International Journal of Scientific Engineering and Technology (ISSN : 2277-1581)
Volume No.2, Issue No.11, pp : 1145-1151 1 Nov. 2013

Performance Comparison of One Cycle and PWM Controlled Active Filters

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Abstract: During the last years, the increasing research in power systems and the electrical engineering development around the world, has given an incentive to new expectations in transmission and distribution. The quality of power that is supplied is also gaining more importance.
Power harmonics are called electrical pollution which will degrade the quality of the power supply. As a result, filtering process for these harmonics is needed in order to improve the quality of the power supply. Generally passive filters are used to suppress the harmonics of specific orders. Separate filters are required to suppress individual lower order harmonics. These usually consist of a bank of tuned LCfilters to suppress harmonics. The passive filters are performing better in the presence of load. In the absence of load or light loading conditions the presence of passive filters resulting in poor power quality.

The Active Power Filters (APF) is used to reduce harmonics based on load variations. The presence of active filter is resulting in reduction of the harmonics to a specific limit. It is proposed to use single active filter in place of passive filters with the objective to reduce harmonic currents. It is proposed to use one cycle controlled APF for suppressing harmonics in the presence of nonlinear loads under different loading conditions and the performance is compared with PWM controlled APF.

Key words:Power harmonics; active filter; passive filter

I. Introduction

Since the rapid development of the semiconductor industry, power electronics devices have gained popularity in converters. Although these power electronics devices have benefited the electrical and electronics industry, these devices are also the main source of power harmonics in the power system. These power harmonics are called electrical pollution which will degrade the quality of the power supply. As a result, filtering process for these harmonics is needed in order to improve the quality of the power supply. Thus, active power filter seems to be a viable alternative for power conditioning to control the harmonics level in the power system nowadays. Power system normally operates at 50 or 60 Hz. However, saturated devices such as transformers, arching loads such as florescent lamp and power electronic devices will produce current and voltage components with higher frequencies into the power line. These higher frequencies of current and voltage components are known as the power harmonics. The harmonics disturbances in the power supply are caused by the nonlinearity characteristic of the loads. Due to the advantages in efficiency and controllability of power electronic devices, their applications can be found in almost all power levels. Here we are using one cycle controlled active filter to reduce the current harmonics and it is compared with the PWM controlled active filter.

II. Control of Power Harmonics

Passive Filters

Traditional solutions for these problems are passive filters due to their easy design, simple structure, low cost and high efficiency. These usually consist of a bank of tuned LCfilters to suppress current harmonics generated by nonlinear loads.

Passive filters have many disadvantages, such as
1) Resonance
2) Large size
3) Fixed compensation character
4) Possible overload

Those kinds of approaches are usually suitable for low-power applications.

Active Filters

To overcome the disadvantages due to Passive Filters, Active Power Filters (APFs) have been presented as a current-harmonic compensator for reducing the total harmonic distortion of the current and correcting the power factor of the input source. The Active Power Filter is connected in parallel with a nonlinear load. The approach is based on the principle of injecting harmonic current into the ac system, of the same amplitude and reverse 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. In this case, only a small portion of the energy is processed, which may result in overall higher energy efficiency and higher power processing capability. These kinds of approaches are applicable for low-power to high-power applications. A three-phase shunt APF is typically composed of a three-phase bridge converter and control circuitry. Most of theprevious 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.
Those control methods require fast and real-time calculation. therefore, a high-speed digital microprocessor and high-performance A/D converters are necessary, which yields high cost, complexity, and low stability.

III. One Cycle Controlled Active Filter

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.

$$\left.\begin{array}{l} V_a = R_e \cdot i_a \\ V_b = R_e \cdot i_b \\ V_c = R_e \cdot i_c \end{array}\right\} \qquad ----(1)$$

Where R_e is the emulated resistance that reflects the real power of the load. This control goal can be realized by controlling the equivalent currents i_p and i_n to follow the voltages V_p^* and V_n^*. The control goal of three-phase APF can be rewritten as

$$\left.\begin{matrix} V_p^* = R_e \cdot i_p \\ V_n^* = R_e \cdot i_n \end{matrix}\right\} \quad ----(2)$$

considering the switch is ON for the entire 60^o region, it is obtained that

$$\left.\begin{matrix} \begin{bmatrix} (1-d_p) \\ (1-d_n) \end{bmatrix} = \frac{R_e}{ER_s} \cdot R_s \begin{bmatrix} 2 & 1 \\ 1 & 2 \end{bmatrix} \cdot \begin{bmatrix} i_p \\ i_n \end{bmatrix} \\ d_t = 1 \end{matrix}\right\} --(3)$$

