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Application of Active Filters to Nonlinear Loads

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Abstract:- During the last years, the increasing research in power transmission and the electrical engineering development around the world, has given an incentive to new expectations in transmission systems.

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. These usually consist of a bank of tuned LC filters to suppress harmonics. It is proposed to use single **active filter** in place of passive filters with the objective to reduce harmonic currents.

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.

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 LC filters 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 the previous 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.

II. PWM CONTROL OF ACTIVE FILTER

The main aim of an active power filter (APF) is to generate compensating currents into the power system for canceling the current harmonics contained in the nonlinear load current. This will thus result in sinusoidal line currents and unity power factor in the input power system.

Fig.1 shows the configuration of a three-phase active power filter. The active power filter is connected in parallel with a nonlinear load. It consists of a power converter, a DC-link capacitor (C_2) and a filter inductor (L_2). To eliminate current harmonic Components generated by nonlinear loads, the active power filter produces equal but opposite harmonic currents to the point of connection with the nonlinear load.

This results in a reduction of the original distortion and correction of the power factor. The inductor L_2 is used to perform the voltage boost operation in combination with the DC-link capacitor C_2 and functions as a low pass filter for the line current of an active power filter.

The exclusive features of this proposed PWM controlled APF are summarized as follows:

(a) The reference frame transformation and a digital low pass filter are used to compute the harmonics of the nonlinear load current.

(b) The voltage decouplers and pole-zero cancellation method are used in the current controllers of the active power filter to provide fast current harmonic compensation and simplify the control scheme.

(c) The delay times of both current response of an active power filter and DC-link voltage feedback are considered. This results in decreasing the settling time of the DC-link voltage and reducing the high frequency current harmonic components of the power system.

In this block diagram (Fig.1) i_{aL}, i_{bL}, i_{cL} are load currents, i_{af}, i_{bf}, i_{cf} are filter compensation currents, V_{dc} is dc link capacitor voltage of the APF. Here load currents, 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.

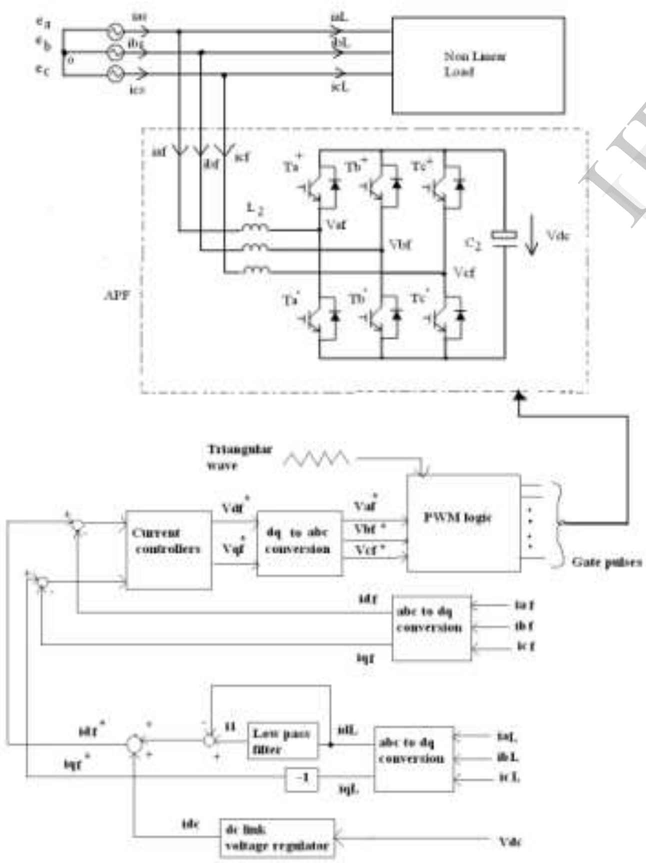


Figure 1: Control Block Diagram of PWM Controlled Active Power Filter

The i_{dL} current is passed through the low pass filter for getting fundamental current i_1, then by making i_{dL}- 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 after that 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.

