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IMPROVEMENT OF POWER QUALITY USING SHUNT ACTIVE POWER FILTER IN AN ELECTRICAL DISTRIBUTION SYSTEM USING EERL-SMC

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Abstract ***– In this paper a three phase Shunt Active Power Filter (ShAPF) is proposed to address the current related issues in a three phase Electrical Distribution System (EDS). A sliding mode controller (SMC) and an Enhanced Exponential Reaching Law based SMC (EERL-SMC) is proposed for a ShAPF to compensate the load current. The controller's performance is tested by injecting the current harmonics into the system. A non-linear load along with different loads on the distribution side is connected in parallel in a distribution network at Point of common coupling (PCC). Modelling of the system is done using state space analysis. Stability of the system is analyzed using the state feedback approach. The reference source currents are generated using instantaneous PQ theory. For variations in the load, the THD in the source current is realized. It is found that EERL-SMC is more effective for a ShAPF in reducing the high frequency oscillations and settling time for convergence. The source voltage and current waveforms are observed to be sinusoidal in nature. Both the controllers are effective in reducing the THD levels in the source current as per the IEEE standards. A comparison between the controllers is presented in terms of settling time, THD in source current. PSCAD v4.6 is used for simulation works.***

Keywords: ***Electrical Distribution System (EDS); Point of Common Coupling (PCC); Sliding Mode Controller (SMC;, Shunt Active Power Filter (ShAPF;, Total Harmonic Distortion (THD; Enhancement Exponential Reaching law (EER-Law).***

1. INTRODUCTION

The loads present in an Electrical Distribution Network are broadly classified in three categories based on their properties. They are Sensitive loads, non-linear loads and Linear loads. All these loads are connected in parallel at PCC. Among the available loads linear loads & sensitive loads are very sensitive to the source voltage and current. Any small deviations in voltages and currents supplied to these loads will result in malfunctioning of these equipment. The non-linear loads which are connected at the PCC draw non-linear currents from the supply. The usage of non-linear loads like computers, Televisions, Printers etc. was drastically increasing day to day and hence increases non-linearity in source current. The increase in the non-linearity of current drawn by the non-linear loads will simultaneously effect the voltage supplied by the source. If such voltages are supplied to the loads then the system performance will be drastically effected [1]. The problem of non-linearity is mainly because of the non-linear loads connected at the PCC. These loads have to be isolated from the linear and sensitive loads to prevent the voltage and current distortions which is not practically possible. So proper preventive measures has to be taken in order to protect the linear and sensitive loads from the source voltage and current distortions. This has led the researchers to design compensating devices which will protect these loads. Passive filters are the conventional filters which can be designed to protect the loads from the harmonics. Due to the development of power semiconductor devices and signal processing devices and availability at reduced cost have attracted the researchers to work with active filters (AF). AF perform multiple functions such as harmonic filtering, damping, voltage regulation, load balancing and other power quality issues arising in a distribution system. AF's are further classified into pure active filters (PAF) and Hybrid active filters (HAF). PAF uses only one single voltage source PWM converter with a DC capacitor. HAF includes multiple or single voltage source PWM converters with passive filters like inductor and capacitor and/or resistors. Generally for high power applications, HAF are more commonly used for harmonic mitigation in terms of performance and cost. In this work a shunt active power filter for harmonic mitigation is presented in a distribution system with the mathematical model and stability analysis.

The main contributions of this work are as follows (i) A ShAPF has been designed and simulated to protect the sensitive loads from current distortions. (ii) Enhancement Exponential Reaching law (EER-Law) is added to the conventional SMC controller to improve the performance of the system. For higher circuits like ShAPF the proposed algorithm reduces the chattering effect and converging time. (iii) A comparative analysis is performed in THD's of the source current with different loads. Section 2 discusses about the Passive filters used for harmonic mitigation. Section 3 describes various shunt active power filters. Section 4 deals with the SMC controller and its implementation. Section 5 and 6 deals with the modeling of the filter using state space analysis with the simulation results. Section 7 deals with the EERL-SMC for a ShAPF in an EDS. Finally conclusions and future scope of the work are presented in section 8.

2. PASSIVE AND ACTIVE POWER FILTERS

There are different kinds of passive filters like low pass filters, high pass filters, single tuned filters, double tuned filters etc. These filters will consists of the passive elements like resistor, inductors and capacitors [2]. As shown in Fig. 1, *R*, *L*, *C* values should be calculated based upon the formulas given in (1).

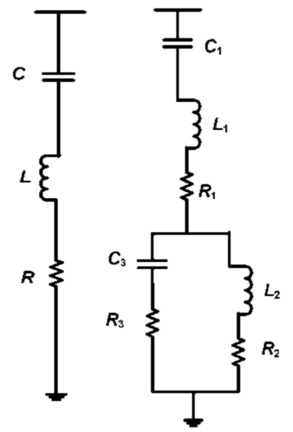
$$\left.\begin{aligned} C &= Q_c / (6.28\,\mathrm{Vf}^2) \\ \mathrm{X} &= 1/(6.28\,\mathrm{fhC}) \\ \mathrm{L} &= \mathrm{X}/2\,\mathrm{hf} \\ Q &= 6.28\,fL/R \\ R &= 1/6.28\,\mathrm{fC} \end{aligned}\right\} \quad (1)$$

Where Q_c= Reactive Power of Filter (MVAR), V= Supply voltage (V), Q = Quality Factor, h = Tuning Harmonic Order of the Filter.

