PERFORMANCE INVESTIGATION OF POWER QUALITY IN DISTRIBUTED GENERATION SYSTEM FED SMART GRID USING DIFFERENT CONTROL STRATEGIES

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Abstract: *Due to increasing energy demand, to reduce carbon footprint, utilities are now forced to move on with Distributed Energy sources (DES) like solar Photo Voltaic cell , fuel cell, etc., to form Distributed Generation system (DGS) where DES is interconnected with conventional energy sources (CES) like thermal, hydro, and nuclear etc., with the help of Grid interfacing converters. Moreover, the usage of DES by customers is also increasing exponentially. Whenever the nonlinear load is being used by customer, power quality problem arises in the supply both in voltage and current profile unlike the non DGS supply where current profile gets affected. The problem is being alleviated by the harmonic resonance introduced by the capacitor banks in the network. In addition, the mal operation of converter is also leads to cause the trouble in the supply. To mitigate it, passive filter, active and hybrid filters are generally used whose successful operation requires proper control strategies. In this paper, novel control algorithm is explored for active filters to compensate the harmonics introduced by the customer and grid interfacing converters into the Grid. The Proposed control strategy combines both fuzzy and sliding mode control, which manages the injected filter current into the PCC proportional to harmonics distortion, resulting in improvement of power quality. A DGS system model has been first developed. The effect of nonlinear load is studied. Different control strategies are implemented and comparison between them carried out to demonstrate the superiority of the control scheme. Also the steady state and dynamic performance is checked out by considering diverse loaded condition. The efficacy of scheme is verified through analysis and simulations. Finally, stability of the proposed control scheme is presented to emphasize its applicability in real time. The obtained result shows that the control scheme yields simple, fast response, improved supply quality and flat capacitor voltage profile of the filter concerned.*

Key words: *Distributed generation (DG), photovoltaic (PV), power quality improvement, harmonic compensation, Total harmonic distortion (THD), Sliding mode control (SMC), Fuzzy control , fuzzy sliding mode control (FSMC), renewable energy, residential distribution system.*

1. Introduction

Generally, conventional power generation schemes such as like thermal, hydro, and nuclear etc., are used to satisfy the energy consumer demand. But due to increasing energy demand, to reduce carbon footprint, difficult to get right of way and more implementation time left the utilities to choose Distributed Energy sources (DES) like solar Photovoltaic cell , fuel cell, etc., to form a interconnected Distributed Generation system (DGS) where DES is interconnected with conventional energy sources (CES) with the help of Grid interfacing converters. In CES system, use of nonlinear load by energy consumer leads to distortion in supply current profiles. Moreover in the DGS, it causes the voltage to be distorted in addition to the current profile distortion unlike the CES. This is all because of source inductance of DGS added in to the system as shown in Fig. 1. As a result, it is important concern to find out solution to since it is suffers from drawbacks like single harmonics elimination, complex design, off line tuning, cost and etc., as in [4]-[5]. Then active filtering concept has been emerged as a solution among the three major types of active filters such as Series, Shunt and Hybrid filters, Shunt Active Power Filter (SAPF) is the most preferable for most of the large scale industries and even in small scale industries. SAPF is constructed with a three phase voltage source inverter along with the controller [5]-[8]. The proper operation of filters depends upon the suitable control algorithm which is discussed in the forthcoming chapters. The design of controller for shunt active power filter involves three steps. Firstly reference current extraction; secondly filter current calculation and finally switching pulse generation. The theme of this paper mainly concentrates on the better control algorithm for the betterment of supply.

