A Fixed Switching Frequency Adaptive Sliding Mode Controller for Shunt Active Power Filter System

Soumya Ranjan Mohapatra, Pravat Kumar Ray

***Abstract*— The theory, design and simulation of a fixed frequency pulse width modulation (PWM) based adaptive sliding mode current control for single phase shunt active power filter (APF) to improve power quality is presented in this article. Artificial neural network (ANN) based modified control strategy is being used to control the DC capacitor voltage as well as to generate reference source current. The application of ANN enhances the convergence rate of APF and also makes it adaptive under variable load conditions. The instantaneous phase of the source voltage is extracted by a phase locked loop (PLL). The same phase is used by ANN for calculating the reference source current. That is why the proposed APF is applicable under both nominal and distorted voltage source. The complete non-linear system is analyzed and simulated using MATLAB/Simulink software. Simulation results are presented to validate the theory.**

***Keywords*— Sliding mode control, Active Power Filter, Artificial Neural Network, Power Quality, Constant Frequency, Harmonics**

I. INTRODUCTION

The extensive use of nonlinear load (computers, TVs, refrigerators, printers, fax machines, etc) causes harmonic distortion. Harmonics increase the conduction losses, eddy current losses and also have bad impacts on other loads connected to the same voltage source. Passive filters can be used to improve the power quality, but these are expensive and bulky solutions. These problems can be overcome by use of active power filter (APF). Two types of APFs exist; shunt APFs and series APFs. Shunt APFs are used to compensate current harmonics, while series APFs are used to compensate the voltage harmonics caused by nonlinear loads. In this article a single phase shunt APF is presented. Different control strategies have been applied to control single phase shunt APFs in the literatures [1]-[8]. However sliding mode (SM) control is well known due to its ease of implementation and robustness. SM controllers have a property of operating at infinite and varying switching frequency such that the state variables of the system follow the required trajectory. However high and varying switching frequency causes losses and even damage of the system.

Various techniques have been proposed in sliding mode controlled APFs [1]-[3] to control the switching frequency. These are mainly based on hysteresis modulation. In literature [7] a adaptive hysteresis band based modulation technique is used to fix the switching frequency. But in DC to DC converters [10] and DC-AC inverters, [12] fixed switching frequency SM controllers are employed using pulse width modulation technique. In the proposed APF system a pulse width modulation (PWM) base SM controller is being used to fix the switching frequency at a constant value. As harmonic content in the source current is reduced significantly in unipolar PWM, unipolar PWM technique is applied in this literature.

APF control techniques mainly divided into two categories such as current control of APF and control of filter capacitor voltage along with generation of reference source current. In literature [1]-[3] a PI controller is being used to control the filter capacitor voltage as well as to generate the reference source current. Literature [8] and [13] has taken the advantages of artificial neural network (ANN) to extract the load harmonics currents. The application of ANN makes the harmonic extraction faster than that of control strategies presented in [1]-[3] and also makes the APF adaptive to various load currents. In this Literature a combined control strategy based on a modified ANN based harmonic extraction circuit and Proportional-Derivative (PD) controller is being used for controlling the DC capacitor voltage and generating the reference current which makes the convergence rate further faster than that of literature [8] and [13]. The Application of SM control strategy, ANN and PD controller makes the APF robust under distorted source and variable load conditions.

This paper is organized as follows. In section II the mathematical model of the single phase shunt APF is described. Theory and derivation of a new control strategy combining both constant frequency sliding mode current control and ANN based adaptive harmonic extraction circuit is presented in section III. Simulation results are presented in section IV to validate the theory of the proposed control strategy. Finally conclusions are given in section 5.

II. SHUNT APF MODEL

Fig.1 shows the configuration of single phase shunt active power filter connected in parallel with both voltage source and nonlinear load. A full bridge rectifier with resister-capacitor (RC) connected in parallel is used as a nonlinear load. The input of the inverter is connected to a large capacitor and output is connected to mains supply through an inductor. This inverter is used to shape the source current same as that of source voltage. To shape the source current it is required to

Soumya Ranjan Mohapatra and Pravat Kumar Ray are with national institute of technology Rourkela, India. E-mail: soumyaranjan597@gmail.com , rayp@nitrkl.ac.in

maintain the capacitor voltage greater than the peak value of source voltage. The value of capacitance and inductance is chosen suitably so as to meet the desired specifications as per literature [1]. As the switches of one leg of an inverter cannot be in on state at a time TABLE I can be assumed. Assuming 'U' as the control input. Considering Table I the mathematical model of the single phase shunt APF can be written as

$$\frac{dI_L}{dt} = \frac{1}{L}(V_S - I_L R - V_C U) \tag{1}$$

$$\frac{dV_C}{dt} = \frac{I_L}{C}(U) \tag{2}$$

III. CONTROL STRATEGY

In this section both constant switching frequency SM current controller design and the application of ANN and PD controller for controlling the DC capacitor voltage along with calculating reference source current is described.