The tuned low pass filter and high pass filters will eliminate the harmonics based upon their cut-off frequency. The designed single tuned filter will eliminate the particular harmonic for which it is tuned. The dominant frequency harmonic component has to be identified in supply voltage or current. This can be done by using Fast Fourier Transforms (FFT) Analysis. The filter has to be designed in such a way to eliminate that harmonic component in voltage or current. The designed filter has to be connected in parallel to the load so that it will eliminate the dominant harmonic component present in system voltage and current. The designed passive filter will deviate the harmonics without reaching the load by acting as a short circuit path to the dominant harmonic component and also act as an open circuit for fundamental frequency component. Thus the resultant THD in voltage and current at the PCC will decrease. In this way the THD can be reduced by using single tuned filters.

Similarly if the two frequency components is found to be dominant then a double tuned filters are preferred. These filters are designed to eliminate the two harmonic frequency components. The main drawback of passive filters is the presence of resonance between the line and the filters. If the impedance of the designed filter and system impedance is equal then the system is said to be in resonance condition. This will inject the abnormal disturbances line noise into the system [3]. The basic drawback of these passive filters is that they can eliminate only the single or double frequency components only. For any variations in the non-linear loads that are in on condition the harmonics occurring in the system will change dynamically.These drawbacks has made many researchers to concentrate their study on the devices which can provide dynamic and effective solutions.

Among the available different Active Power Filter (APF), Shunt Active Power Filter (ShAPF) and Series Active power filters (SeAPF) will function dynamically. These filters can provide effective solutions. The shunt Active power filter can mitigate the current harmonics and series active power filter acts as a voltage regulator.Unlike the traditional passive filters, APF will have the flexibility to provide multiple functions like eliminating multiple harmonic frequency components, reactive power injection for power factor correction, voltage regulation and voltage flicker reduction etc.



(a) (b)

Figure 1. Passive Filters (a) Single tuned passive filter (b) Double tuned passive filter.

Also due to the decrement in the manufacturing cost of power semiconductor devices and signal processing devices manufacturers have shown more interest towards APF's [4], [5]. However the manufacturing cost of APF's is quite high when compared with the conventional passive filters. APF's are mainly classified into two types based upon their application. They are single phase APF and three phase APF. However the usage of single phase APF is only restricted to low power applications. This made the researchers to search for the device which can be used in high power applications i.e. three phase APF. In this paper the performance of the three phase shunt APF is analyzed through simulation works.

3. SHUNT ACTIVE POWER FILTER

These type of filters mainly consists of power electronic converters which is connected in parallel to the load. A controller is used to generate triggering pulses to the current controlled VSC. The combination of VSC and controller is called as ShAPF. Active Power Filter connected in shunt across the load. This current controlled VSC will inject the compensating current to suppress the distortions present in voltage across the and current at PCC [6]. The distortions in load voltage and current are calculated separately and then the resultant total error is calculated by summing the voltage error and current error. The compensation is done by injecting the compensating current which will suppress the distortions in voltage and current.

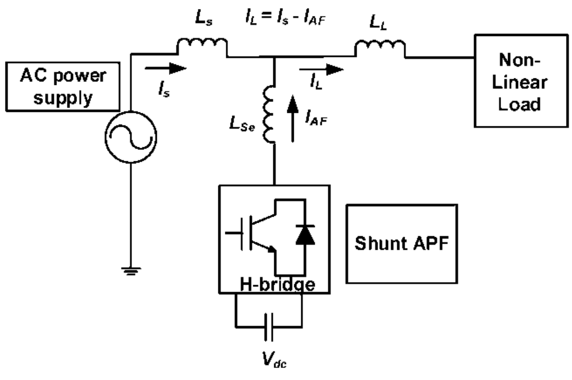


Figure 2 Block diagram of Shunt Active Power Filter.

Fig. 2 shows the block diagram of the ShAPF. It consists of an AC power supply feeding a non-linear load. A shunt APF consisting of a voltage source inverter (VSI) connected in shunt at PCC to inject a shunt current in such a way to nullify the distortions present in source current. L_s and L_L are the source side and load side inductances which plays a prominent role in the compensation. Along with the sensitive loads, non-linear loads are always present in the distribution network. $L_{se}$is the series winding inductance to the VSI and V_{dc} is the input DC voltage supply.

