DESIGN AND SIMULATION OF SLIDING MODE CONTROLLED HYBRID ACTIVE POWER FILTER

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Abstract—This paper presents design and simulation of a three-phase hybrid active power filter to eliminate the harmonics and compensate reactive power generated by non-linear load. A sliding mode controller is used to regulate the DC-bus voltage with hysterisis band current controller. Passive filters are tuned to fifth and seventh harmonic frequencies. Simulation results are presented to verify the performance during steady state as well as during transients. The spectral performance is judged and the results are observed well below the limits imposed by IEEE-519 standards.

Keywords: hybrid active power filter, power quality, harmonics and reactive power, total harmonic distortion (THD), sliding mode controller.

List of symbols

v_{sa}, v_{sb}, v_{sc}	source voltages at phase a, b, c
V_{sm}^*	peak supply voltage
V_{dc}	voltage across DC link capacitor
V_{ref}	reference DC bus voltage
i_{sa}, i_{sb}, i_{sc}	source currents at phase a, b, c
I_{sm}^*	peak supply current
$i_{sa}^*, i_{sb}^*, i_{sc}^*$	reference source currents at phase a, b, c
u_{sa}, u_{sb}, u_{sc}	unit current vectors for phase a, b, c
f_n	n^{th} harmonic frequency
X_{Ln}	inductive reactance at n^{th} harmonic freq.
X_{Cn}	capacitive reactance at n^{th} harmonic freq.
Q_c	VAr size of capacitor
Q	quality factor of inductive coil
s	sliding surface
i_{sx}	source current at phase x, where x = a, b, c
i_{refx}	reference current at phase x, where x = a, b, c
v_{sx}	source voltage at phase x, where x = a, b, c

1. INTRODUCTION

In modern power system, power electronic devices are dominating the consumer end in both industrial and domestic region. Majority of these devices are non-linear in nature, results in injection of harmonics and draw reactive component of current. These non-linearities, if not controlled, may spread further in the whole system deteriorating the system performance [1-3]. To avoid this undesirable effect and to improve the power quality of the system, passive filters were used initially. But their use is limited due to fixed compensation, large size and resonance problems.

Active power filters are seen as a viable alternative to passive filter for reducing current harmonics and reactive power due to their small size, no requirement for tuning and stable operation [4-6]. They act as harmonic current source to provide an effective result to eliminate the harmonic currents and also to compensate the reactive power. The active power filters are broadly classified into two types based on their configuration- voltage source type and current source type. Although active power filters give satisfactory results, some times their ratings are almost equal to the load rating; therefore they are not cost effective solution for both harmonic and reactive power compensation.

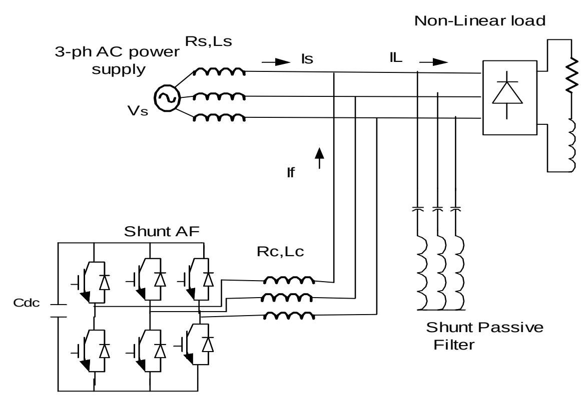
The hybrid active power filter (HAPF) are seen to be more attractive solution for both harmonics and reactive power compensation now a days [7-8], which is basically the combination of active and passive filters. It utilizes the advantages of both type and eliminates the drawbacks of individual filter type. In hybrid active power filter, tuned passive filters are used for compensation of lower order harmonics, while higher order harmonics and reactive power are compensated by active power filter through DC bus voltage regulation. A number of controllers are discussed in literature to control the active power filter based on with and without sensing load VAr method [9-10]. The control of DC link voltage does not require to sense harmonics or reactive power requirement of the load. Sliding mode controller is preferred over other controllers to sense DC link voltage due to its fast, robust and stable response for medium power applications [11]. However design parameters of sliding mode controller in context of hybrid active power filter are not discussed in detail.

This paper presents sliding mode controller to control active power filter of HAPF for compensating harmonics and reactive power. In this paper an attempt is made to describe the theory of sliding mode controller, with complete design of both passive and active power filter. Mostly the controllers used to regulate DC link voltage of active power filter offer slow dynamic response and also the overshoot in DC bus voltage is quite high for the variation in load. The proposed controller exhibits good performance with lower THD in source current with an additional advantage of exhibiting stability against load variations.