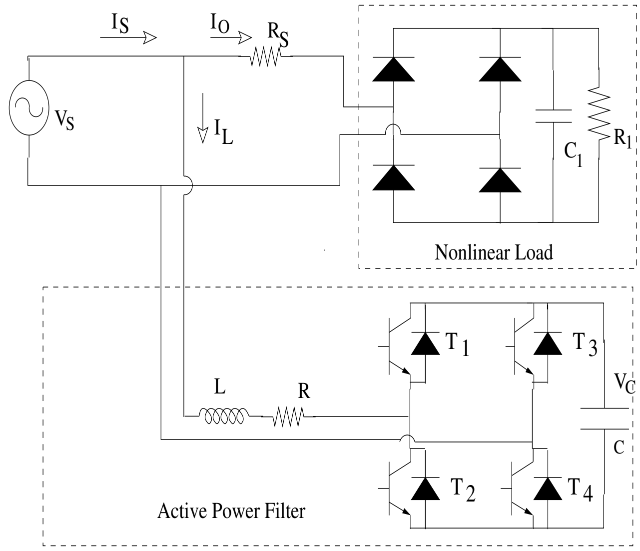

Fig.1. Single phase shunt active power filter

TABLE I

Switching states and control input

T_1	T_4	T_2	T_3	U
ON	ON	OFF	OFF	1
OFF	OFF	ON	ON	-1
OFF	OFF	OFF	OFF	0

A. *Sliding Mode Control*

As the APF system is a nonlinear system and the control of APF is completely based on control of the switches, SM control can be applied to bring the system's state trajectory onto a user defined surface called sliding surface and to maintain the trajectory on that surface for the rest of the time. To make the source current follow reference source current a sliding surface is defined as

$$S = (I_S - I_S^*) + \lambda \int (I_S - I_s^*) \tag{3}$$

Where I_S^* is reference source current and λ is a strictly positive constant known as sliding co-efficient.

After Design of the sliding surface, the next important aspect is to check for existence condition for sliding mode to exist in the vicinity of the sliding surface which is possible only when the tangent to the state trajectory is made to direct towards the sliding surface. As shown in Fig.2 for $S > 0$ the actual trajectory lies above the sliding surface $S = 0$. When $S > 0$, I_S is greater than I_S^*. To bring the trajectory on to the sliding surface the extra amount of current must be used to charge the capacitor. Similarly when $S < 0$ to make actual source current follow the reference source current capacitor must supply the adequate amount of current. With proper control of the switches of the APF the reaching of the trajectory on to the sliding surface and maintaining the trajectory on the surface is possible, which are known as reaching and existence of sliding mode control strategy respectively. As per literature [10] the SM control exists only if local reachability condition was satisfied. This can mathematically expressed as

$$\lim_{S \to 0} S.\dot{S} < 0 \tag{4}$$

The above condition can be satisfied by controlling the sign of $\dot{S}$ which is possible with proper control of the switches. The discrete control law which maintains the state trajectory on the sliding surface $S = 0$ can be expressed as [11]

$$U = \begin{Bmatrix} 1 & \text{if } S>0 \\ -1 & \text{if } S<0 \end{Bmatrix} \tag{5}$$

For ideal SM control to exist the switches of APF must be operated at infinitely high frequency. Different techniques have been applied to limit the switching frequency of the

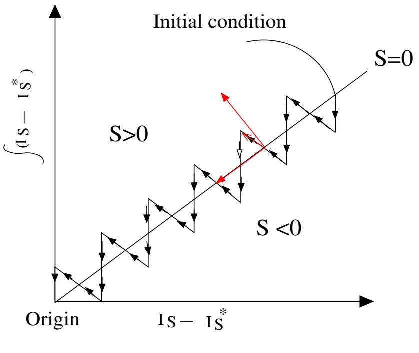

Fig.2. Existence condition

single phase APF to a maximum value in the literature [1]-[3], which causes chattering in the vicinity of the sliding surface. As shown in Fig.2 the actual trajectory has two component, one is perpendicular to sliding surface and another along the sliding surface pointing towards the equilibrium point. The component along the sliding surface is responsible for both sliding motion and stability of the system. Since the movement of the trajectory is due to appropriate control of the switches, which is governed by the discrete control law as in equation (5), the continuous switching action responsible for horizontal component of the trajectory must lie between 0 and 1. This continuous switching action known as equivalent control input (U_{eq}) of the system, which can be found by using the condition $\dot{S} = 0$ as per literature [10].