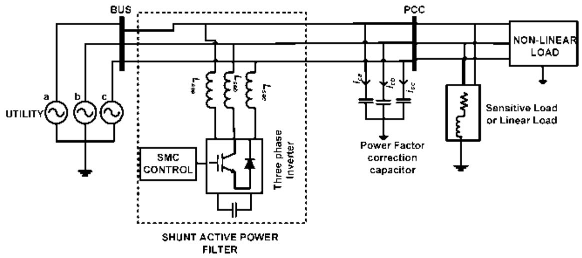


Figure 3 Block diagram of three phase Shunt Active Power Filter.

In the circuit shown in Fig. 3 a three phase Shunt Active Power Filter (ShAPF) is presented with sliding mode controller (SMC) which mainly consists of a current controlled current controlled VSC. This converter should add or subtract the compensating current if needed. The compensating current will be with a phase shift of exactly 180 degrees to the distortion occurred in the source current. Now to inject this compensating current the current controlled voltage source converter should function dynamically and should be turned on instantly [7]-[8]. For this purpose a controller should be designed in such a way that it should generate the firing pulses whenever it is needed for compensation.

4. PROPOSED CONTROLLER

In this controller the instantaneous *PQ* theory is used to calculate the error in the source current. The actual and the reference values of the three phase voltages and currents are converted into stationary reference frame. Then these voltages and currents are multiplied together to generate the actual and reference values of Active and Reactive power. Now the resultant error in powers is calculated by using the Instantaneous P-Q theory equations. The resultant P_{error} and Q_{error} is converted into their respective phase current errors by using the Inverse Instantaneous *PQ* theory. Thus this obtained error signals is given to the pulse width modulator to generate the firing pulses at a desired instant. [9], [10]. The switching frequency chosen is 10 kHz. Fig. 4 shows the controller block diagram.

Sliding Mode Controller (SMC) is one of the robust non-linear controller. It was used in many of the practical applications because of its simple construction and its accuracy. This SMC can vary the reference signals and can easily track the control signals dynamically when compared with other controllers. SMC design will broadly presents two parts. One is choosing the sliding surface and other is fine tuning of the sliding coefficients. In this proposed work, a SMC with linear sliding surface is chosen. This SMC will generate required triggering pulses to the switches present in current controlled VSC which will inject the required compensating current. This compensating current is exactly 180˚ phase shift to harmonics in the source current.

$$P = V_\alpha I_\alpha + V_\beta I_\beta \tag{2}$$

$$Q = V_\beta I_\alpha - V_\alpha I_\beta \tag{3}$$

$$\sigma_s = k_1 (I_{ref} - I_{actual}) \tag{4}$$

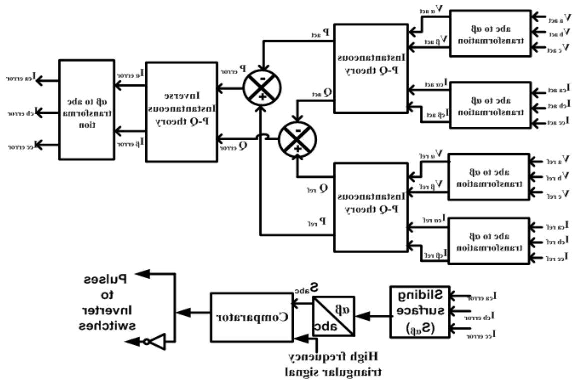


Figure 4 Block diagram of the controller for Shunt Active Power Filter.

5. STATE SPACE MODELLING OF ShAPF:

To determine the stability of the ShAPF the state space equations are formulated by using the state space analysis Voltage across the load (V_L), current injected by the ShAPF (i_{se}) and current through the power factor correction capacitor (i_c) have been considered as state variables. The controller can be designed by considering any one of the state variable as controlling parameter. In this proposed controller the current through the power factor correction capacitor is considered as the controlling parameter [11], [12]. Thestability of the system is analyzed by finding the frequency response characteristic of the designed system.

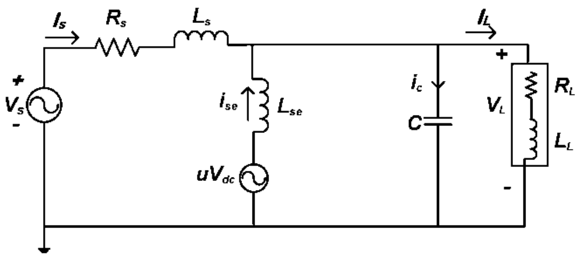


Figure 5 Equivalent circuit for shunt APF.

$$\dot{X} = Ax + b_1 u + b_2 V_s + b_3 i_L \tag{5}$$

$$y = cx \tag{6}$$

where A is the state matrix of order 3x3, b_1 is the input matrix of order 3x1, b_2 is the source voltage matrix of order 3x1, b_3 is the load current matrix of order 3x1. The transfer function of the system without feedback signal is founded by using the equation (8). State feedback approach is used to obtain the frequency response characteristics.