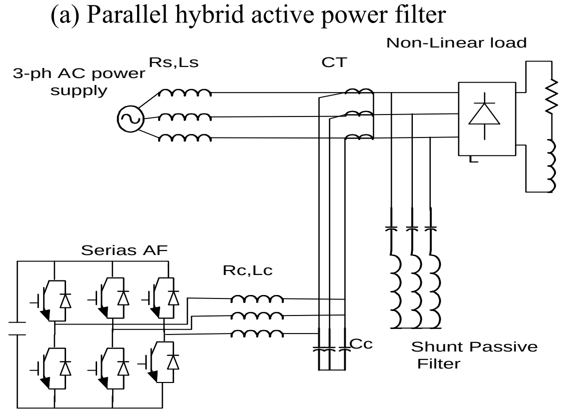
The paper is organized in following sections. In section II the topology of hybrid active power filter considered for study is discussed in detail. Section III deals with control strategy implemented in active power filter. Design aspects of hybrid active power filter and the sliding mode controller is covered in section IV. The outcome of section III and IV is implemented to HAPF in MATLAB/simulink platform; finally the results are analyzed and discussed in section V and VI.

2. HYBRID ACTIVE POWER FILTER

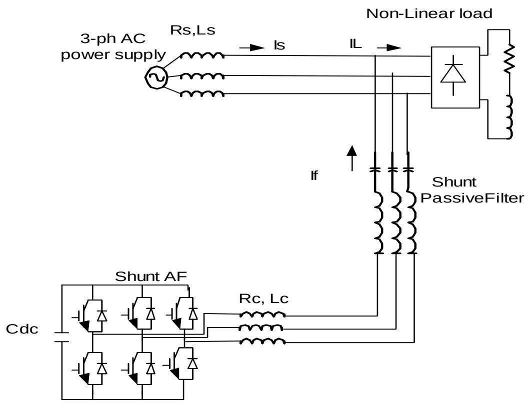
Among the various configurations of hybrid active power filter, i.e. parallel, series and shunt, parallel hybrid active power filter is preferred when the load is current source type [12]. Series hybrid active power filter shown in Fig.1 (b) utilizes shunt passive filter and series active power filter (connected through current transformers to the system). It isolates load from the source by providing path to load current harmonics to shunt passive filter [7], but protection of active power filter during transients is a major problem due to its series connection to the system. Shunt hybrid active power filter (shunt active power filter connected through shunt passive filter to the system) gives satisfactory performance for harmonic compensation with reduced rating of active power filter and elimination of possibility of resonance (Fig.1(c)). This configuration requires less protection, but need of precise tuning of passive filter restrict it from implementation. Parallel operation of shunt active power filter and passive filter as shown in Fig.1 (a) has the advantage of independent operation of passive filter and shunt active power filter. The active power filter works here as a harmonic voltage source, which compensates the voltage drop in passive filter at harmonic frequencies by producing a short circuit across passive filter. At the same time it injects the higher order harmonic currents to the supply system, of the same amplitude and opposite polarity to that of the load harmonic current. Hybrid active power filters are best suited for low and medium kVA rating loads. But the major drawback with the hybrid active power filters is that there rating is decided by the peak harmonic current and therefore they are not suited to the high peak harmonic current producing loads [12].



(a) Parallel hybrid active power filter



(b) Series hybrid active power filter



(c) Shunt hybrid active power filter

Fig.1: Various Configurations of hybrid active power filter

A. PASSIVE FILTER

Passive filters serve the purpose of sinking harmonic currents generated by the load at harmonic frequency, for which they are tuned. Passive filters tuned at fifth and seventh harmonic frequencies, eliminate lower order harmonics generated by non-linear load, simultaneously improving their power factor. Higher order harmonics are passed to active power filter, wherein regulating DC bus voltage eliminates the harmonics; as a result overall power quality of the system is improved. Advantage of this combination is that no perfect tuning of passive filter is required and active power filter can be introduced to the system any time, when passive filter is already installed in the system.

B. ACTIVE POWER FILTER

The active power filter consists of three-phase voltage source inverter with a DC link capacitor. The voltage across DC link capacitor is sensed and compared with the reference voltage; the error signal is processed in sliding mode controller. Sliding mode controller provides conditioned signals to hysterisis band current controller. The hysterisis band current controller is used for triggering pulses for MOSFET's of the VSI bridge. Active power filter supplies compensating current to the system in response to the triggering pulses. Active power filter is also responsible to supply the losses occurring in the system such that the source current remains sinusoidal with unity power factor maintained.