Define

$$V_m = \frac{ER_s}{R_e} \quad ----(4)$$

Where the signal V_m can be generated from the output voltage feedback compensator, which is used to regulate the output capacitor voltage E of the voltage source converter according to the load level; Rs is equivalent current sensing resistance and it is fixed constant. Combining of the two equations 3 and 4 the control key equation is derived as

$$\left.\begin{matrix} V_m \cdot \begin{bmatrix} (1-d_p) \\ (1-d_n) \end{bmatrix} = R_s \cdot \begin{bmatrix} 2 & 1 \\ 1 & 2 \end{bmatrix} \cdot \begin{bmatrix} i_p \\ i_n \end{bmatrix} \\ d_t = 1 \end{matrix}\right\} --(5)$$

The above equation indicates that three-phase power factor can be achieved by controlling the duty ratios of switches so that first-order polynomial equation 5 is satisfied. This can be realized by the one-cycle control core as shown in Fig.1 The operation waveforms are shown in Fig.2.

In the beginning of each switching cycle, the clock pulse sets the two flip-flops. The currents i_p and i_n from the current selection logic is linearly combined to form an input to each of the two comparators. At other input of the two comparators is the value of V_m minus the integrated value of V_m. Signal $V_m\left(1-\frac{t}{T_s}\right)$ is compared with

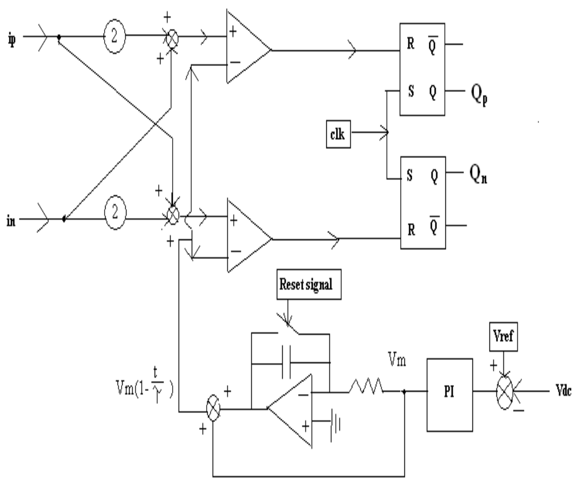

Fig .1 One- cycle control logic

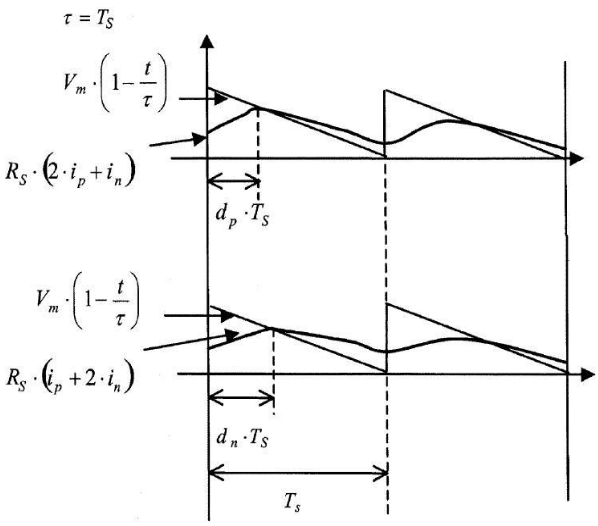

Fig.2 Operation waveforms of one-cycle controlled APF controller

$R_s(2i_p + i_n)$in the upper comparator and is compared with $R_s(i_p + 2i_n)$ in the lower comparator as shown. The comparator changes its state, which resets the correspondent flip-flop. As a result, the correspondent switch is turned off. Therefore, the duty ratios d_p and d_n are determined for the correspondent switch in each switching cycle.