$$\begin{bmatrix}\dot{v}_L\\ \dot{i}_C\\ \dot{i}_{se}\end{bmatrix} = \begin{bmatrix}0 & \frac{1}{C} & 0\\ 0 & -\frac{1}{L_s}-\frac{1}{L_L} & -\frac{R_s}{L_s}\\ 1 & 0 & -\frac{R_{se}}{L_{se}}\end{bmatrix}\begin{bmatrix}v_L\\ i_C\\ i_{se}\end{bmatrix} + \begin{bmatrix}0\\ 0\\ \frac{V_{dc}}{L_{se}}\end{bmatrix}u + \begin{bmatrix}0\\ \frac{1}{L_s}\\ 0\end{bmatrix}V_s + \begin{bmatrix}0\\ -\frac{R_s}{L_s}+\frac{R_L}{L_L}\\ 0\end{bmatrix}i_L \tag{7}$$

$$G(s) = C(SI - A)^{-1} b_1 \quad (8)$$

The stability of the system can be determined from its frequency response characteristics shown in figure 6. The transfer function obtained is given in (9)

$$G(s) = \frac{-1e08s}{s^3 + 5.002e05s^2 + 3.535e-09s + 2.193e06} \quad (9)$$

It is observed that designed ShAPF is having infinite gain margin & 90 degrees Phase margin which indicates that the system is stable. Hence it can be concluded that high stability margins can be obtained with the state variable considered. The controller works effectively with these state variable.

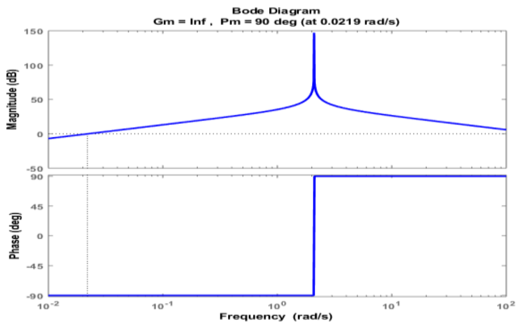


Figure 6.Frequency response of single phase ShAPF.

6. SIMULATION RESULTS

Table I represents the configuration parameters. The rating of the ShAPF is 1.431 kVA for a three phase distribution system. Any electrical network consists of different kinds of loads like linear loads, non-linear loads & sensitive loads. Among the available loads, the non-linear will draw the nonlinear currents from the source. These non-linear currents can simultaneously effects the source voltage, if the same non-linear voltage or non-linear current is fed to the critical loads like hospitals. Then these loads performance is affected very much.

Table 1 System Parameters

Symbol	Definition	Value
V_s	Supply voltage (L-N)	141.4 (max)
f	Supply frequency	50 Hz
L_s	Line Inductance	10 µH
R_s	Line resistance	0.5 Ω
R_{non}, L_{non}	Non-linear Load (Thyristor Rectifier)	10 Ω, 16 mH
P_L	Power rating of the linear load	477 VA
L_{Se}	Switching ripple filter inductance	5 mH
Filter	Power factor capacitor Capacitance	228 µF
pf	Load power factor	0.8 lag

The work considers the said loads in the electrical network for simulation purpose. The current drawn from the source is as shown in Fig. 7 for a non-linear load shown in Fig. 8(a). All the three phases of the source current are said to be non-linear. The nonlinear load considered is a three phase diode thyristor rectifier with different combination of loads on the DC side [13]-[15]. The magnitude of the load current is 10 A (peak/phase).

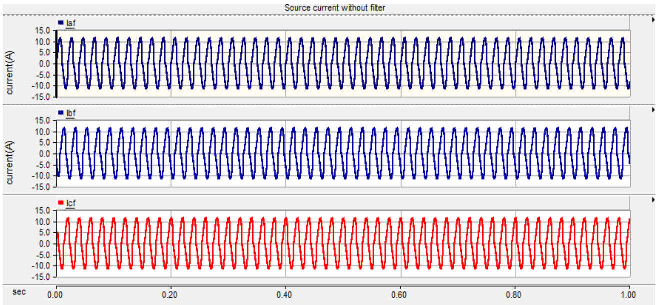
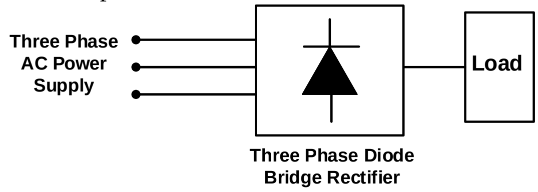
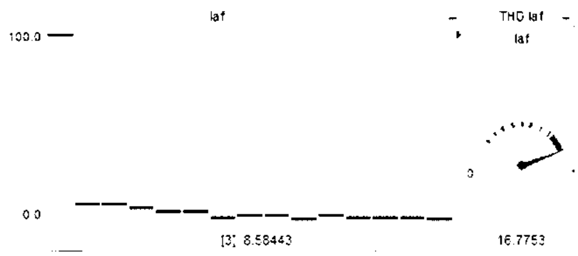


Figure 7: Waveform of source current in phases *A*, *B* and *C*.