3. CONTROL STRATEGIES FOR ACTIVE POWER FILTER

The objective of controlling the active power filter is to provide compensating signal to the system in such a way, that the supply current waveform remain sinusoidal and at the same time the harmonic currents are supplied to the non-linear load [9-10]. It is done in three steps as shown in Fig. 2,

1. Signal conditioning,
2. Estimation of compensating signals,
3. Generation of firing pulses for switching devices.

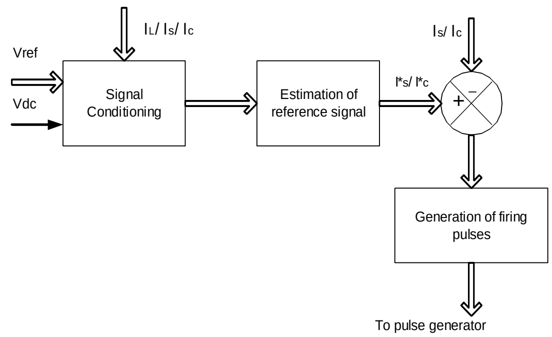


Fig.2: Block diagram of control strategy for active power filter

The reference supply currents can be obtained by applying the filtering algorithm such as Instantaneous Reactive Power (IRP) theory, Synchronous Reference Frame (SRF) or by Indirect method of sensing current. The instantaneous reactive power theory as introduced by Akagi et al [13] is based on transformation from abc reference frame to $\alpha\beta$ reference frame of the instantaneous power, voltage and current signals. The methods based on IRP theory provide good compensation with zero time delay, but the circuit configuration is complicate to implement. Synchronous reference frame theory [14] is used to find the reference source current at fundamental frequency; here extraction of fundamental component from source signal is performed. The control also incorporates the command for maintaining average DC bus voltage of an active filter to a constant value. This method is simple and easy to implement, but do not provide adequate solution under severe conditions of harmonics. Both these methods are unable to suggest control for proper operation of passive filter under transient conditions. The indirect method of taking unit current vectors from the supply and then multiplying them with the output of DC voltage controller provides the reference currents for respective phases. This control approach is simple, low cost and presents acceptable results when compared with p-q theory or SRF control [15].

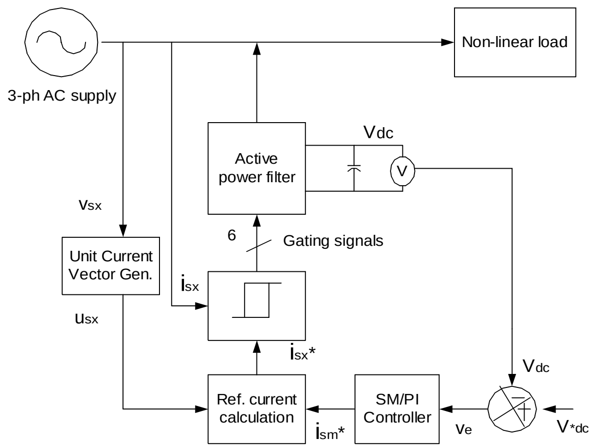


Fig.3: Control scheme of active power filter

Regulation of DC link voltage is another popular method preferred for low and medium power application [8, 9], which is simple and easy to implement and do not require to sense harmonics and VAr. It ensures effective current control at the input of the active power filter, therefore the feedback signal from DC bus voltage is considered while calculating reference current. For regulating the DC bus voltage there are three types of controllers available in the literature- PI controller, sliding mode controller, Fuzzy controller. In this technique the DC bus voltage is sensed and compared with the DC reference voltage as shown in Fig.3. The error signal is then conditioned and considered as the reference supply current I^*_{sm}. The three phase unit current vectors (u_{sa}, u_{sb}, u_{sc}) are obtained from the supply voltages (v_{sa}, v_{sb}, v_{sc}) and the peak supply voltage (V_m). These unit current vectors, when multiplied with reference supply current (I^*_{sm}), result in three phase reference supply currents (i^*_{sa}, i^*_{sb}, i^*_{sc}). The reference supply currents and sensed supply currents (i_{sa}, i_{sb}, i_{sc}) are the inputs for the pulse generator, generating the firing pulses as gating signals to the MOSFETs of the active power filter. The PI- controlled hybrid active power filter does not work satisfactorily under load variations; the SMC is preferred to regulate the DC bus voltage of APF under such conditions. Here sliding mode control is implemented to achieve the desired result.

A. SLIDING MODE CONTROL

The sliding mode control has been in use with active power filter for more than one decade. It is preferred over other controllers due to its fastness, robustness and stability under large load variations. The concept behind sliding mode control is defining a surface called sliding surface s, within which the system is controlled in a desired manner [16-20].

The three basic steps in preparing the SMC model are-

1. Proposal of a sliding surface,
2. Test of the sliding mode surface existence,
3. Control must observe the state of the sliding plane.

The APF model for operation in single-phase equivalent circuit is shown in the Fig. 4. The main aim is that when non-linear load and active power filter are combined, they should present unity power factor load to the supply system. Here switching function u represents the path of current i_c through MOSFETs of active power filter.

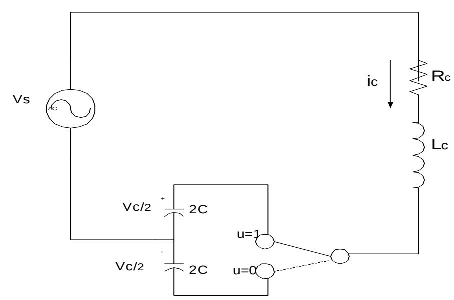


Fig-4: Equivalent circuit for APF modeling

From the sliding mode concept the sliding surface or trajectories for the line current can be defined as-

$$i_{\text{ref }x} = \text{K}\,(v_{sx}) \quad (1)$$

Where K is a constant depending upon the power requirement of the load.