From Fig.1

$$I_S = I_L + I_O \qquad (6)$$

Also we can write

$$I_S^* = I_L^* + I_O \qquad (7)$$

Where I_L^* is the reference compensating current.

Considering (1),(3), (6) and (7)

$$\frac{1}{L}\{V_S - I_L R - V_C U\} - \frac{dI_L^*}{dt} + \lambda(I_S - I_S^*) = 0 \qquad (8)$$

From (8) we can obtain

$$U_{eq} = \frac{1}{V_c}\left\{V_S - I_L R - L\frac{dI_L^*}{dt} + \lambda L(I_S - I_S^*)\right\} \qquad (9)$$

As U_{eq} is continuous and lies between 0 and 1, considering (9) we obtain

$$0 < \frac{1}{V_C}\left\{V_S - I_L R - L\frac{dI_L^*}{dt} + \lambda L(I_S - I_S^*)\right\} < 1 \qquad (10)$$

In classical PWM based APF as in [14] duty ratio (d) can be expressed as

$$d = \frac{U_{ref}}{V_{tri}} \qquad (11)$$

Where U_{ref} is the control modulating signal and V_{tri} is the peak amplitude of triangular signal. Also 'd' can again be expressed as

$$d = \frac{T_{ON}}{T} \qquad (12)$$

Where T_{ON} is on time and T is total time period in which switches operates, which is constant in PWM. From (12) we can write

$$0 < d < 1 \qquad (13)$$

Comparing duty ratio control of classical PWM based APF and equivalent control input of proposed SM control based APF and considering (10) and (13) and taking $V_{tri} = 1$ one can obtain

$$U_{ref} = \frac{1}{V_C}\left\{V_S - I_L R - L\frac{dI_L^*}{dt} + \lambda L(I_S - I_S^*)\right\} \qquad 14)$$

The above calculated U_{ref} is used as modulating signal for unipolar PWM as per literature [12]. The switches of the APF operate at constant frequency which is nothing but the frequency of the triangular wave used as a carrier wave in unipolar PWM. The difference in PWM technique proposed in [14] and this paper is only with the modulating control signal used for PWM.

B. Modified ANN Based Control Strategy

The discretized instantaneous nonlinear load current can be represented by

$$I_O = \sum_{n=1}^{\infty} I_n \sin(kn\omega\Delta\tau - \theta_n) \qquad (15)$$

Where I_o is the load current, I_n is the peak value of various components of load current, θ_n is the phase angle difference between source voltage and various components load current, $\Delta\tau$ is the discrete sampling time interval and $k\omega\Delta\tau$ is the instantaneous phase of source voltage, where $k = 0,1,2...$ The load current can be further expressed as

$$I_O = W_1^1 \sin(k\omega\Delta\tau) + W_2^1 \cos(k\omega\Delta\tau) + \sum_{n=2}^{\infty}[W_1^n \sin(nk\omega\Delta\tau) + W_2^n \cos(nk\omega\Delta\tau)] \qquad (16)$$

Where $W_1^1, W_2^1 ... W_1^n, W_2^n$ are constants. $W_1^1 \sin(k\omega\Delta\tau)$ is the fundamental source current and $W_2^1 \cos(k\omega\Delta\tau)$ is the fundamental quadrature current. In literature [8] and [13], (16) is used by ANN for extracting the fundamental source current from load current. This is a lengthy process as all $2n$ number of weights have to be updated to slow varying variables to get the fundamental source current.

In this literature a modified ANN based fundamental source current extraction circuit is presented as in [15] which reduces weight updating time from 2 to 3 cycle to almost half cycle of source voltage signal. Considering (16) one can obtain

$$I_O = W_1^1 \sin(k\omega\Delta\tau) + W_2^1 \cos(k\omega\Delta\tau) + periodic\ signal \qquad (17)$$

In this paper instead of updating $2n$ weights only 2 weights W_1^1 and W_2^1 are updated to slow varying variables to get the fundamental source current.