It is clear that the source current waveform is highly non-linear. The % of THD in the current by the load from the source in phase *A* is observed to be 16.8991%. This THD percentage is above the allowable limits according to the IEEE 519-1992 standard. If same current is fed to the critical loads then there will adverse effect on linear or sensitive loads. Hence an appropriate filter should be designed which injects the compensating current with exactly 180 degrees phase shift to nullify this harmonic current. Fig. 8 (b) shows the harmonic spectrum of the non-linear source current.



(a)



(b)

Figure 8 (a) Non-Linear Load, (b) THD spectrum in the source current.

6.1Rectifier with R-Load

Assume that linear and non-linear load (assume that there will be a three phase bridge rectifier connected to an Resistive load) is connected at the PCC. The load voltages and load currents at the linear load is as shown in Fig. 9. The magnitudes of the load voltage and current are 100 V (rms), 15 A (rms). Fig. 10 shows the current through the non-linear load, the compensated current, current drawn from the source.

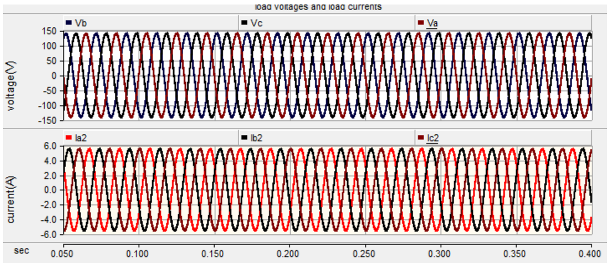


Figure 9 Waveforms of Load voltage (phase-neutral) & linear load current.

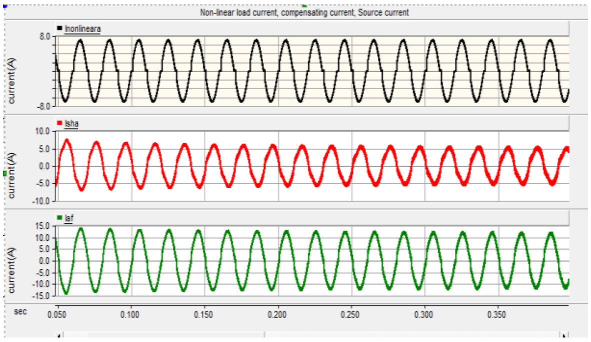


Figure 10: Waveforms of current drawn by non-linear load I_{nL}, shunt APF current I_{AF}, source current I_s.

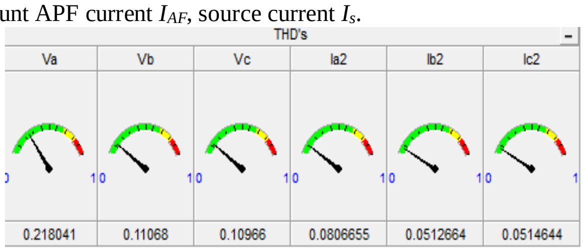


Figure 11 THD in load voltages and load currents.

It is observed that the source current THD is 0.75% which is within allowable limits as per the *IEEE* 519 standard.

6.2 Rectifier with RL-Load

Now with the rectifier RL load, the THD of the source current is observed to be 22.44%. Now the ShAPF is connected to the circuit and simulated. The Linear load voltage and current flowing through linear load is shown in Fig. 12.

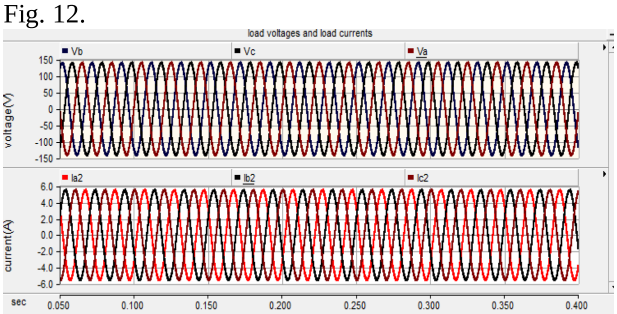


Figure 12 Waveforms of Linear load voltage & linear load current.

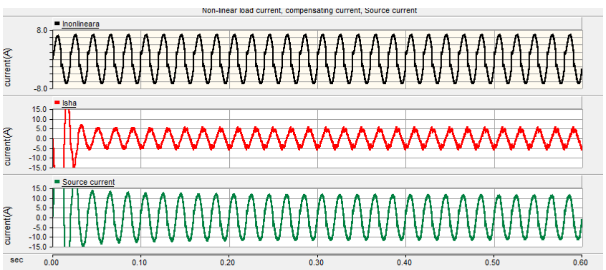


Figure 13 Waveform of current flowing through non-linear load I_{nL}, shunt APF current I_{AF}, source current I_s.

Fig. 12 shows the waveforms for load voltage and current when the systems is fed with a rectifier with RL-load. The magnitudes of the load voltage is 100V (rms) and the magnitude of Load current at the PCC is 10.25A (rms).