Now for the sliding surface *s*,

$$s_x = [i_{sx} - \text{K}\,(\text{v}_{sx})] = 0 \quad (2)$$

When the state is on the sliding surface, there should be a natural control to satisfy condition

$$s\dot{s} < 0 \quad (3)$$

at all instant, for all state conditions.

If the equivalent control to the circuit is such that $-1 \le u_{eq} \le 1$, we observe for the switching action *u*,

If $u = -1$ then $\dot{s} < 0$, at all times i. e. for all values that state may experience.

Here if *u* is within natural control wounds of the physical system for $\dot{s} = 0$, then the system would remain on the sliding surface for all the times.

If, *u* exceeds the natural bound imposed by sliding surface, the system would be unable to remain on the sliding surface.

From discontinuous control law for the first order system, equation (3) must be satisfied to ensure the switching action driving the state toward the sliding surface.

Also if $u < u_{eq}$ then $\dot{s} < 0$,

If $u > u_{eq}$ then $\dot{s} > 0$

If the equivalent control to the circuit is such that $-1 \le u_{eq} \le 1$, we observe

If $u = -1$ then $\dot{s} < 0$,

If $u = 1$ then $\dot{s} > 0$

From above we see that

If $s < 0$, then $u = 1$

If $s > 0$, then $u = -1$

satisfies eqn.(3). To apply this control to active power filter, at each sample time the status of state s is checked and discontinuous control law is implemented through sliding mode controller.

B. GENERATION OF UNIT CURRENT VECTOR

The peak amplitude of the supply voltage is derived from sensed three-phase sinusoidal voltages as-

$$V_{sm} = [\frac{2}{3}(v_{sa}{}^{2} + v_{sb}{}^{2} + v_{sc}{}^{2})]^{1/2} \tag{4}$$

Now the three phase unit vectors can be taken as-

$$u_{sa} = \frac{v_{sa}}{V_{sm}}, u_{sb} = \frac{v_{sb}}{V_{sm}}, u_{sc} = \frac{v_{sc}}{V_{sm}} \tag{5}$$

These unit current vectors, when multiplied with the reference supply current I_{sm}^{*} provide with the three phase reference sinusoidal currents in phase with the supply voltage -

$$i_{sa}^{*} = I_{sm}^{*} * u_{sa}, i_{sb}^{*} = I_{sm}^{*} * u_{sb}, i_{sc}^{*} = I_{sm}^{*} * u_{sc}, \tag{6}$$

The reference currents when compared with the sensed actual currents in the hysteresis band current controller provide with the switching signals for the active power filter.

C. HYSTERISIS BAND CURRENT CONTROLLER

A carrier less hysterisis band current controller is used over the reference currents ($i^{*}_{sa}, i^{*}_{sb}, i^{*}_{sc}$) and sensed supply currents (i_{sa}, i_{sb}, i_{sc}) to generate the switching signals for the MOSFETs of the current controlled VSI working as an active power filter. The switching signals are obtained as follows-

If $i_{sx} > (i^{*}_{sx} + hb)$, upper switch of xth leg is ON and lower switch is OFF, and

If $i_{sx} < (i^{*}_{sx} + hb)$, upper switch of xth leg is OFF and lower switch is ON,

Where 'hb' is the hysterisis band around the reference current and $x = a, b, c$, which stands for three legs of PWM converter.

In response to the switching signals generated by controller, active power filter shapes the supply currents to sinusoidal and it compensates the power factor, harmonics and reactive power of the nonlinear load.

4. DESIGN OF HYBRID ACTIVE POWER FILTER

A. DESIGN OF PASSIVE FILTER

Passive filters are designed to eliminate the lower order harmonics and to supply the reactive power consumed by the non-linear load. Design of passive filter capacitance is decided by the reactive power requirement, while the inductive reactance is decided by resonance phenomenon for the tuned harmonic frequency [21-22].

For n^{th} harmonic frequency (f_n)–

$$X_{Ln} = h_n X_{L1} = X_{Cn} = \frac{X_{C1}}{h_n} = X_n \tag{7}$$

Where h_n is the tuning order corresponding to resonant frequency $h_n = f_n/f_1$.

Capacitive reactance of a single tuned filter can be given by-

$$X_c = \frac{v^2}{Q_c} \tag{8}$$

Where Q_c is the VAr size of the capacitor.

And inductive reactance and resistance are given by-

$$X_L = \frac{X_c}{h_n{}^2} \tag{9}$$

$$R_L = \frac{X_1}{Q} \tag{10}$$

Where Q is the quality factor of the inductive coil.