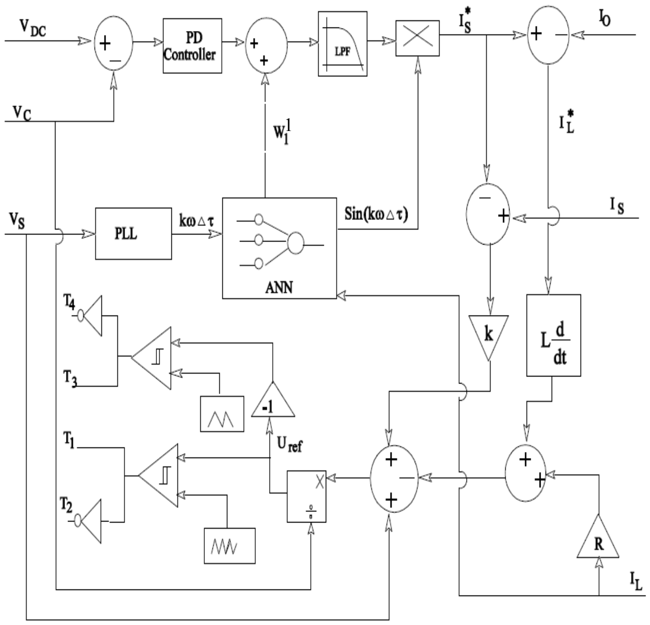

Fig.3. Adaptive sliding mode controller

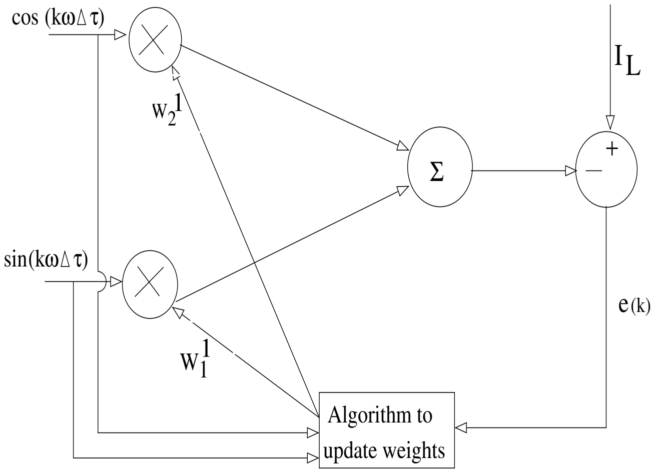

Fig.4. Modified ANN based extraction circuit

As shown in Fig.2 the input vector is taken as a matrix $X=\begin{pmatrix}\sin(k\omega\Delta\tau)\\ \cos(k\omega\Delta\tau\end{pmatrix}$ and the weight vector is taken as a matrix $W=\begin{pmatrix}W_1^1\\ W_2^1\end{pmatrix}$. A modified Widrow-Hoff delta rule based weight updating algorithm is being used to update the weights W_1^1 and W_2^1. The algorithm can be stated as follows

$$W(k+1)=W(k)+\Delta W \tag{18}$$

Where $\Delta W=\dfrac{\rho e(k)X(k)}{X^T(k)X(k)}$, ρ is the learning rate which is always greater than zero.

The error between actual load current and estimated load current $e(k)$ instead of converging close to zero converges to a periodic signal almost equal to sum of all harmonic components of load current put together. As discrete sampling time interval ($\Delta\tau$) in which updating process is carried out is much less than that of period of variation of $e(k)$, updating process takes place easily. Learning rate is an important factor in the weight updating process. Lower value of learning rate takes a long time to update the weights to their desired value. While higher value of learning rate causes oscillation of the weights around their desired value. A suitable value of learning rate is chosen by taking care of amplitude of oscillation of weights and updating time.

For APF to work, the capacitor voltage must be kept above than peak value of source voltage. To keep the capacitor voltage at desired level a PD controller is used. Proportionality constant (k_p) of PD controller depends on the real power loss in the active power filter to maintain the capacitor voltage level. As per [5] k_p can be calculated by the formula given below.

$$k_p=\frac{2CfV_{DC}}{V_p} \tag{19}$$

Where C is the capacitance value, f is the frequency of the source voltage, V_{DC} is the reference filter capacitor voltage, and V_p is the peak value of source voltage. As derivative controller improves the transient response and reduces the peak overshoot, derivative constant (k_d) of the PD controller is properly adjusted by heat and trial for a better capacitor voltage regulation.

