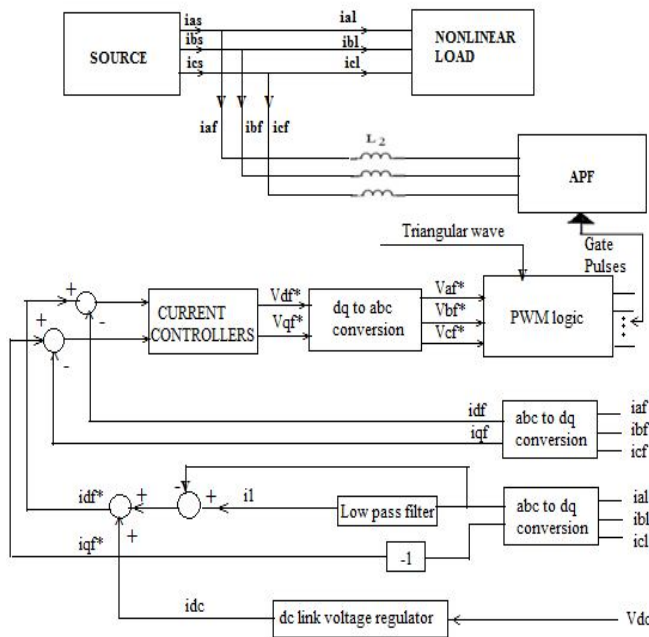


Fig.8. Block diagram of PWM controlled APF

i_{cl} are load currents, i_{af}, i_{bf}, i_{cf} are filtering compensation currents, and V_{dc} is DC link capacitor voltage of the APF. Here

filter currents and DC link capacitor voltages are taken as feedback components. After that load currents, and filter currents are transformed from abc model to dq model through reference frame transformation. I_{dl} current is passed through the low pass filter for getting fundamental current i_1 , then by making $(idl - i_1)$ gets total harmonic currents as reference. Here dc link voltage regulator current also taken into consideration for making direct axis filter reference current i_{df}^* . q-axis filter reference current i_{qf}^* is getting simply by making negative of that i_{ql} . Now these two currents are compared with the actual filter currents i_{df}, i_{qf} and produce the error. This error is now passed through the current controllers for getting reference voltages. Again these reference voltages are transformed into abc model. These three reference voltages are compared with the triangular wave, and by the method of bipolar voltage switching produce switching pulses for the APF power converter IGBT switches.

5.1 DESIGN OF CONTROLLERS

In PWM circuits the three phase voltage commands are compared with a triangular wave carrier of 10 kHz. The PWM output signals are used to switch ON or OFF the IGBT devices. The total control block as shown as below.

For the design of controllers [14], the system parameter used as follows:

$$V_m = 98V \quad \omega_e = 377 \text{ rad/s} \quad L_s = 0.4\text{mH}$$

$$V_c = 240V \quad L_2 = 0.25\text{mH} \quad R_2 = 0.03\Omega$$

$$C_2 = 4800\mu\text{F}$$

Non linear load components are as follows:
Diode Bridge Rectifier with

$$R_o = 8.67 \Omega,$$

$$C_o = 3300 \mu\text{F},$$

$$L_o = 3.1 \text{ mH}.$$

VI. EXPERIMENTAL RESULTS

A three phase APF with six switch bridge source converters was built to verify the concept of control by applying two methods named one cycle control and PWM control. The experimental waveforms for one cycle control with and without APF are shown above in the Fig.9. The

applied phase voltage of gridline is shown in Fig (a) due to nonlinear load whatever harmonic current is observed it is

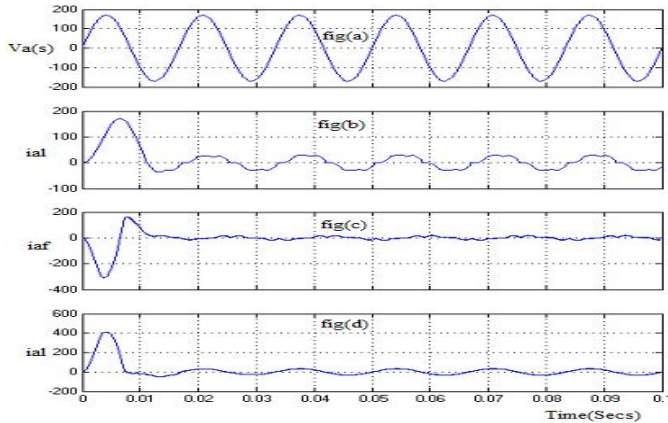


Fig.9. Measured experimental waveforms for Phase A using one cycle control In this fig.9(a) is the phase voltage of the grid line, fig.9(b) is the distorted load current ial, fig.9(c) is the reactive component iaf, fig.9(d) is the compensated current ial which is free from harmonics.

shown in Fig (b). This gets compensated by the reactive component of current shown in Fig (c) which is provided by the active power filter and the resulted compensated current waveform is shown in Fig (d).The measured harmonic spectrum is shown in fig.10 shown below.