Size of the passive filter in VArs can be given by-

$$Q_F = \frac{v^2}{(X_C - X_L)} = \frac{v^2}{(X_C - X_C / h_n^2)} \tag{11}$$

Or

$$Q_F = \frac{h_n^2}{(h_n^2 - 1)} * \frac{v_2}{X_C} = \frac{h_n^2}{(h_n^2 - 1)} * Q_C \tag{12}$$

Based on above equations parameters are decided and the optimum performance output of the system is observed at the calculated values by comparison with the performance at nearby values as given in Table-1.

TABLE-1
LIST OF VARIOUS COMBINATIONS OF PASSIVE FILTER COMPONENTS

Value of component			Parameter variation	
R_5 Ω	L_5 mH	C_5 µF	Power factor	%THD
0.1	3.4	120	0.9954	2.38%
0.1	***4***	***100***	***0.9999***	***2.43%***
0.1	6.89	80	0.9978	2.66%

A. FIFTH HARMONIC TUNED PASSIVE FILTER

Value of component			Parameter variation	
R_7 Ω	L_7 mH	C_7 µF	Power factor	%THD
0.1	7	30	1.007	2.58%
0.1	***4***	***50***	***0.9999***	***2.43%***
0.1	2.58	80	0.9961	2.11%

B. SEVENTH HARMONIC TUNED PASSIVE FILTER

B. DESIGN OF ACTIVE POWER FILTER

A voltage source inverter is used as the active power filter, for which the input DC voltage is essentially constant and independent of the load current drawn [23-24]. A large capacitor is placed across the DC input line to the inverter. The capacitor ensures that any switching event within the inverter do not significantly change the DC input voltage. On the AC side of the VSI, ripple filter is connected, which compensates for the ripples generated in the APF current due to fast switching of MOSFETs.

SELECTION OF L_c, C_{dc}, V_{dc}

To keep harmonic distortion in source current within limits, a desirable condition is that the DC bus voltage across the capacitor should rise up to around double the peak source voltage [24]. This choice makes the transient response of the active filter better, as capacitor has sufficient stored energy to meet the requirement of sudden load changes. While deciding rating of DC link capacitor following points are to be considered-

1. Power factor close to unity should be achieved with any type of load,
2. A constant DC voltage should be maintained across the capacitor with minimum ripples,
3. Steady state as well as transient response must be fast.

The DC bus capacitance of the APF system can be calculated from the energy requirement of the capacitor [23]-

$$\Delta e_{dc} = \frac{1}{2} C_{dc}[(V_{dc}^{*})^2 - (V_{dc})^2] \tag{13}$$

Here Δe_{dc} is the energy required by the capacitor to be stored for keeping the DC bus voltage near reference value.

Design of filter inductance (R_c, L_c) depends upon the switching frequency of the hysterisis band current controller. The APF circuit shown in Fig.1 can be represented by equation-

$$R_c i_c + L_c \frac{di_c}{dt} + v_c = v_s \tag{14}$$

where v_c is the voltage at the VSI-mid point. Average value of v_c is assumed equal to the addition of votlage v_s and voltage drop across ripple filter (L_c, R_c). Voltage drop across inductor of the ripple filter is considered to be around 10% of the supply voltage, drop across resistance R_c is very small compared to that across L_c and therefore can be neglected. Therefore the voltage across ripple filter can be taken as v_c=1.1V_{sm}.

Thus the equation (14) becomes-

$$L_c \frac{di_c}{dt} = -v_c + v_s = -1.1V_{sm} + V_{sm} \tag{15}$$

Lower value of ripple filter inductance is selected for taking into account the variation in switching frequency. Hysterisis bandwidth of controller is taken as ±0.2. Calculated values of C_{dc}, V_{dc} and L_c and nearer values are implemented on the system and system performance judged on parameters like power factor, transient response and %THD (Table-2-4). The calculated system parameters are- C_{dc}=2200 µF, V_{dc}= 680V and L_c=3.35mH.

TABLE-2
SYSTEM PERFORMANCE AS REFERENCE DC LINK CAPACITOR VOLTAGE VARIES

DC link Cap. Voltage V_{dc}(Volt)	Power factor	%Rise/ fall in V_{dc}	Settling time	%THD
650	0.9887	0.1%	0.001sec.	2.98%
680	***0.9999***	***0.04%***	***0.02sec.***	***2.43%***
700	0.9743	7.14%	0.02sec.	2.08%

TABLE-3
SYSTEM PERFORMANCE AS DC LINK CAPACITOR VALUE VARIES

DC link Capacitor C_{dc} (μF)	%THD	%Rise/ fall in V_{dc}	Settling time	Peak to peak ripple in V_{dc}
1800	2.55%	0.44% fall	0.01sec.	0.3V
2200	***2.43%***	***4.04% rise***	***0.02sec.***	***0.55V***
2400	2.31%	5.88% rise	0.02sec.	0.9V

TABLE-4
SYSTEM PERFORMANCE AS FILTER INDUCTANCE VALUE VARIES

Filter Inductance L_C (mH)	Power factor	%THD
3.00	0.9830	2.04%
3.35	***0.9999***	***2.43%***
3.65	0.9972	2.61%

C. SELECTION OF SMC PARAMETERS

Sliding mode control can be defined as a means to maintain the system within a surface called sliding surface and hence obtaining a desired system output.