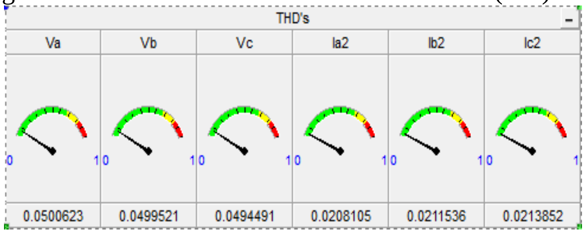


Figure 14(a): THD in Linear Load Voltage & Linear Load current.

TABLE 2 Source Current THD with non-linear loadconnected firing angle of 36°

S. No.	Resistance (Ω)	Inductance (mH)	% of THD in source current
1	16	16	1.21
2	16	20	0.88
3	20	16	1.06
4	20	24	0.75
5	24	24	0.75

From Fig. 14(a) it is clear that the designed shunt APF is injecting the compensating current to maintain the THD in the load current within the permissible limits. SMC along with the ShAPF is said to work well in compensating the current harmonics.

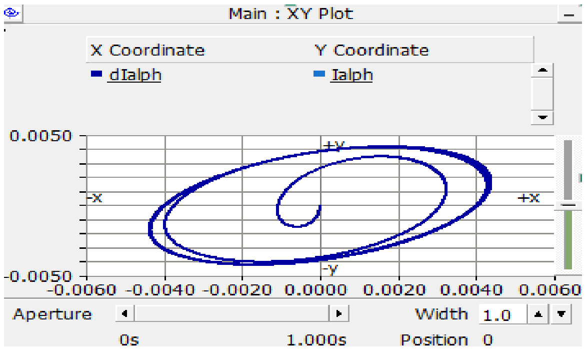


Figure 14 (b) Phase plane projection of sliding surface and its derivative through simulation.

Fig. 14 (b) shows the locus of the sliding surface with its derivative. It is evident that the system reaches origin within a finite period of 3 ms with high frequency oscillations i.e. chattering is present in SMC [16]-[19]. The chattering and hence the settling time can be reduced by using an enhanced exponential sliding Mode controller (EERL-SMC) as discussed in section VII.

7. EER-LAW BASED SLIDING MODE CONTROL FOR SHAPF

The basic drawback SMC's is the chattering effect which was overcome by choosing the SMC of higher order. In this proposed work an EER-Law is added to the existing SMC to reduce the steady state error, response time eliminating the chattering effect and decreasing the response time. So this EERL- SMC can be used as an alternative instead of going for the higher order SMC which is presented in this proposed work. Here in this case the linear sliding surface chosen is as shown in the (10). Exponential reaching will have the high adaptive function when it is compared with the traditional controllers. The error signal obtained at the sliding surface will be given to the EERL as shown in Fig. 15. The equation of EERL-SMC is as shown in the Equation (10).

$$\dot{s} = -\lambda s - \left(\frac{\xi}{D(S)} |s|^{\gamma} .\text{sgn}(s) \right) \qquad (10)$$

Here $D(s) = \alpha + (1-\alpha)e^{-\beta_x |s|} > 0$ &$D(s)$ will not have any sort of control over the stability of the considered system. λ, ξ and β_x will be always a positive integers. Their values are in the range of 0 and 1. The time for reaching of the system depends on $|s|$. As the value of $|s|$ decreases the chattering effect can be minimized. The $S_{\alpha\beta}$ obtained is passed through (10) and converted to S_{abc} which is then compared with a repetitive waveform operating at 10 kHz to generate the switching pulses to the VSI circuit. The simulation results obtained by adding the Exponential law to the presented SMC is given in the sections a & section b [19]-[20].

7.1 Non-Linear Load (R-load)

In this simulation, only the non-linear load of 15A (max. value) is connected at the PCC. Then the resultant current drawn from the source is observed.

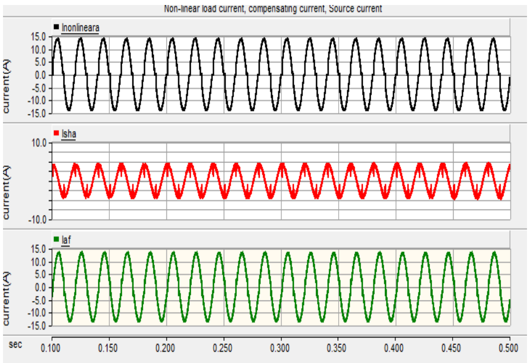


Figure 15 Waveforms of load, current injected by the shunt APF & Source current.

Figure 15, 16 & 17 presents the results obtained through simulation. Also it can be concluded that the resultant current drawn source current is free of distortions when ShAPF is connected in the network. The THD present in source current is observed to be 2.27% which is in the allowable limits according to IEEE standards. Also the THD in voltage at the PCC is within the allowable limits as per the standards.