The implementation of equ. (5) by one-cycle control results in the proposed controller. Fig.1 shows the general diagram of the three-phase APF that employs a three-phase bridge converter and the extended one-cycle controller, where i_a ,i_b ,$i_c$represent the phase A, B, and C grid currents, respectively. The controller contains four blocks. The first block is the region selection circuit that is used to indicate the region where the grid voltage vector is located. The second block is the input multiplex circuit, which is used to select the grid ac current in order to configure the equivalent currents i_p and i_n . The third block is the one-cycle control core to implement the control key. It includes an adder, two comparators and an integrator with reset as well as two flip-flops. The integration time constant of integrator is set to be equal the switching period. The operation waveforms are shown in Fig.4.10. The fourth block is the output logic circuit, which applies the equivalent switching control signal Q_p and Q_n to the corresponding switches.

Table 1. Control Algorithm for Converter

Region	i_p	i_n	d_p	d_n	d_t	Q_{ap}	Q_{an}	Q_{bp}	Q_{bn}	Q_{cp}	Q_{cn}
0^o~60^o	i_a	i_c	d_{an}	d_{cn}	d_{bn}	$\overline{Qp}$	Q_p	OFF	ON	$\overline{Qn}$	Q_n
60^o~120^o	$-i_b$	$-i_c$	d_{bp}	d_{cp}	d_{ap}	ON	OFF	Q_p	$\overline{Qp}$	Q_n	$\overline{Qn}$
120^o~180^o	i_b	i_a	d_{bn}	d_{an}	d_{cn}	$\overline{Qn}$	Q_n	$\overline{Qp}$	Q_p	OFF	ON
180^o~240^o	$-i_c$	$-i_a$	d_{cp}	d_{ap}	d_{bp}	Q_n	$\overline{Qn}$	ON	OFF	Q_p	$\overline{Qp}$
240^o~300^o	i_c	i_b	d_{cn}	d_{bn}	d_{an}	OFF	ON	$\overline{Qn}$	Q_n	$\overline{Qp}$	Q_p
300^o~360^o	$-i_a$	$-i_b$	d_{ap}	d_{bp}	d_{cp}	Q_p	$\overline{Qp}$	Q_n	$\overline{Qn}$	ON	OFF

The control signal of the switches can be implemented based on the control algorithm as shown in Table 1. For example, from Table 1, switch S_{ab} will be completely

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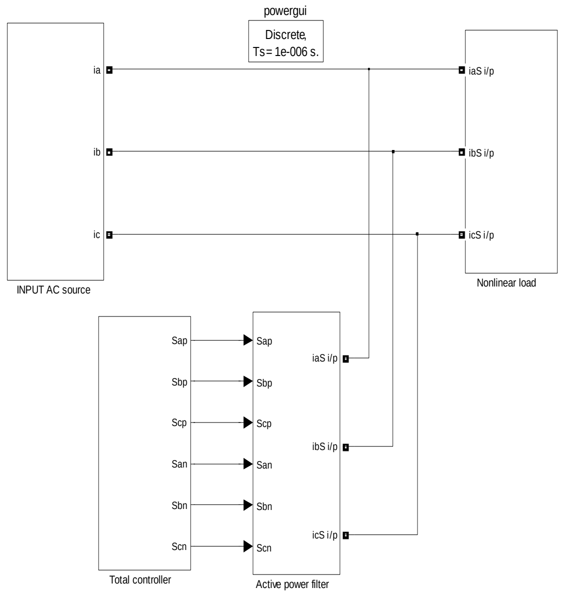

turned on during region (0^o~60^o) and completely off during region (240^o~300^o). During region (300^o~360^o), the switch is controlled by the signal from flip-flop Q_p.

The Presented One-Cycle Control Approach has the Following Features

- Three-phase unity-power-factor and low total harmonic distortion (THD) are achieved by one integrator with reset as well as several logic and linear components. It is simple and reliable.
- Only ac mains current and voltage zero-crossing points are sensed. No sensors for the load current and the APF inductor current are required.
- There is no need to calculate the reference for APF inductor current so that complicated digital computation is eliminated.
- No multipliers are required.
- Constant switching frequency, which is desirable for industrial applications, is achieved.
- For the three-phase bridge converter, only two switches are operated in high frequency, and switching losses are reduced compared to PWM-operated ones.