In sliding mode controller the peak value of supply current is calculated with the help of DC link capacitor voltage V_{dc} and the reference voltage V_{dc}^*.

The error v_e at any instant is defined as-

$$v_e(t) = V_{dc}^*(t) - V_{dc}(t) = x_1 \quad (16)$$

And its derivative at that instant is defined as-

$$x_2 = \dot{x}_1 = [v_e(t) - v_e(t-1)] \quad (17)$$

Where x_1 and x_2 are the state variables.

In sliding surface, the switching functions y_1 and y_2 are given by-

$$y_1 = +1 \text{ If } zx_1 > 0$$
$$= -1 \text{ If } zx_1 < 0$$
$$y_2 = +1 \text{ If } zx_2 > 0$$
$$= -1 \text{ If } zx_2 < 0$$

Where $z = c_1x_1 + c_2x_2$ is the switching variable for the sliding surface.

Now the output of the SMC can be calculated as peak supply current I_{sm}^* as-

$$U(t) = c_3x_1y_1 + c_4x_2y_2 = I_{sm}^* \quad (18)$$

Where c_1, c_2, c_3, c_4 are the constants of sliding mode controller. The controller parameters must be positive to assure the existence condition of the sliding mode and to have a good behavior of the controlled system. Based on above calculation empirical values of sliding mode controller parameters and respective changes in THD and steady state DC bus voltage are listed below in Table-5 and constant values selected for system under study are c_1=1.0, c_2=1.05, c_3=0.045, c_4=0.065.

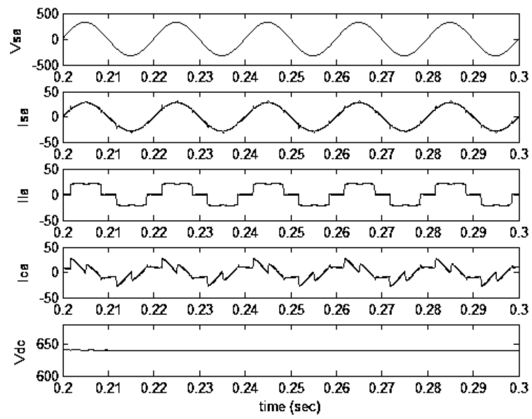
5. SIMULATION RESULTS

A simulation model of the studied hybrid active power filter is developed in MATLAB environment. The supply system used is 230V, 3-Φ, 3-line, 50 Hz sinusoidal. The non-linear load considered for compensation is 4kVA diode rectifier with RL-load. Simulation results are obtained for both steady state and transient conditions. Different parameters used for simulation study are listed in Appendix-I. Fig.5 shows the simulation waveforms in steady state and Fig.6 (a-c) show %THD of load current and source current for SM-controlled and PI- controlled hybrid active power filters respectively. The source current is observed to be sinusoidal with power factor approaching unity, while the %THD in the source current is well below the IEEE 519 limits in both the cases. It is observed that the DC link voltage settles to a lower value in SM controlled HAPF as compared to PI- controlled HAPF, with lower transients in source current. In Fig.7 (a-b) the simulation results for active power filter switched on and in Fig.8 (a-b) change in load for HAPF with both the controllers respectively are given. The active power filter is switched on at 0.1 sec. It is found that the supply current, active power filter current and DC- bus voltage settles to steady state condition in less than 1 cycle after the active power filter is switched on in case of SM controlled HAPF as compared to slow responding PI-controlled HAPF, wherein the steady state value is reached after 2 cycles. As the load current increased or decreased, the supply current also changes accordingly and active power filter current changes to meet the requirement. At transient condition i.e. under load changes the SM controlled HAPF again shows faster response with less overshoot/ dip in DC link voltage as compared to PI- controlled HAPF. The sliding mode controlled hybrid active power filter compensate harmonics and reactive power effectively under steady state as well as during transients.