The output of the PD controller gives the peak value of the filter capacitor charging current and the value of the weight W_1^1 of ANN based extraction circuit gives peak value of the fundamental source current. The peak value of the reference source current is calculated as sum of weight W_1^1 and the output of the PD controller. The peak value of the reference source current is then passed through the low pass filter to remove the high frequency component, which helps in reducing the harmonic content in the source current. After getting reference source current SM current control strategy is being applied to control the switches of the APF.

IV. RESULT ANALYSIS

To validate the system performance overall APF model is computer simulated using MATLAB/Simulink software version 2013 (a). The solution method chosen was runga-kutta (order 4) with fixed step size $1e^{-06}$. The simulation was carried out in discrete time domain with sampling time interval $1e^{-06}$. The parameters used for simulation are given below.

R_S-2Ω		V_{DC}-	200V	ρ -	0.00002
R-0.7Ω		$V_{S\,(R.M.S)}$-	110V	λ-	20000
C-1500 μ F		k_p -	0.24		
L-4mH		k_d -	0.001		

R_S is the source resistance. Derivative constant k_d is taken with filter coefficient as1. The cut-off frequency of low pass filter is set as 90Hz. Switching frequency is taken as 20000 Hz and source voltage frequency is taken as 60Hz. System performance is analyzed on two different load condition, such as: 1) high load (real power and reactive power consumed by non-linear load is 975 watts and -309 watts respectively); 2) low load (real power and reactive power consumed by non-linear load is 663 watts and -183 watts respectively). Fig.5 shows the source voltage and load current waveforms under high load conditions when the source is nominal. The Total Harmonic Distortion (THD) of all voltage and current wave forms are measured up to 50th harmonic to validate the theory.

The THD of source voltage and load current is found to be 0% and 52.92 % respectively. After the application of proposed APF, harmonics are compensated to give the shape of source current same as that of source voltage as shown in Fig. 6. THD of the source current is found to be 2.87% measured at time 0.06 second for 2 cycles. In reality voltage source waveforms are found to be distorted. APF proposed in [2] is applicable for both distorted and nominal voltage source, but it is not suitable when frequency of the source voltage is varied more than 2%. The APF proposed in this literature is suitable in wide variation of amplitude and frequency of the source voltage.

Fig.7 shows the source voltage and source current waveforms when source is distorted and load is high. Source voltage and load current THD are found to be 7.05% and 59.30% respectively. After compensation THD in the source current is reduced to 2.88% which is very close to the THD in the source current under nominal source and same load conditions. From this it is clear that proposed control strategy is not much affected by source voltage distortion.

Fig 8 shows the adaptive behavior of the proposed control strategy under step load changes. The variation of the source current with high to low nonlinear load variation is shown in Fig.8. Fig. 9 shows the behavior of the proposed control strategy under wide range of frequency variation. It is clear that propose APF adopts itself to different frequencies within very short interval of time so there is no significant phase difference between source voltage and source current. . From both the Figures it is clear that proposed control strategy gives good transient response and adaptive behavior under both step load changes and frequency changes.

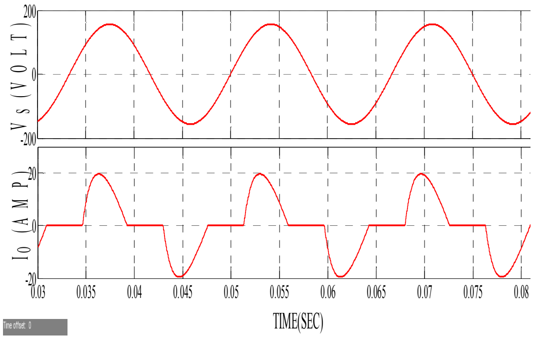

Fig.5 Source voltage (top), load current (bottom), nominal source

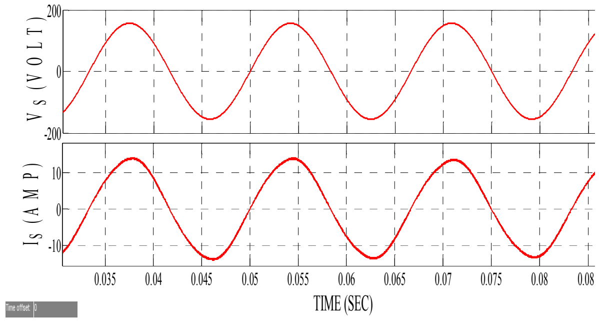

Fig. 6 Source voltage (top), source current (bottom)