IV. Design Considerations

DC-Link Capacitor Design

The output dc-link capacitor of voltage source converter is determined by the output voltage ripple. The equation is given by

$$C \geq \frac{P_o}{2 \cdot f_{line}(V_{omax}^2 - V_{omin}^2)} \quad ----(6)$$

Where V_{omax},V_{omin} is the peak to peak of the output dc-link voltage ripple.

For example, suppose the power is 7000 W; APF and output voltage is 400 V with 2% ripple. The line frequency is 60 Hz. The capacitance is calculated by

$$C \geq \frac{7000}{2 \cdot 60 \cdot 400^2 \cdot [(1+0.02)^2 - (1-0.02)^2]}$$

$$C \geq 0.0048\ F$$

Selection of APF Inductance

The concept of the proposed control is using one-cycle control to implement the control key equation as follows:

$$R_s i_{eq} = V_m[1-d] \quad ----(7)$$

Where

$$i_{eq} = (2i_p + i_n)\ (or)\ (i_p + 2i_n)$$

Similar to the peak current model control, there is the convergence condition.

The stability condition is given by

$$m_c \geq \frac{(m_2 - m_1)}{2} \quad ----(8)$$

Where m_1 is the ON slope of the input current and m_2 is the OFF slope of the input current; m_c is the equivalent slope of the carrier signal, which is implemented by integrator with reset.

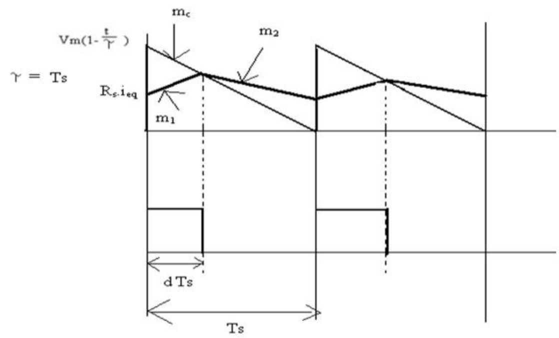

Fig.3 Operation waveforms for the control block

Fig.4 Simulink Model of One-Cycle Controlled APF for the Three-Phase Power System

Considering that the load current is low frequency and the influence of load current can be neglected, we only concern the inductor current in the stability analysis, we have

$$\left.\begin{aligned} m_1 &= R_s \cdot \frac{V_g}{L} \\ m_2 &= R_s \cdot \frac{V_o - V_g}{L} \\ m_c &= \frac{V_m}{\tau} = \frac{V_m}{T_s} \end{aligned}\right\} \quad ----(9)$$

Where $\tau = T_s$

Substitution of (5.16) into (5.15) yields the convergence condition

$$V_m \geq \frac{R_s \cdot T_s}{2L} \cdot (V_o - 2|V_g|) \quad ----(10)$$

$$\geq \frac{R_s \cdot T_s}{2L} \cdot (V_o - 2V_{grms}|\sin(\omega t)|)$$

The convergence condition is dependent on the angular angle of input voltage *wt* and the V_m, which is related to the output power and input voltage. When the convergence condition is satisfied partially, the system will still be stable.

Convergence condition for region 0^o~360^o is given by

$$V_m \geq \frac{R_s \cdot T_s}{2L} \cdot V_o \quad ----(11)$$

But

$$V_m = \frac{V_o \cdot R_s}{R_e} \quad ----(12)$$

V_m is related to input voltage and output power through (5.19). It can be rewritten as

$$V_m = \frac{P_o \cdot R_s \cdot V_o}{\eta \cdot V_{grms}^2} \quad ----(13)$$

Where η is the estimated efficiency. Combination of the above equations yields

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$$L \geq \frac{1}{2} \cdot \eta \cdot T_s \cdot \frac{V_{grms}^2}{P_o} \quad ----(14)$$

The above equation was used to determine the size of inductor. At full load and maximum input voltage condition, the system should be fully stable, and then the inductor can be selected by

$$L \geq \frac{1}{2} \cdot \eta \cdot T_s \cdot \frac{max(V_{grms}^2)}{max(P_o)} \quad ----(15)$$

For η=90%, Ts=20μs, max (V_{grms}) =170 v, max (P_o) =7000W then the minimum inductance is calculated as L = 250μH.