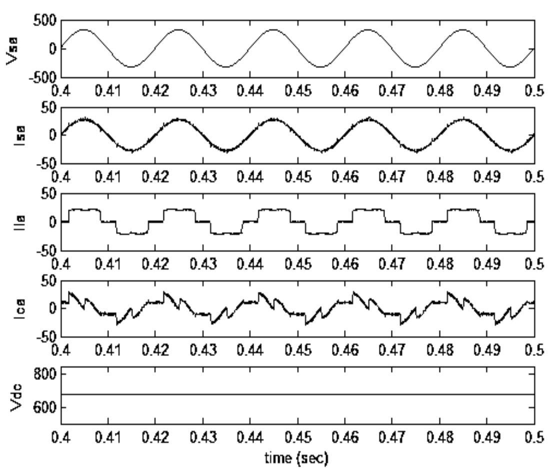
TABLE-5

CHANGE IN %THD AND V_{DC} WITH THE VARIATION IN SMC PARAMETERS

SMC parameter				Performance with Non-linear load		
c_1	c_2	c_3	c_4	%THD	%Rise in V_{dc}	Settling time
2.0	2.1	0.045	0.065	2.12%	7.35%	0.02sec.
1.0	***1.05***	***0.045***	***0.065***	***2.26%***	***4.04%***	***0.02 sec.***
2.0	2.1	0.095	1.25	2.17%	7.64%	0.1sec.

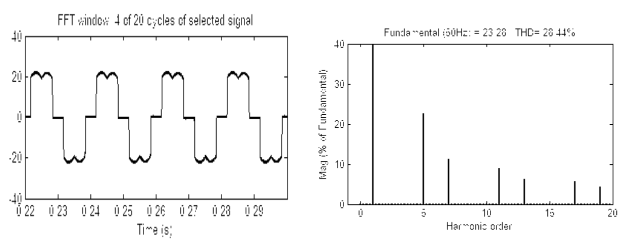


(a)

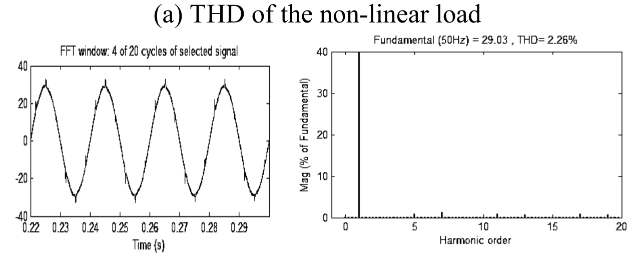


(b)

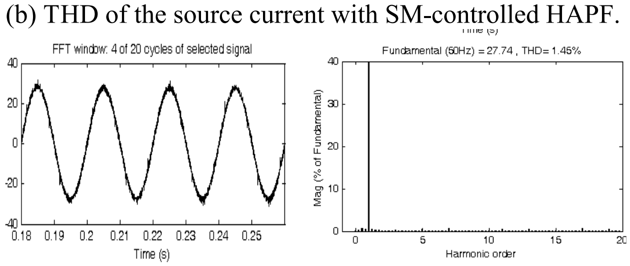
Fig. 5: Source voltage, source current, load current, AF current and DC link capacitor voltage waveforms for (a) SM-controlled and (b) PI-controlled HAPF in steady–state.



(a) THD of the non-linear load

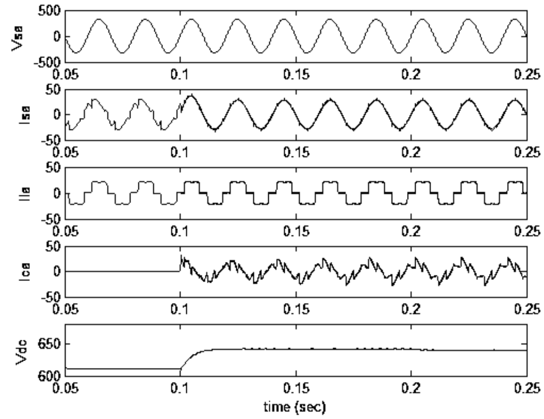


(b) THD of the source current with SM-controlled HAPF.

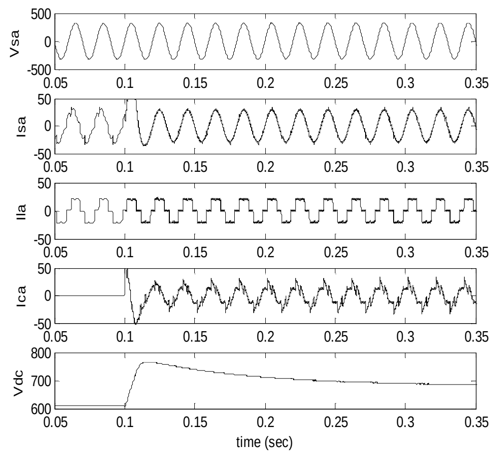


(c) THD of the source current with PI-controlled HAPF.

Fig.6: THD of various currents at steady state of the HAPF.