Compensating current calculations:

Consider Fig.1, where e_a, e_b, e_c and V_{af}, V_{bf}, V_{cf} represent the phase voltages of a power system and the input voltages of a power converter, i_{af}, i_{bf}, i_{cf} and V_{dc2} denote the input currents of the active power filter and the DC-link voltage, respectively. Neglecting the reactors L_s of the input power system, the differential equations of the three-phase active Power filter in Fig. .1 can be described as follows.

$$L_2 \frac{d}{dt} i_{af} = e_a - R_2 i_{af} - v_{af} \quad ----(1)$$

$$L_2 \frac{d}{dt} i_{bf} = e_b - R_2 i_{bf} - v_{bf} \quad ----(2)$$

$$L_2 \frac{d}{dt} i_{cf} = e_c - R_2 i_{cf} - v_{cf} \quad ----(3)$$

$$C_2 \frac{d}{dt} v_{dc2} = f_a i_{af} + f_b i_{bf} + f_c i_{cf} ----(4)$$

Where C_2 is the capacitance of the DC-link capacitor, R_2 and L_2 are the resistance and inductance of the active power filter line reactors, respectively, f_a, f_b, f_c are Switching functions, and the possible values are $0, \pm\frac{1}{3}$ *and* $\pm\frac{2}{3}$. For model analysis and controller design, the three-phase voltages, currents and switching functions can be transformed to a *d-q-o* rotating frame. This yield,

$$\begin{bmatrix} X_d \\ X_q \\ X_o \end{bmatrix} = \frac{2}{3} \begin{bmatrix} \sin\theta_e & \sin\left(\theta_e - \frac{2\pi}{3}\right) & \sin\left(\theta_e + \frac{2\pi}{3}\right) \\ \cos\theta_e & \cos\left(\theta_e - \frac{2\pi}{3}\right) & \cos\left(\theta_e + \frac{2\pi}{3}\right) \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix} \cdot \begin{bmatrix} X_a \\ X_b \\ X_c \end{bmatrix}$$

Where θ_e the transformation angle of the rotating frame and x is denotes currents, voltages or switching functions. From equations (1)-(5), the state model in the rotating frame can be written as

$$L_2 \frac{d}{dt} i_{df} = e_d - R_2 i_{df} + \omega_e L_2 i_{qf} - v_{df} \quad --(6)$$

$$L_2\frac{d}{dt}i_{qf} = e_q - R_2 i_{qf} - \omega_e L_2 i_{df} - v_{qf} \quad --(7)$$
$$C_2\frac{d}{dt}v_{dc2} = \frac{3}{2}(f_d i_{df} + f_q i_{qf}) \quad --(8)$$

Where

$$v_{df} = f_d v_{dc2} \quad --(9)$$
$$v_{qf} = f_q v_{dc2} \quad --(10)$$

ω_e is the frequency of the power system and the subscripts *'d* and *'q'* are used to denote the components of the *d*- and *q*-axis in the rotating frame, respectively. Equations (6) - (8) will be used to derive the block diagram of the active power fitter and calculate the input voltage commands of power converter.

Let transformation angle θ_e be equal to the angle of phase voltage. Assume that the three-phase voltages are balanced. This yields the voltage components:

$$e_d = V_m \quad ----(11)$$
$$e_q = 0 \quad ----(12)$$

Where V_m is the peak value of the phase voltage of the input power system.

When the phase voltages of power system are balanced, P_L and q_L depend only on i_{dL} and i_{qL}, respectively. For a fully harmonic-current compensated active power filter system, the instantaneous real power P_s and reactive power q_s from the power system can be expressed as:

$$P_S = \frac{3}{2}V_m i_1 \quad ----(13)$$
$$q_s = 0 \quad ----(14)$$

Where the fundamental component of the load current i_1 can be obtained from the *d*-axis current i_{dL} by means of a low pass filter. The corresponding reference currents, i_{df}^* and i_{qf}^* of the active power filter in the rotating frame are

$$i_{df}^* = i_1 - i_{dL} \quad ----(15)$$
$$i_{qf}^* = -i_{ql} \quad ----(16)$$

Equ. (15) and equ. (16) are obtained from the proposed novel calculation method for reference currents of the active power filter by using the load current feedback, reference frame transformation and a digital low pass filter. It is noted that the reference currents can be obtained simply by subtracting the fundamental component from the measured load currents regardless of whether the load is balanced or not.

III. DESIGN CONSIDERATIONS

In this, design of Low Pass Filter for Reference Current calculation, Design of DC-link Voltage Regulator, Design of Current Regulators etc. are explained in detail.