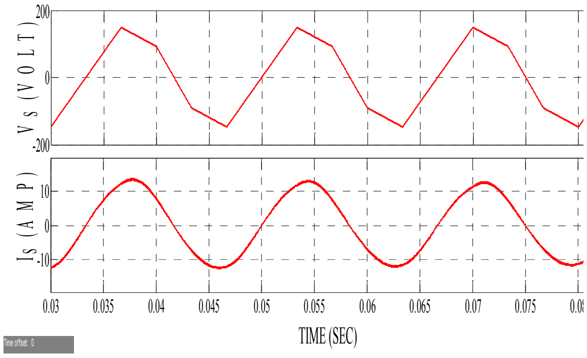

Fig.7 Source voltage (top), source current (bottom), distorted source

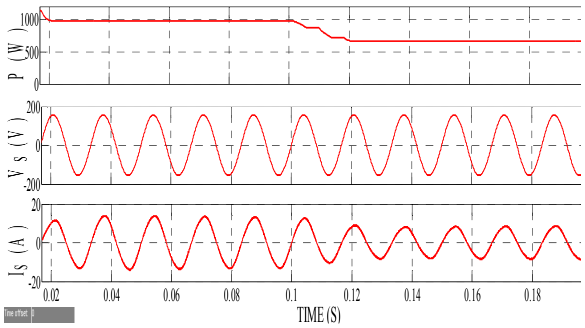

Fig.8 Load real power (top), source voltage (middle), load current (bottom), high to low nonlinear load

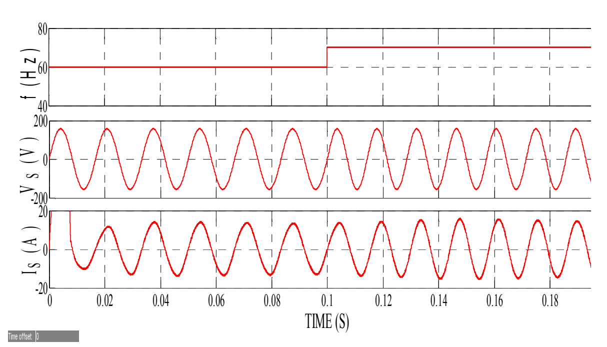

Fig.9 Source voltage frequency (top), source voltage (middle), load current (bottom), high to low frequency

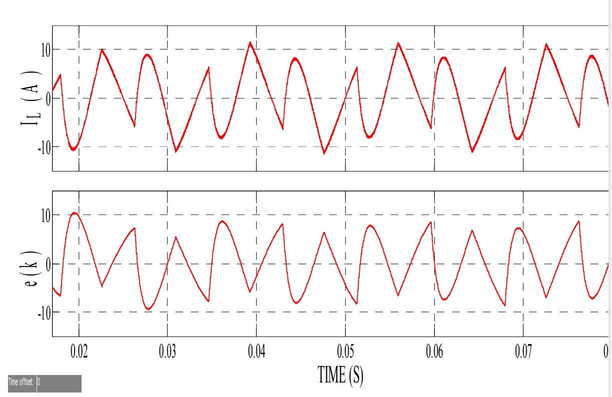

Fig.10 Compensating current (top), error signal (bottom), nominal source.

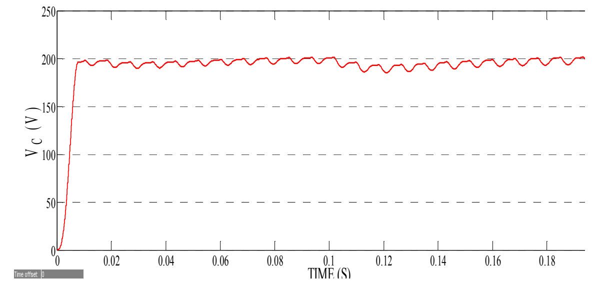

Fig.11 Response of APF capacitor voltage.

