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Capacitor Voltage Regulation in Shunt Active Power Filter using Sliding Mode Controller

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Abstract— **Nowadays power quality problem is a very important issue in power sector and various methods are developed to mitigate them. Shunt active power filter (APF) is used for current harmonics compensation. Synchronous Reference Frame theory is used for control of Shunt APF. In case of Voltage Source Inverter (VSI) based Shunt APF capacitor is used as energy source element. So, the performance of Shunt APF is entirely dependent on capacitor voltage regulation. Traditional approach which uses PI – controller has slow response, has overshoot & settling time is also high. A new control approach which uses Sliding mode technique is proposed. This control approach uses Power Rate reaching law. So the settling time improves with no overshoot. Also the stability of overall system is examined by giving step change in load. Simulation results are given which shows validity of proposed approach.**

Keywords— Active Power Filter (APF), Synchronous Reference Frame theory (SRF Theory), Sliding Mode Control (SMC).

I. Introduction

With advent of modern technology for comfort of human life, the problem of power quality distortion also increased. The increased use of devices which uses large number of power electronic switches, like transistors in computers and various types of robots etc. work as non-linear loads. They tend to draw non-sinusoidal current. So they introduce large number of harmonics in supply mains.

Lots of literatures are available to address above problems and also number of techniques are developed to mitigate these problems. These techniques can be classified into two categories: 1) Passive and 2) Active techniques. The former techniques aim to mitigate selected harmonics, if used for harmonic elimination. For example, passive filters tuned for 5^{th} and 7^{th} harmonics is used at arc furnaces load. As, this technique, requires passive elements like L – C, the system becomes bulky, costly and less attractive. Also, frequent maintenance of capacitors is required, therefore, efficiency is low. On the other hand, active techniques are applicable to the loads, where large or any range of harmonics compensation is required. As they uses converters composed of switches, the system uses less number of passive elements. So, the system becomes cost effective, more attractive and efficient. Shunt active power filter (Shunt APF) is used to compensate source current harmonics [1], [2]. Shunt APF can also be used to supply reactive power [3], [4].

Large numbers of techniques are developed by last two decades considering Shunt APF. They can be categorized as:
1) Control technique used, e.g. d-q-0 based, P-Q theory etc.
2) Type of converter used, e.g. two level or multi – level
3) Type of voltage regulator used, e.g. PI controller [5], fuzzy controller [6], ANN controller [7], sliding mode controller etc.

In VSI based Shunt APF capacitor is used as energy source element. The main problem in designing VSI based Shunt APF is regulation of capacitor voltage. The Shunt APF won't work until the capacitor voltage is balanced. Its working degrades with capacitor voltage unbalancing. The traditional approach which uses PI – controller has some drawbacks. They have sluggish response, settling time is high, & overshoot is also present. This affects the performance of Shunt APF in turns. In other words, the performance of Shunt APF is entirely governed by the response of controller used.

In proposed approach, sliding mode controller [8], [9] is used for capacitor voltage balancing. A new control approach based on Power Rate reaching law is used. Sliding mode controller has the advantage of fast response with no overshoot. Thus, the performance of Shunt APF is improved. Synchronous Reference Frame theory also called as d-q-0 theory [10], [11] is used for operation of Shunt APF. The performance of Sliding Mode Controller and hence Shunt APF is examined for step change in load. The proposed approach is simulated using MatLab/Simulink software. Simulation results are also given which shows validation of proposed approach.

II. Shunt Active Power Filter

Shunt Active Power Filters are mainly operated as harmonic isolator between nonlinear load and utility system. The Shunt APF connected in parallel to supply system protects utility from harmonics generated by non-linear load. It can be used to provide reactive power to the load as well. Fig. 1 shows basic schematic of Shunt Active Power Filter constituting of following steps:

- Measurement of Current and Voltage signals
- Capacitor Voltage Balancing
- Reference Current generation
- Pulses generation for operation Inverter

The SRF theory is used for control of Shunt APF. The control algorithm has to do the work of pulse generation as well as capacitor voltage balancing at a time. Sliding Mode Controller is used for capacitor voltage balancing. Hysteresis PWM is used for pulse generation for inverter operation.