Design of Low Pass Filter for Reference Current calculation

When ω_a is small, the current harmonics on the source side and the DC-link fluctuation voltages will decrease, while the settling time of the DC-link voltage and the compensation time of current harmonics will increase. Therefore, the design of the cutoff frequency ω_a will strikingly affect the active power filter compensation characteristics. For balanced load.

$$i_{al} = i_1 \sin(\theta_e - \varphi_1) + \sum_{n=2}^{\infty} i_n \sin(n\theta_e - \varphi_n) \quad --(17)$$

$$i_{bl} = i_1 \sin\left(\theta_e - \frac{2\pi}{3} - \varphi_1\right) + \sum_{n=2}^{\infty} i_n \sin\left[n\left(\theta_e - \frac{2\pi}{3}\right) - \varphi_n\right] \quad --(18)$$

$$i_{cl} = i_1 \sin\left(\theta_e + \frac{2\pi}{3} - \varphi_1\right) + \sum_{n=2}^{\infty} i_n \sin\left[n\left(\theta_e + \frac{2\pi}{3}\right) - \varphi_n\right] \quad --(19)$$

Introducing the frame transformation of equation (5) to equations (17 to 19) the *d*-axis current for balanced load can be written as.

$$i_{dl} = i_1 \cos\varphi_1 + \sum_{n=3,6,9,..}^{\infty}[i_{n+1}\cos(n\theta_e - \varphi_{n+1}) - i_{n-1}\cos(n\theta_e - \varphi_{n-1})] \quad --(20)$$

Similarly for unbalanced load

$$i'_{dL} = \frac{i'_1}{\sqrt{3}}\cos\left(\frac{\pi}{6} - \varphi'_1\right) - \frac{i'_1}{\sqrt{3}}\cos\left(2\theta_e - \frac{\pi}{6} - \varphi'_1\right) + \sum_{n=2}^{\infty}\frac{i'_n}{\sqrt{3}}\left\{\cos\left[(n-1)\theta_e + \frac{\pi}{6} - \varphi'_n\right] - \cos\left[(n-1)\theta_e - \frac{\pi}{6} - \varphi'_n\right]\right\} \quad ---(21)$$

It can be seen from equations (20) and (21) that the first are the fundamental component of the load current and both are of DC values. The lowest frequency in the *d*-axis current is the third harmonic for the balanced load and the fundamental frequency for the case of unbalanced load. Thus, to obtain the fundamental component for both the cases of balanced and unbalanced loads, the cutoff frequency ω_a must lie between the DC frequency (0 rad/sec) and the fundamental frequency (377 rad/sec). In this paper, $\omega_a = 100\ rad/sec$ is chosen. This yields a delay time constant T_a of 10ms.

IV. SIMULATION RESULTS AND ANALYSIS

The simulation was performed on the

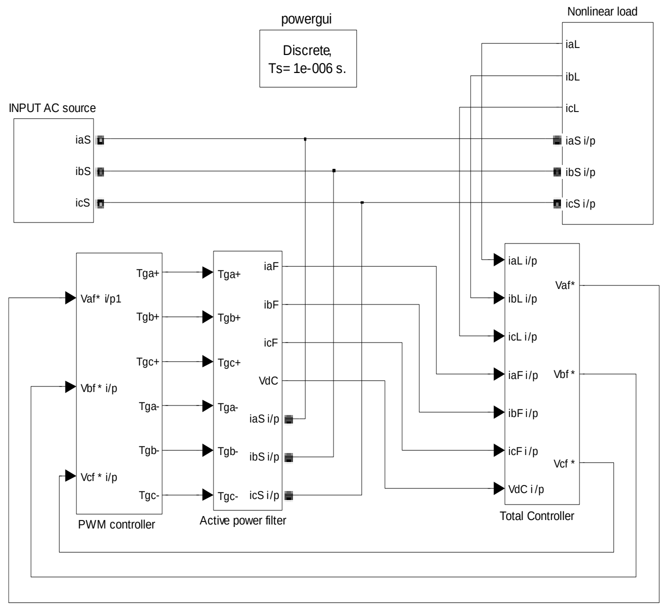


Fig. Simulink Model of PWM Controlled APF for the Three-Phase Power System.

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.

SIMULINK MODELS OF PWM CONTROLLED APF

Detailed simulink models of power system along with the active power filter is shown below.