V. Simulation Results and Analysis

The simulation was performed on theSimulink Model of One Cycle Controlled APF for the Three-Phase Power System.

MATLAB/SIMULINK package. Simulink is a software package for modeling, simulating and analyzing dynamic systems. It supports linear and nonlinear systems, modeled in continuous time, sampled time, or a hybrid of the two. The simulation models are built by using the MATLAB7.9 (R2009), Simulink toolbox and are simulated using variable step type of solver.

Test system data:

Table 2

Three-Phase Supply	RMS Voltage (V_{rms}) = 120v , Source inductance(L_s) = 0.4 mH , Supply Frequency (f) = 60 HZ.
Nonlinear Load components	Diode Bridge Rectifier with R_1 = 8.67 Ω ,C_1 =3300 μF,L_o= 3.1mH.
Active Power Filter components	Input Resistance(R_2) = 0.03 Ω , Inductance(L_2) = 0.25mH, Dc-Link Capacitor Capacitance(C_3) = 4800 μF.
Dc-Link capacitor	Voltage (V_C) = 400V.

Here in Fig.4 total system is shown as four sub systems, those are three phase ac source, which is supplying for nonlinear load. Active Power Filter (APF) ,that is connected parallel to the load and also Total control circuit which is giving pulses to the APF such that it will inject compensation currents into the power line which are opposite in phase to the harmonic currents introduced by the nonlinear loads. Ultimate goal is to improve source side power factor to unity, and protects the power grid from the harmonic currents, so improving the power quality.

VI.Results and Discussions

Here the simulation results are cosidered for different cases i.e, without filter, with passive filter and with PWM controlled APF and the results are compared.

Case 1: Simulation results of controlled rectifier load without filter:

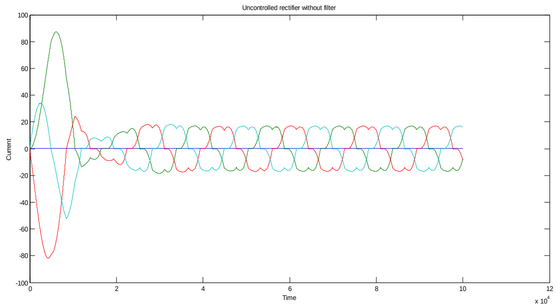

Fig.1A: Three Phase source currents $I_{abc}$with controlled rectifier load without filter