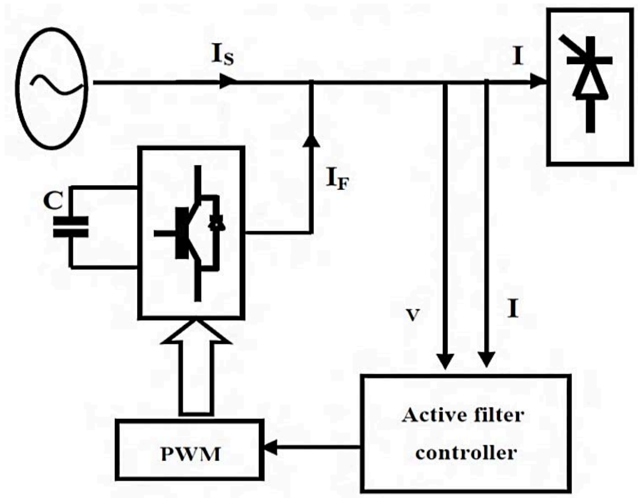


Fig. 1. Shunt Active Filter

A. SRF Theory

The Shunt APF is used to compensate current harmonics generated due to non-linear load. The Shunt APF control algorithm block diagram representing reference current signal generation is shown in Figure 2. The SRF theory is used to calculate reference current signals.

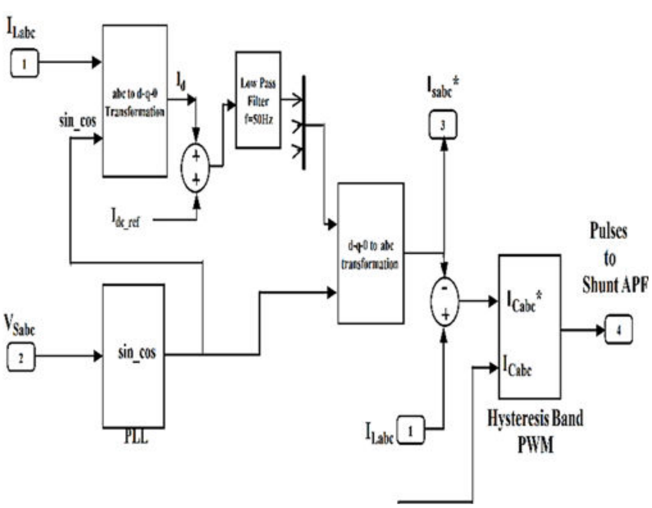


Fig. 2. Shunt APF Reference Current Generation

The three-phase load currents iLa , iLb and iLc are transformed from three phase (a-b-c) reference frame to two phase $(qs - ds)$ stationary reference frame currents i_d^s and i_q^s using equation (1) below.

$$\begin{bmatrix} \text{ids} \\ \text{iqs} \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -\frac{1}{2} & \frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} iLa \\ iLb \\ iLc \end{bmatrix} \tag{1}$$

A PLL (Phase Locked Loop) is used to generate unit vectors $\cos(\omega t)$ and $\sin(\omega t)$ from the three-phase source voltages Vsa, Vsb, Vsc. Stationary reference frame currents i_d^s and i_q^s are converted into Synchronous reference frame currents $i_d^e$and i_q^e as shown in equation (2) below.

$$\begin{bmatrix} i_d^e \\ i_q^e \end{bmatrix} = \begin{bmatrix} \sin(\omega t) & -\cos(\omega t) \\ \cos(\omega t) & \sin(\omega t) \end{bmatrix} \begin{bmatrix} i_d^s \\ i_q^s \end{bmatrix} \tag{2}$$

The currents calculated in equation (2) contain fundamental as well as harmonic components.

i.e. $i_d^e = i_{df} + i_{dh}$ (3)