Test system data:

TABLE 1

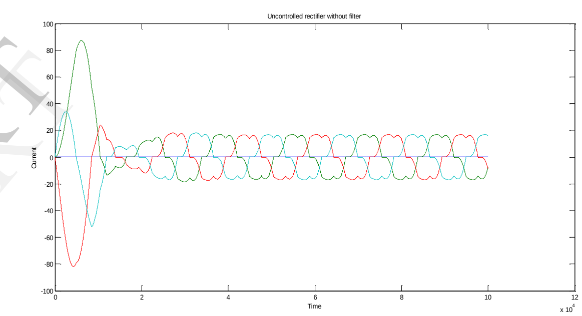
Three-Phase Supply	RMS Voltage (V_{rms}) = 120v , Source inductance(L_s) = 0.4 mH , Supply Frequency (f) = 60 HZ.
Nonlinear Load components	Diode Bridge Rectifier with R_1 = 8.67 Ω , C_1 =3300 µF, L_o= 3.1 mH.
Active Power Filter components	Input Resistance(R_2) = 0.03 Ω , Inductance(L_2) = 0.25mH, Dc-Link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

Here in Fig. total system is shown as five 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.

V.RESULTS AND DISCUSSIONS

Here the simulation results are shown 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 uncontrolled rectifier load without filter:



FigA: Three Phase source currents Iabc with uncontrolled rectifier load without filter