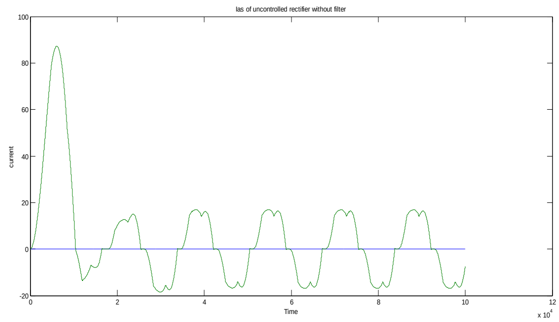

Fig.1B: Phase current Ia of source with controlled rectifier without filter

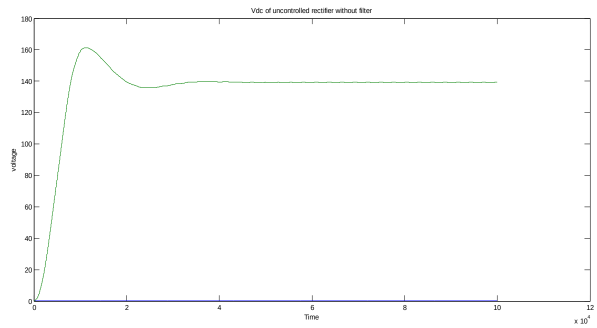

Fig.1C: Vdc ofcontrolled rectifier without filter

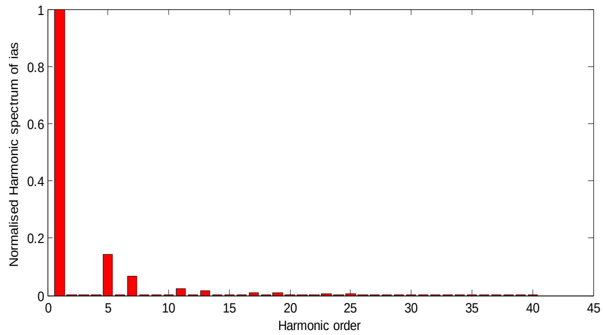

Fig.1D: Harmonic magnitudes of source current without filter

Fig.1A shows the three phase source currents and. Fig.1B shows the source current in phase A for the non linear load without filter. From fig.1A&1B it is clear that the source currents are non sinusoidal and results in presence of harmonic components in the system. Fig.1C shows the output voltage of rectifier.From FFT analysis of source current Harmonic magnitudes in their order are obtained and are shown in Fig.1D. It is observed that 5^{th} ,7^{th} ,11^{th}, 13^{th} ,17^{th} and 19^{th} order harmonics are injected into source current. The system performance can be improved by eliminating the lower order harmonics. The THD obtained in this case is 16.06%.

CASE 2: Simulation results of controlled rectifier load with passive filter:

From fig.2A&2B it is clear that the source currents are non-sinusoidal but improved in shape compared to Fig.1A&1B. Fig.2C shows the output voltage of rectifier. From Fig.2D it is observed that 3rd , 5th ,7th ,11th, 13th ,17th and 19th order harmonics are injected into source current.

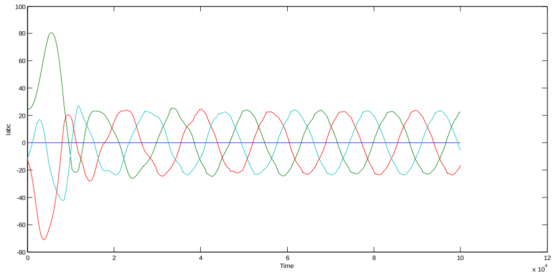

Fig.2A: Three Phase source currents I_{abc} of controlled rectifier load with passive filter

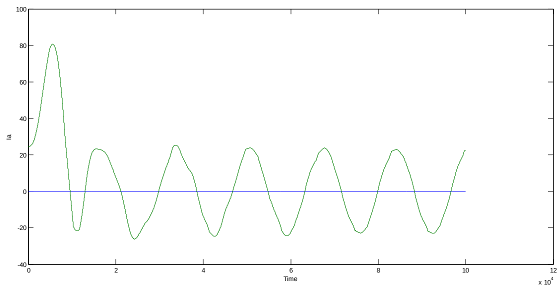

Fig.2B: I_a of controlled rectifier with passive filter

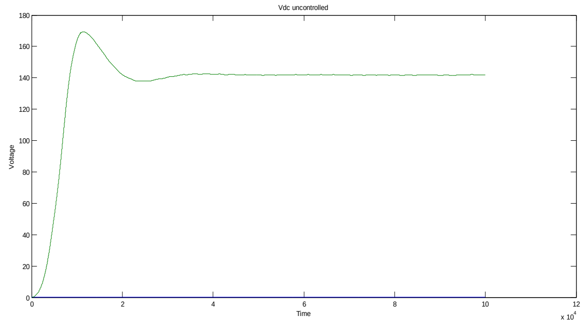

Fig.2C: V_{dc} of controlled rectifier with passive filter

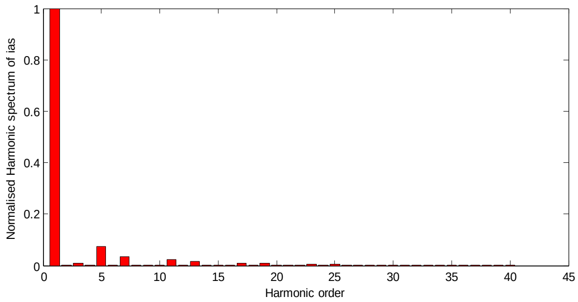

Fig.2D: Harmonic magnitudes of source current with passive filter

The magnitudes of 5th, 7th,11th and 13th harmonics are reduced compare to the Fig.1D. The THD in this case is 8.81% is very less when compared to the THD obtained without filter.