So, second order Low Pass Filter tuned at 50 Hz is used to extract fundamental frequency components from input current. Then again by applying inverse transformation (d-q-0 to a-b-c), the currents containing fundamental components only isa^*, $isb^*$and isc^* are calculated as shown in equation (4) below.

$$\begin{bmatrix} i_{df}^s \\ i_{qf}^s \end{bmatrix} = \begin{bmatrix} \sin(\omega t) & -\cos(\omega t) \\ \cos(\omega t) & \sin(\omega t) \end{bmatrix} \begin{bmatrix} i_{df} + I_{dcref}^* \\ 0 \end{bmatrix} \tag{4}$$

Shunt APF control algorithm has to calculate compensating currents as well as it has to regulate capacitor voltage. I_{dcref}^* is added to ensure the energy supply capacity of capacitor become constant throughout the operation of Shunt APF.

$$\begin{bmatrix} isa^* \\ isb^* \\ isc^* \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & 0 \\ \frac{1}{2} & \frac{\sqrt{3}}{2} \\ -\frac{1}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} i_{df}^s \\ i_{qf}^s \end{bmatrix} \tag{5}$$

These fundamental currents are compared against actual load currents to calculate reference compensating currentsica^*, icb^*, icc^* that Shunt APF must supply. These reference compensating currents are then compared against actual compensating currents ica, icb, icc. The difference is then given to Hysteresis Band PWM, which generates appropriate pulses for operation of Shunt APF.

III. CAPACITOR VOLTAGE REGULATION

Better operation of Shunt APF is guaranteed, if the voltage across DC link capacitor is maintained at prescribed reference DC voltage. Sliding Mode Controller is used to regulate voltage across capacitor by comparing it with reference DC voltage. The controller sets a reference DC current required to maintain the voltage across capacitor constant. This is done as shown in Figure 3 below.

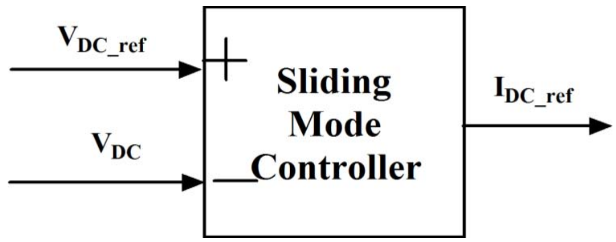


Fig. 3. Capacitor Voltage Regulation using Sliding Mode Controller

The reference dc current I_{DC_ref} is calculated as follows. The DC bus voltage error is calculated as difference between reference and measured DC voltage.

$$x_1 = V_{DC}^* - V_{DC} = e(n) \tag{8}$$

The derivative of error,

$$x_2 = \dot{x_1} = \frac{1}{T}[e(n) - e(n-1)] \tag{9}$$

Where, T is sampling interval and x_1, x_2 are state variables. The state equation is given by equation (10) below.

$$\dot{x} = \begin{bmatrix} \dot{x_1} \\ \dot{x_2} \end{bmatrix} = \begin{bmatrix} 0 & 1 \\ 0 & 0 \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} + \begin{bmatrix} 0 \\ -k \end{bmatrix} u \tag{10}$$

The sliding mode plane is represented by equation (11) below.

$$s = \begin{bmatrix} C & 1 \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} = Cx_1 + x_2 \tag{11}$$

And $\dot{s}$ is given by,

$$\dot{s} = \begin{bmatrix} C & 1 \end{bmatrix} \begin{bmatrix} \dot{x_1} \\ \dot{x_2} \end{bmatrix} = C\dot{x_1} + \dot{x_2} \tag{12}$$

In this paper Power rate reaching law is used which is given as,

$$\dot{s} = -L|s|^{\alpha} sgn(s) \tag{13}$$

$$\text{Where } sgn(s) = \begin{cases} 1 & s > 0 \\ -1 & s < 0 \end{cases} \tag{14}$$

Putting equation (10) in (12) and after that equating it with equation (13), we can get the required control law (u), as shown below.

$$u = \frac{1}{K}[cx_2 + L|s|^{\alpha} sgn(s)] \tag{15}$$

The output of sliding mode control is taken as I_{DC_ref}, which is required to charge the capacitor.