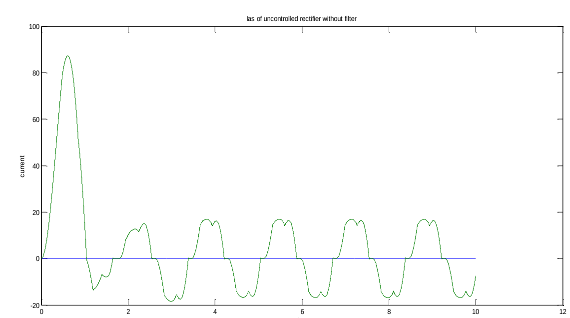


Fig B: Phase current Ia of source with uncontrolled rectifier without filter

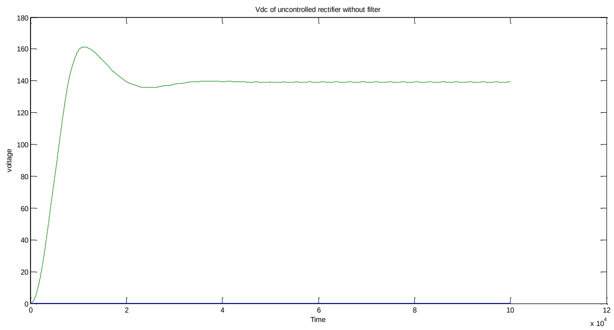


Fig C: Vdc of uncontrolled rectifier without filter

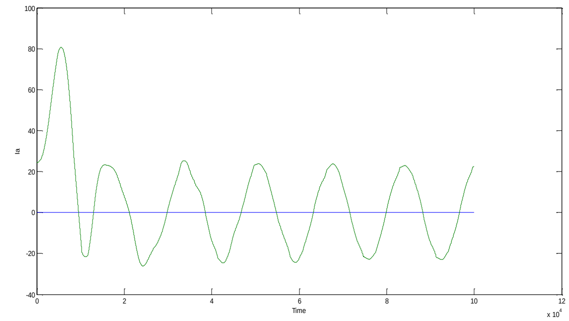


Fig.B: Ia of uncontrolled rectifier with passive filter

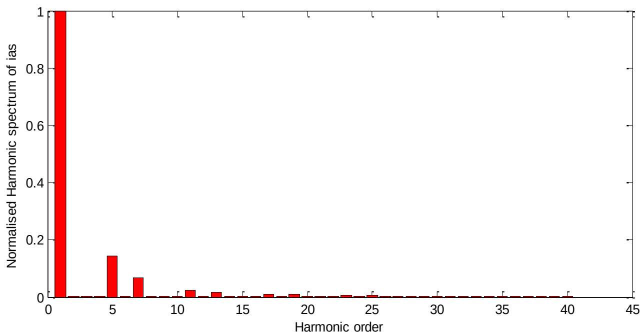


Fig D: Harmonic magnitudes of source current without filter

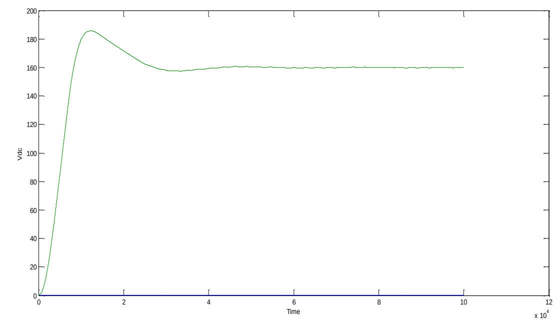


Fig.C: Vdc of uncontrolled rectifier with passive filter

Fig.A shows the three phase source currents and. Fig.B shows the source current in phase A for the non linear load without filter. From fig.A&B it is clear that the source currents are non sinusoidal and results in presence harmonic components in the system. Fig.C shows the output voltage of rectifier .From FFT analysis of source current Harmonic magnitudes in their order are obtained and are shown in Fig.D. 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 in this case is 16.06%.

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

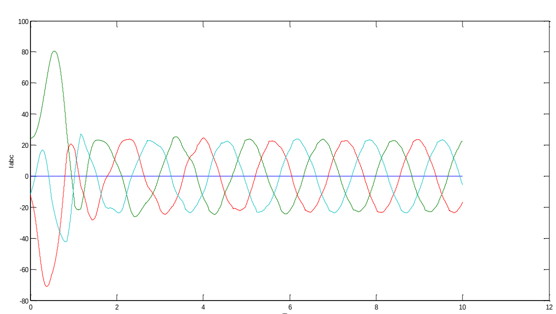


Fig.A: Three Phase source currents Iabc of uncontrolled rectifier load with passive filter

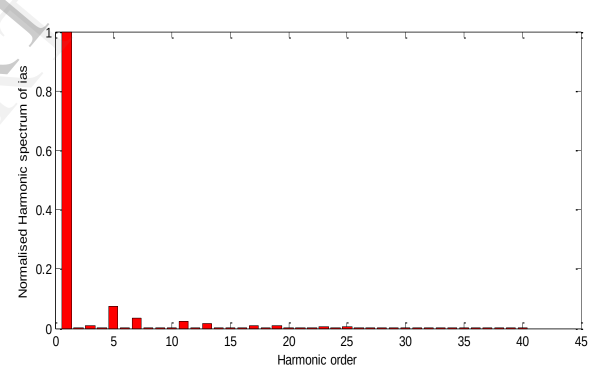


Fig.D: Harmonic magnitudes of source current with passive filter

Fig.A shows the three phase source currents and Fig.B shows the source current in phase A for the non linear load with passive filter. From fig.A&B it is clear that the source currents are non sinusoidal but improved compare with previous A&B that is without filter. Fig.C shows the output voltage of rectifier .From FFT analysis the source current Harmonic magnitudes in their order are obtained and are shown in Fig.D. t is observed that 3^{rd} , 5^{th} ,7^{th} ,11^{th}, 13^{th} ,17^{th} and 19^{th} order harmonics are injected into source current. The magnitudes of 5^{th} , 7^{th} ,11^{th} and 13^{th} harmonics are reduced compare to the fig.D. The THD in this case is 8.81%.