CASE 3: Simulation results of controlled rectifier load with PWM controlled Active Power Filter (APF):

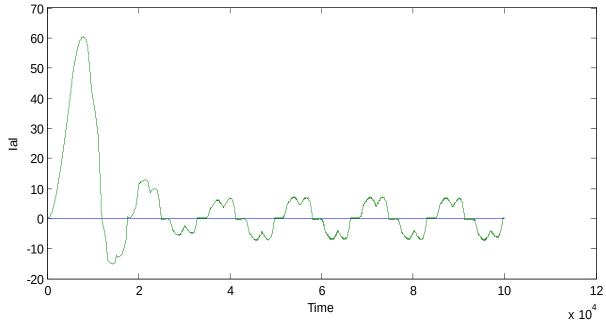

Fig.3A: Load current of phase A with PWM Controlled APF

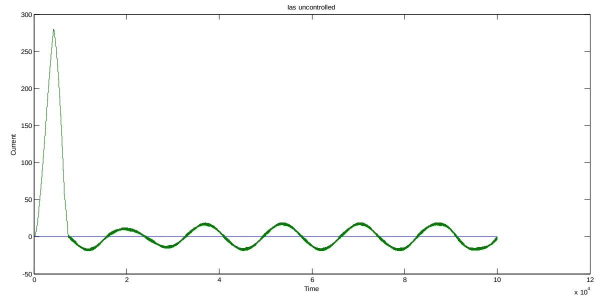

Fig.3B: Source current of phase A with PWM Controlled APF

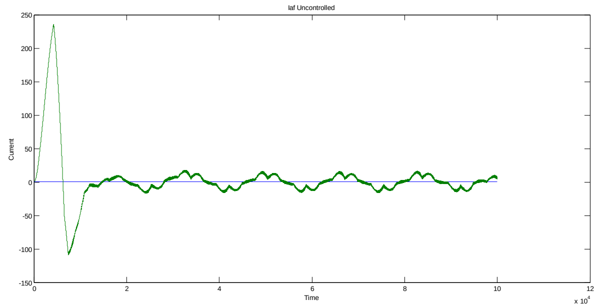

Fig.3C: current in phase Aof PWM Controlled APF

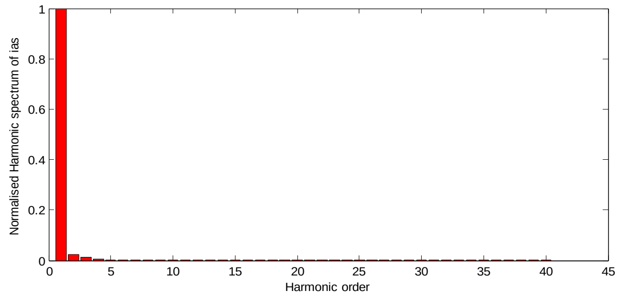

Fig.3E: Harmonic magnitudes of source current with PWM Controlled APF

Fig.3A shows the load current in phase A, Fig.3B shows the source current in phase A and Fig.3C shows the filter current for the non linear load with PWM controlled active filter. From fig.3B it is clear that the source currents are almost sinusoidal. From Fig.3E It is observed that 3rd and 5th order harmonics are injected into source current. Themagnitudes of 5th and 7th harmonics are very much reduced compare to their magnitudes obtained with passive filter. THD obtained in this case is 6.31%, which is less than its value with passive filter.

CASE 4: Simulation results of controlled rectifier load with One Cycle Controlled Active Power Filter (APF):

From fig.4B it is clear that the source currents are almost sinusoidal. From FFT analysis the source current Harmonic magnitudes in their order are obtained and are shown in Fig.4E. It is observed that 3rd and 5th order harmonics are injected into source current.

Table 3 Harmonic values in percentage of fundamental value for α = 0

Harmonic	3rd	5th	7th	11th	13th	17th	19th
Without filter	0	14.2	6.41	2.28	1.55	0.93	0.78
With passive filter	0.87	7.28	3.55	2.5	1.77	0.79	0.73
With PWM active filter	0.75	2.79	0.65	0	0	0	0
With One cycle active filter	0.65	1.56	0.43	0	0	0	0