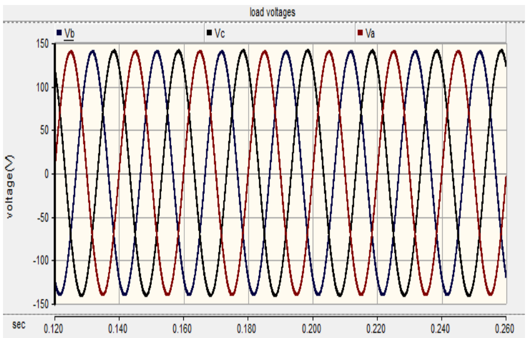


Figure 16 Waveform of Phase to Neutral Voltage at Linear Load.

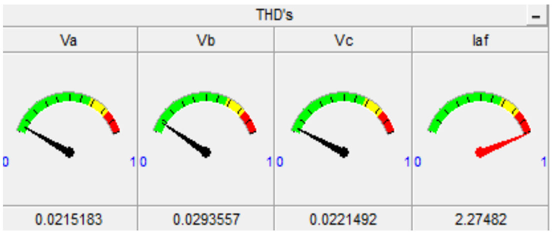


Figure 17 THD in Linear Load Voltage and Linear load current.

7.2 Non-Linear Load (RL-load)

The performance of the designed controller with EERL-SMC is analysed by connecting the Non-Linear load with RL-load. In this simulation a controlled rectifier is operated at a firing angle of 90 degrees. The resultant wave forms obtained is represented in the below waveforms.

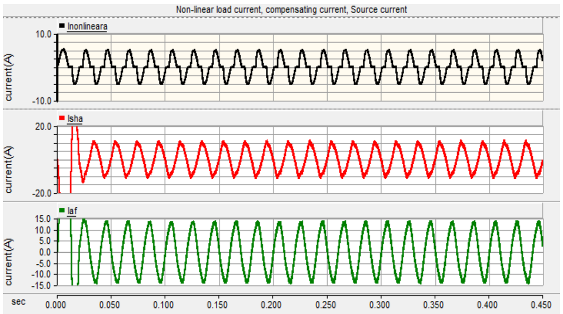


Figure 18 Waveform of current drawn by the non-linear load for a firing angle of 90 degrees, current injected by the shunt APF, source current.

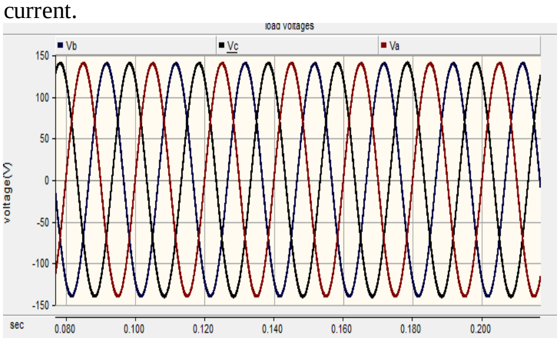
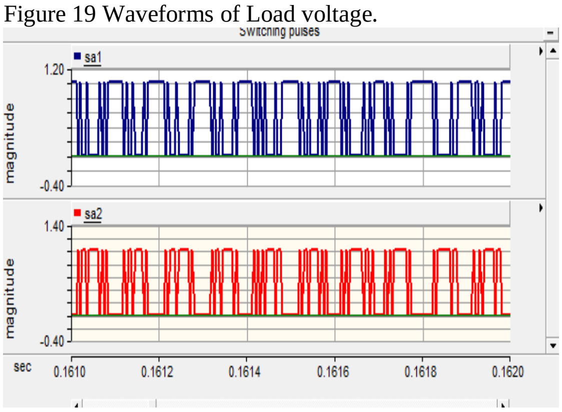
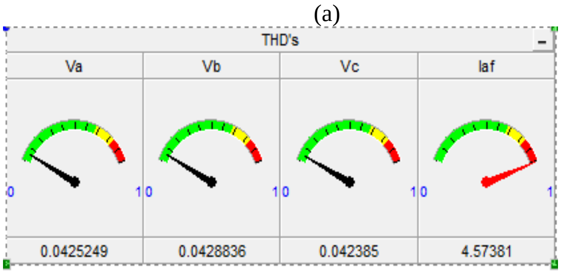


Figure 19 Waveforms of Load voltage.



(a)



(b)

Figure 20 (a) Switching pulses generated by the controller. (b) THD in linear load voltage and linear load current.

This designed filter was tested by changing the load parameters. The non-linear load (controlled rectifier fed *RL* load) is connected at the PCC. The controlled rectifier is operated at a firing angle of α=36˚. The deviation of Source current waveform from sin wave form is observed and its corresponding THD is measured and is listed in Table 3.

TABLE 3 Source Current THD with Non-linear load ConnectedtoRL-Load Operated at α =36˚.