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

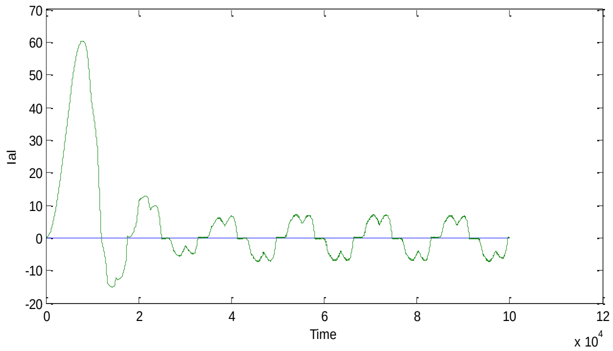


Fig.A: Load current of phase A with APF

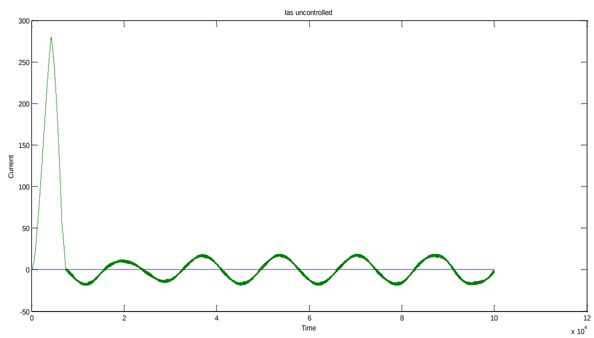


Fig.B: Source current of phase A with APF

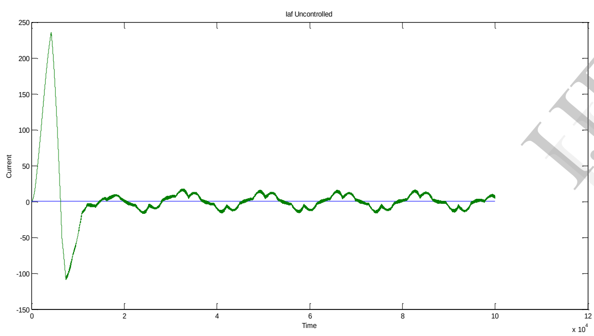


Fig.C: Filter current of phase A

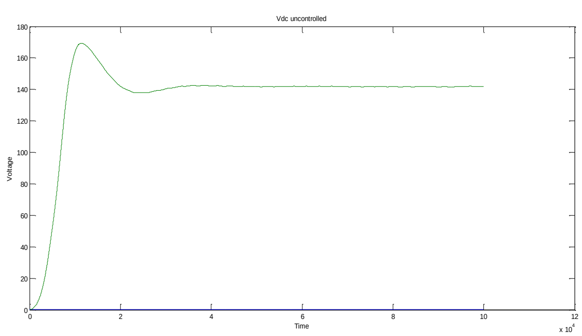


Fig.D: Vdc of uncontrolled rectifier load with APF

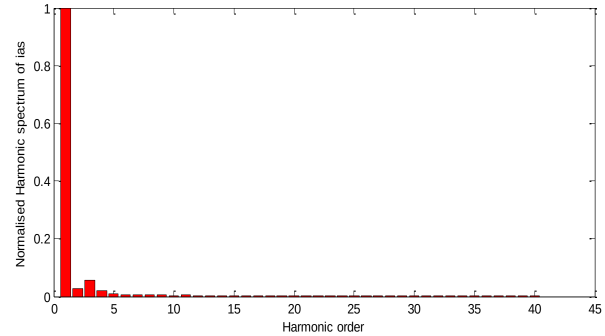


Fig.E: Harmonic magnitudes of source current with APF

Fig.A shows the load of phase A current, Fig.B shows the source current of phase A and Fig.C shows the filter current for the non linear load with active filter. From fig.B it is clear that the source currents are almost sinusoidal. Fig.D shows the output voltage of rectifier .From FFT analysis the source current Harmonic magnitudes in their order are obtained and are shown in Fig.E. It is observed that 3rd and 5th order harmonics are injected into source current. The magnitudes of 5th and 7th harmonics are very much reduced compare to the previous two cases. The THD in this case is 6.31% only.

TABLE 5.2 comparison of THD for different cases

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

Table5.3 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	0.784
With passive filter	.877	7.28	3.55	2.5	1.77	0.79	0.738
With active filter	4.87	1.79	0.4	0	0	0	0

Table5.4 Harmonic values in percentage of fundamental value for α = 30

Harmonic	3^{rd}	5^{th}	7^{th}	11th	13th	17^{th}	19^{th}
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 active filter	5.88	0.93	0.4	0	0	0	0

The Magnitudes of harmonic components in percentage of fundamental frequency components for α = 0 is shown in Table5.3. It is observed that passive filter is able to reduce the magnitudes of harmonic components but is not able to eliminated them completely. But Active filter is able to eliminate harmonics of 11^{th} and above. It is able to reduce the magnitude of 5^{th} and 7^{th} orders.

The Magnitudes of harmonic components in percentage of fundamental frequency components for α = 30 is shown in Table5.3. It is observed that passive filter is able to reduce the magnitudes of harmonic components but is not able to eliminated them completely. But Active filter is able to eliminate harmonics of 11^{th} and above. It is able to reduce the magnitude of 5^{th} and 7^{th} order harmonics.

VI. CONCLUSION

In this project, a three-phase shunt APF with 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 have demonstrated that the proposed approach effectively cancels the harmonic component of the load, so that the all three-phase line current are near sinusoidal.

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