IV. Hysteresis PWM

Hysteresis Current Controller, an instantaneous feedback system which detects the current error and produces directly the drive commands for the switches when the error exceeds an assigned band. The hysteresis controller is used to control the current and determine the switching signals for inverter gates.

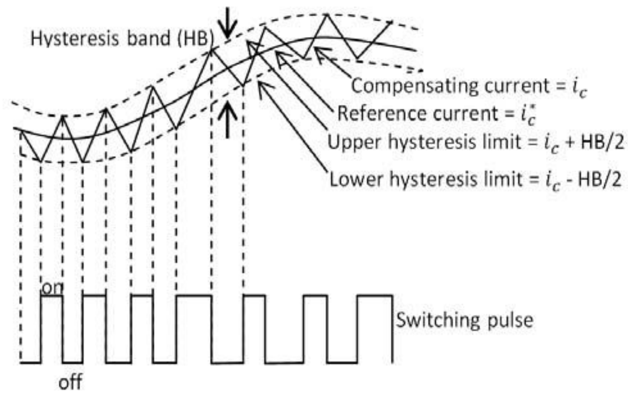


Fig. 4. Hysteresis Current Controller

When $I_{ca} > I_{ca}^* + (HB/2)$ then hysteresis controller gives output 0. When $I_{ca} < I_{ca}^* - (HB/2)$ then it gives output equal to one. In this way, Hysteresis PWM is used as pulse generator for inverter, so that current tracks the reference.

V. Simulation Results

In this paper, an improved control algorithm for capacitor voltage balancing of Shunt APF is proposed. The performance of Shunt APF is evaluated by using simulation results given in MatLab/Simulink software under distorted load current conditions. Simulation block diagram in MATLAB/Simulink for source current compensation under non-linear load conditions is shown in figure 5. The simulated Shunt APF system parameters are given in Table I. In simulation studies, the results are specified before and after operation of Shunt APF system. Before harmonic compensation, the THD of the supply current is >23%. The obtained results show that the proposed control technique allows the <1% mitigation of all harmonic components.

TABLE I. Shunt APF System Parameters

Parameters	Rating
Source	400 V_{rms}, 50 Hz
3-phase Resistive load	Active power = 10^4W
DC side Load Resistance	30 Ω
DC link capacitor	700 V, 1100 µF
Shunt APF side coupling inductance	3mH