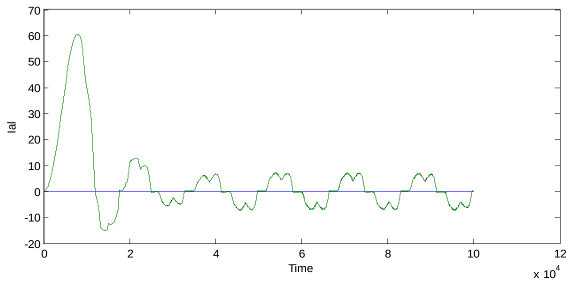

Fig.4A: Load current of phase A with One Cycle controlled APF

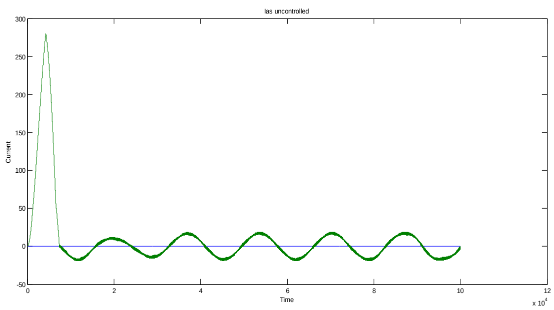

Fig.4B: Source current of phase A with Cycle controlled APF

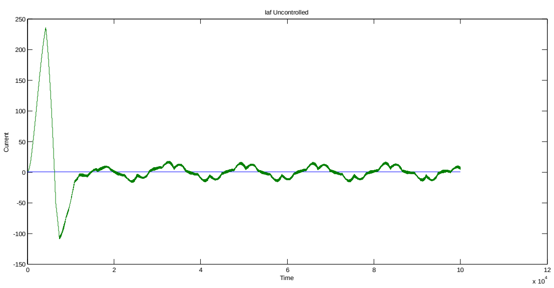

Fig. 4C: current in phase A of One Cycle Controlled APF

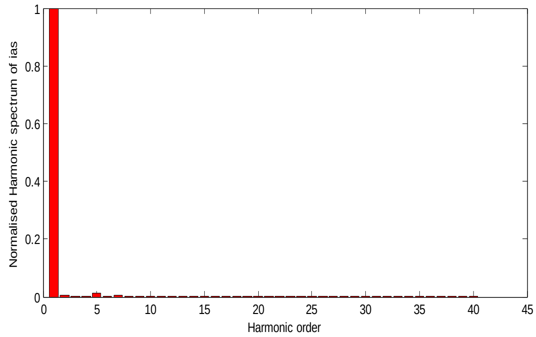

Fig.4D: Harmonic magnitudes of source current with APF

The magnitudes of 5th and 7th harmonics are very much reduced compare to their corresponding magnitudes with PWM Controlled APF. The THD in this case is 2.59% which is very much less than the value obtained with PWM Controlled APF .

Table 4 Harmonic values in percentage of fundamental value for α = 30

Harmonic	3rd	5th	7th	11th	13th	17th	19th
Without filter	0	36.4	5.62	8.39	1.41	3.85	1.31
With passive filter	0.45	12.2	3.88	5.06	0.66	2.42	0.53
With PWM active filter	0.35	4.65	1.45	0	0	0	0
With One cycle active filter	0.27	2.06	0.78	0	0	0	0

Table5 comparison of THD for different cases

Alfa(degree)	THD without filter (%)	THD with passive filter (%)	THD with PWM controlled APF (%)	THD with One cycle controlled APF (%)
Uncontrolled case	13.23	4.98	4.53	2.59
0	10.14	5.54	4.54	2.59
30	15.12	5.78	5.1	2.85
60	18.84	8.27	7.49	7.28

The Magnitudes of harmonic components in percentage of fundamental frequency components for α = 0& α = 30 is shown in Table.3 and Table.4 respectively. It is observed that passive filter is able to reduce the magnitudes of harmonic components but is not able to eliminate them completely. But Active filter is able to eliminate harmonics of 11th and above. It is able to reduce the magnitude of 5th and 7th orders. One Cycle controlled APF is able to Reduce the harmonic magnitudes to very low values in comparison to other filters.

VII. Conclusion

In this paper, a three-phase shunt APF with One cycle control and PWM control has been proposed. The proposed control approach senses only the mains current and the zero crossing of grid voltage. Furthermore, there is no need to calculate the reference for APF inductor current so that the intensive digital computation is eliminated. The proposed approach employs constant switching frequency modulation that is desirable for industrial applications. The simulation results show that the proposed approach effectively cancels the harmonic component of the load, so that the all three-phase line currentsare near sinusoidal.

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