The experimental conditions of one cycle controlled APF are as follows: The phase voltage of the grid is 169.70Vrms, the APF dc-link voltage is about 400V; the input impedance is 0.4mH; the filter inductance is 0.25mH; the switching frequency is about 60Hz.The THD of load current is about 16.02%. After compensation, the THD of the line current decreased to 2.95%. The same active power filter is verified by using PWM control and the obtained results are shown in Fig.11. and the respective harmonic spectrum is shown in fig.12.

Fig.10.Harmonic spectrum of phase A current using one cycle control.

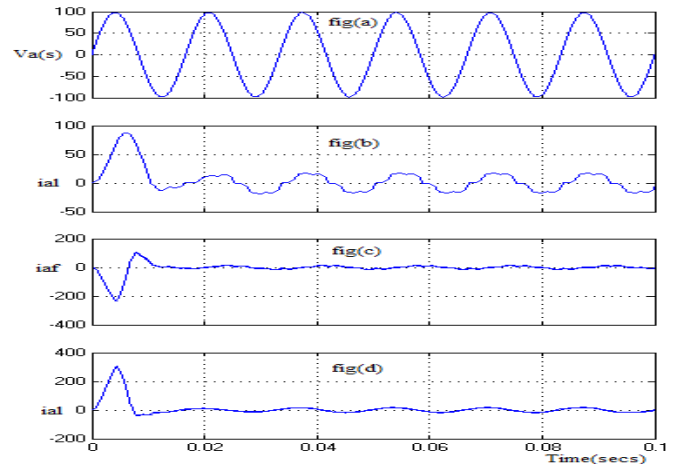
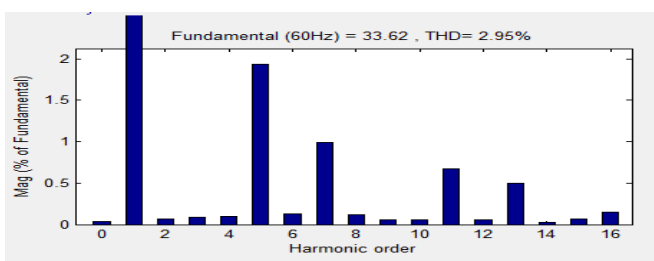


Fig.11. Measured experimental waveforms for Phase A using PWM control. In this fig.11 (a) is the phase voltage of the grid line, fig.11 (b) is the distorted load current ial, fig.11(c) is the reactive component iaf, fig.11 (d) is the compensated current ial.

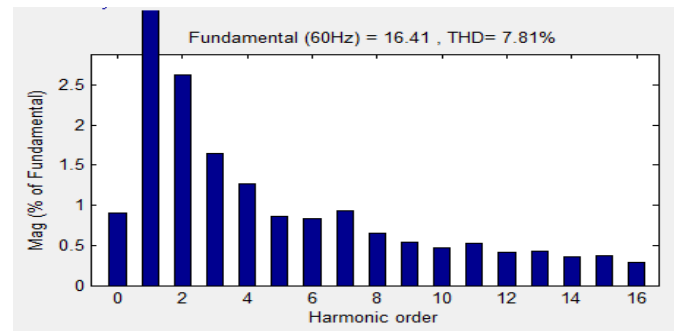


Fig.12. Harmonic spectrum of phase A current using PWM control

The experimental conditions for PWM controlled APF are as follows: The phase voltage of the grid is 98Vrms, the APF dc-link voltage is about 240V; the input impedance is 0.4mH; the filter inductance is 0.25mH; the switching frequency is about 60Hz.The THD of load current is about 15.73%.After compensation, the THD of the line current decreased to 7.81%.

From the results obtained we can demonstrate that the one cycle controller is best compared to PWM controller can effectively cancels the harmonics of the load and improve the power factor. The comparison is shown in the Table IV.

TABLE IV
PERFORMANCE COMPARISON OF PWM, ONE-CYCLE CONTROLLED APF

Controller Type	THD without Active Filter	THD with Active Filter	Power factor
PWM controller	15.73%	7.81%	0.98
One-Cycle controller	16.02%	2.95%	0.9996

VII. CONCLUSION

In this paper, a three-phase shunt APF with extended one-cycle control has been used. The control approach senses only the mains current and the zero crossing of grid voltage. In addition to this, there is no need to calculate the reference for APF inductor current so that the complicated digital computation is eliminated. The control approach employs constant switching frequency modulation that is desirable for industrial applications. The control circuit contains one integrator with reset along with several logic and linear components to achieve unity power factor in all three phases. This APF is connected in shunt with the nonlinear load; so that it provides harmonics and reactive power to cancel the harmonics generated by the nonlinear load or sources. This APF compensates for systems with multiple loads therefore, it is a cost effective solution. The same controlling was done using PWM controller and the simulation results were compared to choose the best controller. The simulation results have demonstrated that the one cycle control of shunt active power filter can effectively cancels the reactive and harmonic component of the load compared to PWM, so that all the three-phase line currents are near sinusoidal.

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