As shown in Fig.11 the filter capacitor voltage is maintained at desired reference level of 200 V. For time $(t < 0.01)$ low load is applied and after that high load is applied. Fig 10 shows the compensating current for compensating the harmonics from the source current and the error signal $e(k)$ which instead of converging to 0 converges to a periodic wave

V. CONCLUSION

Proper combinations of fixed frequency sliding mode current control, ANN based fundamental source current extraction circuit and unipolar PWM increases the dynamic response of APF system with reduced harmonic content in the source current. Fixed frequency SM current control strategy is explained properly. Reference current calculation using ANN and PD controller is explained. Simulation results are analyzed under different load and source conditions. Proposed APF is applicable under distorted voltage source with wide range of frequency variation.

REFERENCE

[1] D. A. Torrey and A. M. A. M. Al-Zamel,"Single-phase active power filters for multiple nonlinear loads," *IEEE* Trans. *Power Electron.*, vol. 10, no. 3, pp. 263–272, May 1995.

[2] J. Miret, M. Castilla, J. Matas, J. M. Guerrero, Luis Garcia de Vicuna, "Design of an analog Quasi-steady-state nonlinear current mode controller for single phase active power filter". *IEEE Trans. Ind. Electron.*, vol. 56, no. 12, pp. 4872-4881, Dec 2009.

[3] J. Matas, Luis Garcia de Vicuna, J. Miret, J. M. Guerrero, M. Castilla, "Feedback linearization of single phase active power filter via sliding mode control". *IEEE Trans. power. Electron.*, vol. 23, no. 1, pp. 116-125, Jan 2008.

[4] H. Komurcugil and O. Kukrer, "A new control strategy for single-phase shunt active power filters using a Lyapunov function," *IEEE Trans. Ind. Electron.*, vol. 53, no. 1, pp. 305–312, Feb. 2006.

[5] C.Y.Hsu and H.Y.Wu, "A new single phase active power filter with reduced energy-storage capacity," *IEE proceedings on electric power applications*. vol. 143, no. 1, pp. 25-30, 1996.

[6] M. Angulo, D.A. Ruiz-Caballero, J.Lago, M. L. Heldwein, S.A. Mussa. "Active power filter control strategy with implicit closed-loop current control and resonant controller". *IEEE Trans. Ind. Electron.*, vol.60, no. 7, pp. 2721-2730, july 2013.

[7] P.karuppanan,S.R.Prusty,K.K. Mahapatra, " Adaptive- hysteresis current controller based active power filter for power quality enhancement". *SEISCON*, pp. 1-6, 2011.

[8] P. Salmeron, J.R. Vazquez, "Practical design of a three phase active power line conditioner controlled by artificial neural network". *IEEE Trans. Power delivery,* vol.20, no. 2, pp. 1037-1044, april 2005.

[9] V.B. Sriram, S. SenGupta, A. Patra, "Indirect current control of a single-phase voltage-sourced boost-type bridge converter operated in rectifier mode". *IEEE Trans. power Electron*, vol.18, no.5, pp. 1130-1137, sep 2003.

[10] Siew-Chong Tan, Y.M. Lai, C.K. Tse. , "A unified approach to the design of PWM-base sliding mode controller for basic DC-DC converters in continuous conduction mode". *IEEE Trans. circuits and systems*, vol.53, no.8, pp. 1816-1827, aug 2006.

[11] R.A. DeCarlo, S.H. Zak, G.P. Matthews, "Variable structure control of nonlinear multivariable systems: a tutorial". *Proceedings of IEEE,* vol.76, no.3, pp. 212-232, 1988.

[12] A.Abrishamifar, A.A.Ahamad, M,Mohamadian, "Fixed switching frequency sliding mode control for single-phase unipolar inverter". *IEEE Trans. power Electron*, vol.27, no.5, pp. 2507-2514, may 2012.

[13] D.O Abdeslam, P Wira, J. Merckle, D Flieller, Y. A Chapuis, "A unified artificial neural network architecture for active power filters". *IEEE Trans. Ind. Electron.*, vol.54, no. 1, pp. 61-76, Feb 2007.

[14] F. Pottker, I. Barbi, "Power factor correction of nonlinear loads employing a single phase active power filter: control strategy, design methodology and experimentation". *Power Electron Specialists conference,* vol.1, pp.412-417, 1997.

[15] L. H. Tey and Y. C. Chu, "Improvement of power quality using adaptive shunt active power filter". *IEEE Trans. on power delivery*, vol.20, pp. 1558-1568, 2006.