Resistance (Ω)	Inductance (mH)	% of THD in source current
16	16	3.12
16	20	3.62
20	16	2.42
20	24	2.89
24	24	2.22

With the support of results shown in Table 3 it is can concluded that the designed ShAPF is having the capability to inject the compensating current whenever it is needed. Thus it can be concluded that the designed ShAPF can act dynamically and mitigate the current distortions that are occurred in the system. The convergence plot of the controller is drawn by considering the sliding surface on the X-axis and its derivative on the Y-axis. Then the resultant plot obtained is as shown in the Fig. 21. Thus from the figure shown it is clear that the resultant is converging towards the origin which indicates that the system is stable. The convergence time taken by the controller with EERL-SMC is quite less i.e. 0.1 ms when the phase plots of the controller with and without EER-law are compared. Thus it can be concluded that the controller with EER- Law will have less response time of 0.1 ms when compared with the classical SMC controller.

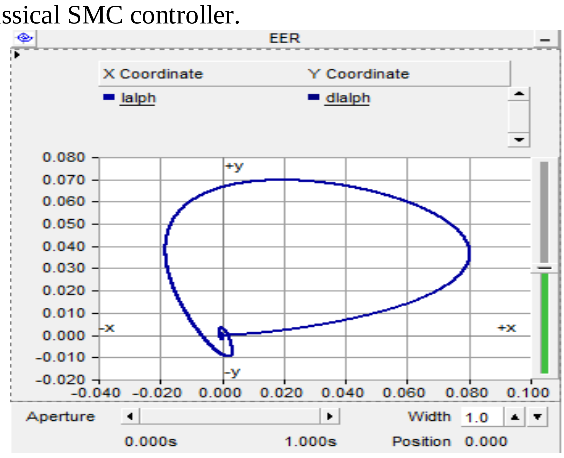


Figure 21 Phase plane projection of sliding surface and its derivative through simulation.

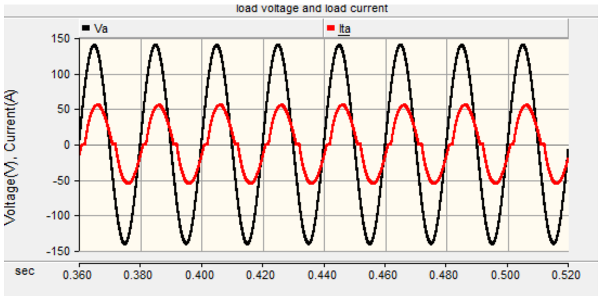


Fig. 22 Load voltage and load current with only non-linear load at PCC.

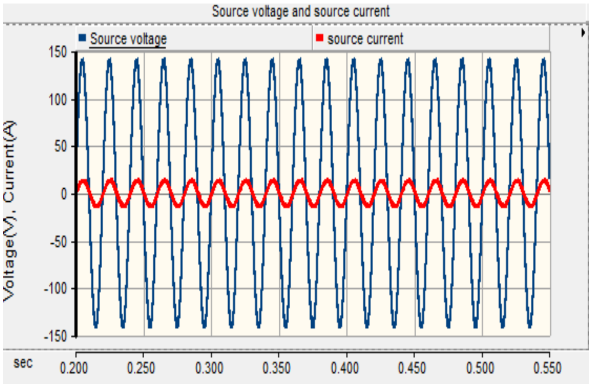


Fig. 23: Source voltage and current.

TABLE 4 Comparison of SMC and EERL-SMC for ShAPF

Parameters	SMC	EERL-SMC
% of THD in load current	0.053	0.056
% of THD in load voltage	0.21	0.22
Settling time	3 ms	0.1 ms
% of THD in load current	0.053	0.056
% of THD in load voltage	0.21	0.22

Fig. 22 shows the load phase voltage of 100 V (rms) and load phase current of 3.97 A (rms) when a non-linear load is placed at PCC. The controller effectively improves the source current waveform to be sinusoidal as shown in Fig. 23. Table 4 shows the performance comparison of SMC and EERL-SMC. It is clear that both of them work effectively maintain the THD within permissible limits. The EERL-SMC is better with less settling time during convergence.

8 Conclusions

In this paper a shunt APF performance is simulated by connecting the non-linear load at the PCC. Both the conventional SMC and EERL-SMC are used to compensate the effects of connected non-linear load at the PCC. It was Founded that the designed ShAPF is having the capability to compensate the distortions occurred in source current. The current references are generated using instantaneous *P-Q* theory. The designed controller performance is analyzed for ShAPF. Its mitigation capability is observed in 3-phase systems by adding *R* and *RL* elements on the DC side to the Non-linear load. For the connected system in the simulation it was found that linear load voltage and linear load current is made free of distortions by the designed controller. The THD obtained using both the controllers are well within the allowable limits as per the IEEE-519 1992 standard. It highlights the need for a reliable power supply for critical loads and with an increase in the number of non-linear loads. Stability of the system is analyzed using Bode plot. It was identified that the designed system is stable. The finite time convergence is indicated through a phase plot which clearly realizes a faster settling time of 0.1 ms using EERL-SMC compared to 3 ms in a conventional SMC. The EERL-SMC is an alternative to the higher order SMC for chattering reduction and finite time convergence. The main applications of ShAPF are in PV systems, smart grid networks, distributed generation and machine control.

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