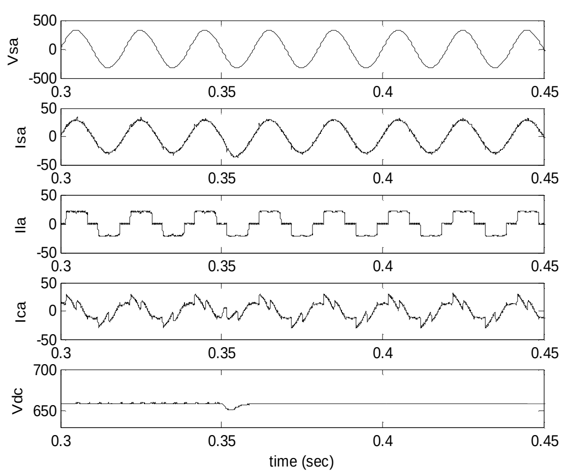


(a) Switch-in response for SM-controlled HAPF

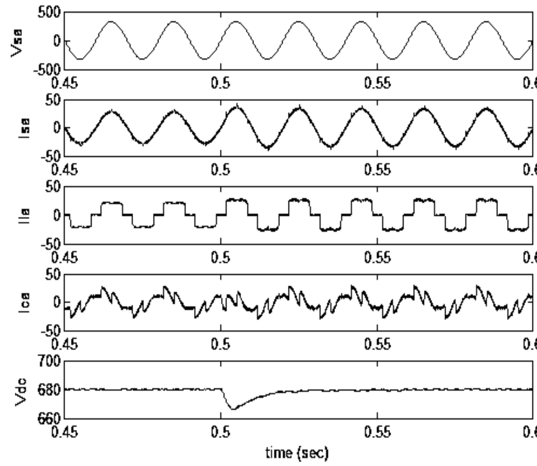


(b) Switch-in response for PI-controlled HAPF

Fig. 7: Source voltage, source current, load current, AF current and DC link capacitor voltage waveforms for (a) SM-controlled and (b) PI-controlled HAPF, when active power filter switched in.



(a) Load perturbation response for SM-controlled HAPF



(b) Load perturbation response for PI-controlled HAPF

Fig. 8: Source voltage, source current, load current, AF current and DC link capacitor voltage waveforms for (a) SM-controlled APF-The APF is switched on at 0.1 sec and load changes at 0.3 sec and (b) PI-controlled HAPF-The APF is switched on at 0.1 sec and load changes at 0.5 sec.

Based on above discussion and simulation results the relative comparison of hybrid active power filter response with both type of controllers based on results obtained is listed in Table-7.

TABLE- 7
RELATIVE COMPARISON OF SLIDING MODE CONTROLLED AND PI-CONTROLLED HYBRID APF RESPONSE

Parameters	SM-controller	PI-controller
Mode of operation	Continuous	Continuous
Reactive power compensation	Completely	Completely
Power factor	0.9999	0.9731
THD %	Below 5%	Below 5%
Settling time	1cycle	2½cycle
% Fall in Vdc with rise in load	1.42%	2.05%
Stress on elements	Low	High
Peak to peak ripples in DC link voltage	0.55V	0.25V
Transient response	Fast	Relatively slow

6. CONCLUSIONS

Performance of sliding mode controlled hybrid active power filter is investigated in the paper. It is found that sliding mode controlled hybrid active power filter effectively compensates harmonics and reactive power and makes the power system operate near unity power factor for varying load conditions. Complete design of passive and active power filter as well as sliding mode controller is presented. Sliding mode controlled HAPF offers fast dynamic response and simple implementation of the algorithm as compared to PI-controlled HAPF. The drawback associated with SMC is the presence of steady state error in DC bus voltage, tuning of the parameters of SMC can control this drawback. Above all the load invariance characteristic out ways the drawbacks associated with the sliding mode controller.

APPENDIX- I

System parameters

Source voltageV_s(rms/phase)	230V, 50Hz
R_s , L_s	0.1 Ω , 0.15 mH
R_c , L_c	0.3 Ω, 3.35mH
Non linear load	4KVA, 230V
C_{dc}, R_{dc}	2200µF, 10000Ω
SMC- C_1, C_2, C_3, C_4	1.0,1.05,0.045,0.65
R_5, L_5, C_5	0.1Ω, 4mH, 100µF
R_7, L_7, C_7	0.1Ω, 4mH, 50µF

APPENDIX- II

PI-Controller

PI controller is used to maintain the DC bus voltage of APF to its reference value and compensates for inverter losses required to regulate the DC link voltage. The required filtering to DC bus voltage is dependent on the value of capacitor, which in turn is sized according to the voltage ripples. The sensed DC link voltage *(V_{dc})* of the APF is compared with its reference counterpart *(V^*_{dc})*.

The peak current amplitude I^*_{sm} in case of PI- controller is calculated as –

The DC bus voltage error at nth sampling instant is-

$$V_{e(n)} = V^*{}_{dc(n)} - V_{dc(n)},$$

The error signal $V_{e(n)}$ is processed in PI controller. The output $K_{(n)}$ at nth sampling instant is-

$$K_{(n)} = K_{(n-1)} + K_p(V_{e(n)} - V_{e(n-1)}) + K_i(V_{e(n)}),$$

Where K_p and K_i are the gains of the PI- controller.

The output after a limit is considered as amplitude of supply current and is denoted as I^*_{sm}.

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