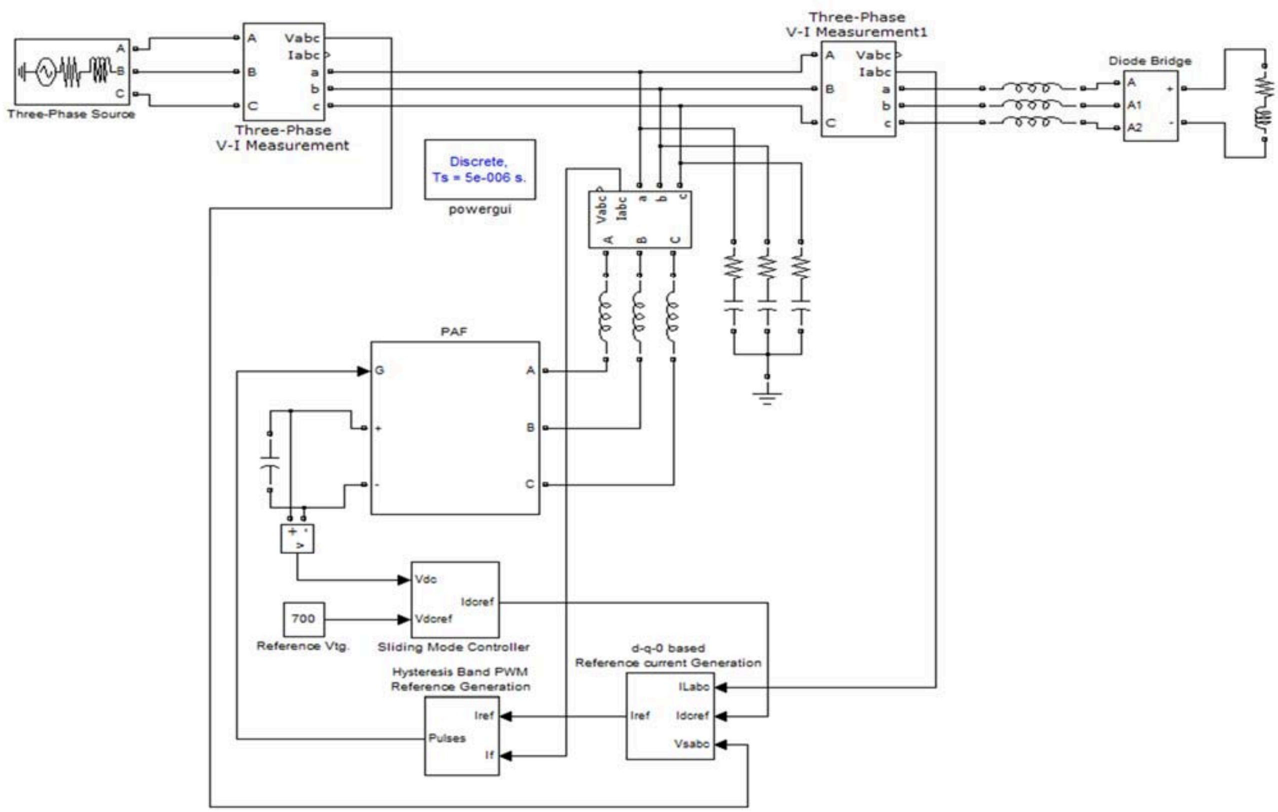


Fig. 5. MatLab/Simulink Block Diagram of Shunt APF

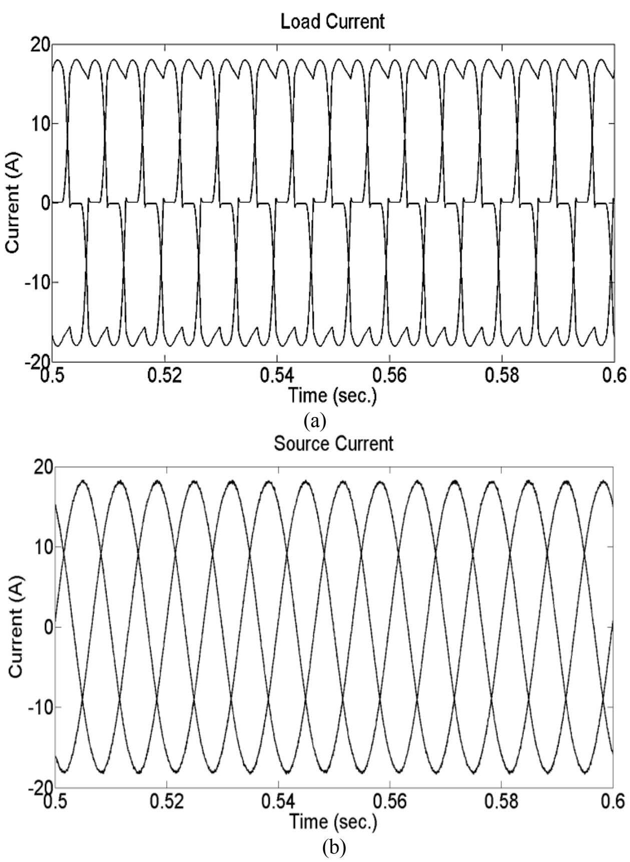


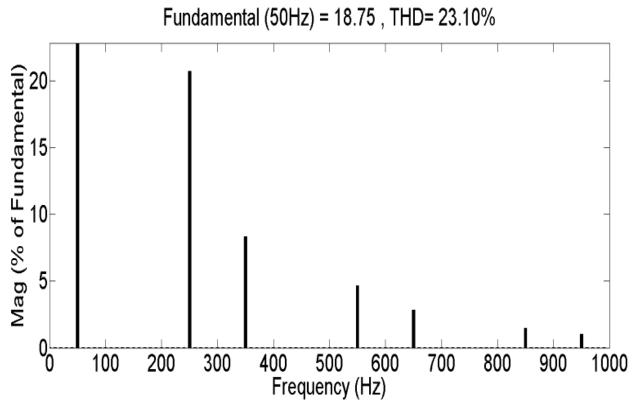
Fig. 6. Simulation Results (a) Load Current, (b) Source Current

Fig. 5 shows simulation diagram of Shunt APF using Sliding Mode Controller with R – L load connected through Diode Bridge rectifier. Such load consisting of number of switches work as non-linear load. Simulation results of given system are shown in Fig. 6. Because of non-linear loads connected to the bus, load current becomes non sinusoidal. So that source current distorts. After application of Shunt APF system, source current improves and becomes harmonic less. Table II shows results under different load conditions.

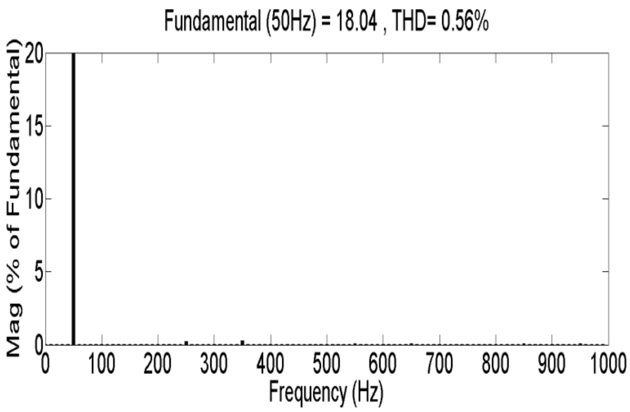
TABLE II. RESULTS OF % THD OF CURRENT

Type of Load	Firing angle (α)	% THD of load current	% THD of source current after compensation
Diode Bridge		23.10	0.56
Thyristor Bridge operation for different firing angles	$\alpha^{\circ} = 10$	24.91	0.56
	$\alpha^{\circ} = 20$	27.38	0.71
	$\alpha^{\circ} = 30$	29.64	0.86

FFT analysis of load current and source current for three phase Diode Bridge rectifier with R – L load on DC side is shown in figure 7. From FFT analysis we see that the performance of Shunt APF has improved when sliding mode controller is used.



(a)



(b)

Fig. 7. FFT Analysis (a) Load Current (b) Source Current after compensation

The same system is also simulated with PI – controller for capacitor voltage regulation. The response of it is given in figure 8 below and it is compared with response of sliding mode controller.

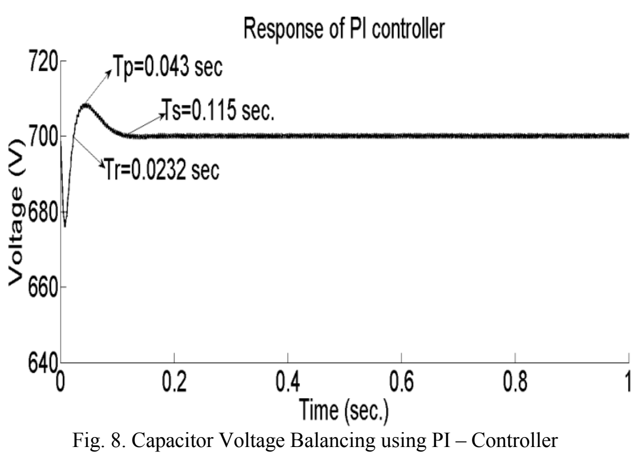


Fig. 8. Capacitor Voltage Balancing using PI – Controller

From figure 8 we see that, Rise time $T_r = 0.0232\ s$, Settling time $T_s = 0.115\ s$, Peak time $T_p = 0.043\ s$ with damping factor ζ=0.5414 and % overshoot equal to 13.22%.

Figure 9 shows response of SMC controller for capacitor voltage regulation. For sliding mode controller, settling time is $T_s = 0.06\ s$ with no overshoot. So, we can say that the performance of SMC – controller is better than PI – controller.

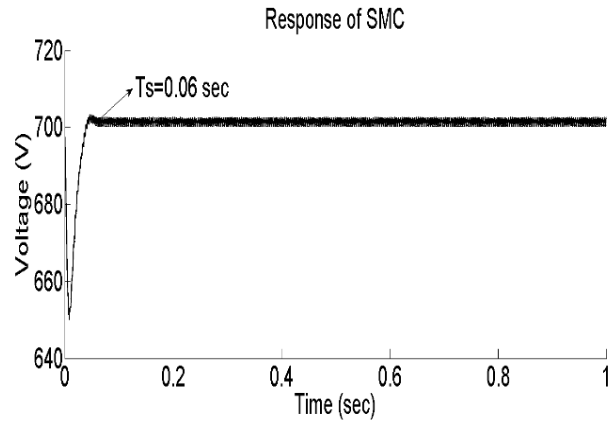
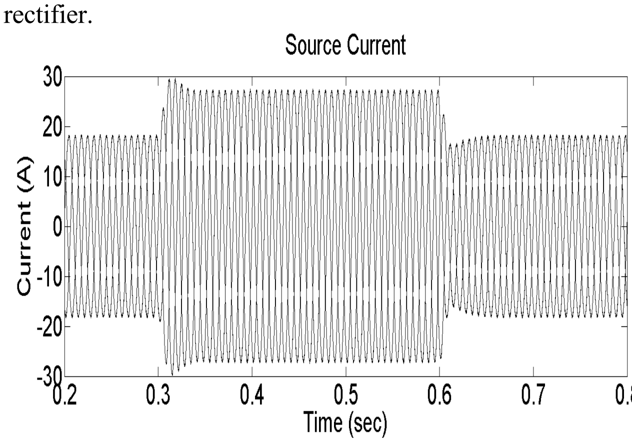
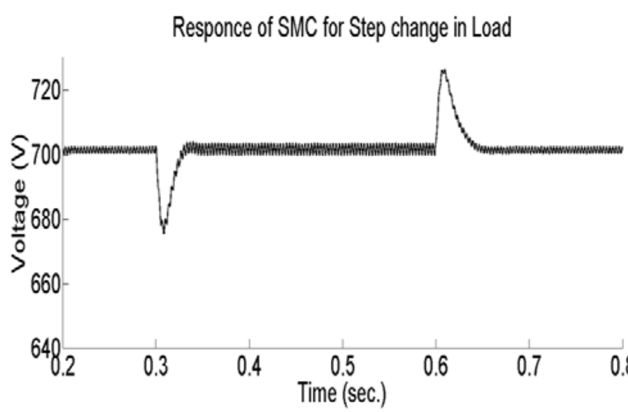


Fig. 9. Capacitor voltage balancing using SMC – Controller

The performance of sliding mode controller is also examined by giving step change in load. i.e. adding an extra load for short time of interval at dc side of Diode Bridge rectifier.



(a)



(b)

Fig. 10 Dynamic Response of SMC (a) Source Current, (b) SMC Response

From fig. 10, it is clear that the Sliding Mode Controller gives fast response to change in load and it immediately tracks the reference capacitor voltage. Also the % THD of source current is 0.56% before and after step change in load and 0.43% during change in load.

VI. CONCLUSION

This paper describes an improved control strategy for Shunt APF system operation using Sliding Mode Controller. A new control law is developed using Power Rate reaching law for SMC operation. The proposed SMC control law enables to improve the settling time with no overshoot. With this method, the capacitor voltage regulation is improved with better response as compared to PI – Controller. This approach for shunt APF enables to reduce the % THD of Source current less than 0.6% for Diode Bridge load and less than 0.9% for Thyristor Bridge rectifier. Thus, the transient as well as steady state performance of Shunt APF is improved.

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