Literally so many control schemes has been put-forth towards power quality improvement starts from classical control scheme such as p-q theory, reference frame schemes and SRF theory, followed with nonlinear control techniques such as Lyapunov-function-based control and sliding mode control [15], continued with implementation of soft computing techniques such as neural network, iterative learning control (ILC) fuzzy logic and adaptive neuro-fuzzy, PLL etc. are yielding a good result [15-18]. But the issues like more analytical calculation involved, slow response time, chattering phenomenon and the presence of delay and error involved due to training of networks, in appropriate calculation and adaptation of error calculation between the output and their target values and upgrading of training weights leads to

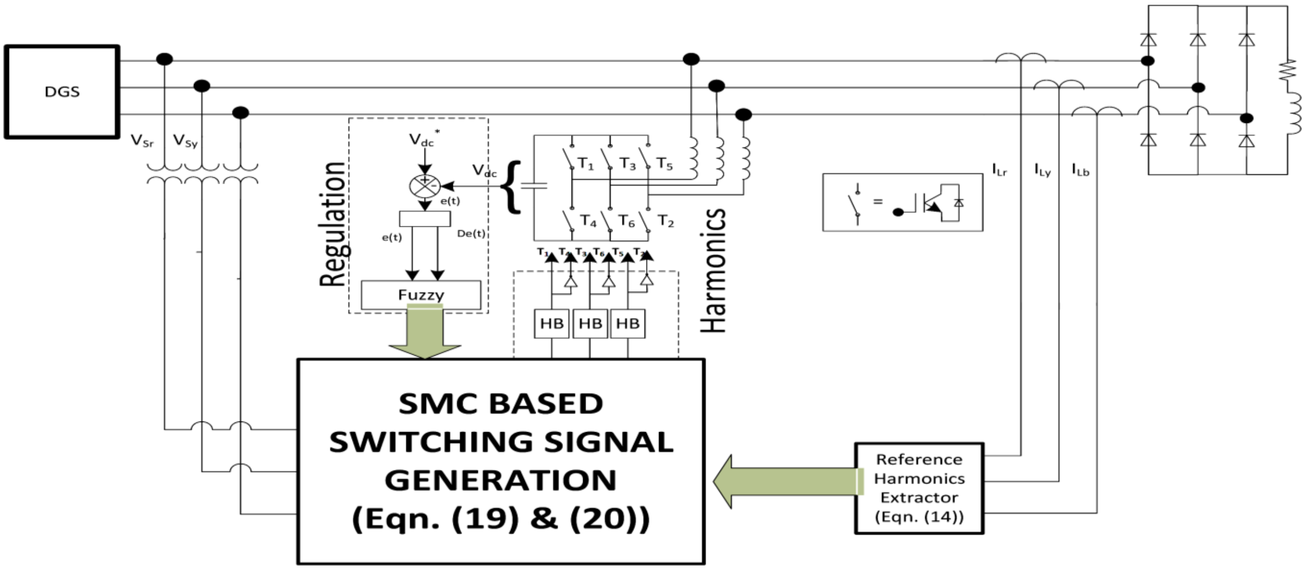


Fig.1. Complete Block Diagram of Experimental Study Setup

rethink when it is come for implementation. In this paper a novel control schemes are proposed. It is used for enhancing the power quality by increasing real power flow, decreasing reactive power flow from the utility and improved power factor, reduction in harmonics, load balancing with zero dc voltage regulation of the active filter. It composes into fuzzy and sliding mode control (SMC). SMC is preferred because of its simple implementation by adopting modelling approach which is based on Fourier Transform applied to the inverter leading a state space model in the (a, b, c) frame. This modelling alternative is quite simple to handle and exhibit good dynamic response, robustness, disturbance rejection capabilities and stability. But the limitation is presence of chattering phenomenon in the SMC will lead to higher voltage regulation in the SAPF, which will introduces additional problem in the power quality. Hence fuzzy is used along with the SMC to avoid the above said drawback by regulating the DC voltage of the three phase inverter.

This paper is briefs the scheme in the following sections: Section 2 describes the experimental study model and its mathematical modelling. Section IV Discusses the design aspects of Shunt Active Power Filter (SAPF). Section V reports the conventional controller which is available in literature also it includes the proposed control scheme adopted for the SAPF. Section VI discusses simulation results of control scheme for the SAPF. Section VII enlightens the performance of the proposed control scheme by evaluating the proposed system with its counterparts available in the literature. Section VIII concludes with the features of the proposed system and its future enhancements.

2. System Modelling

Complete block diagram of system structure with proposed control strategy is shown in Fig .1. It consists of DGS is connected to the nonlinear load with SAPF. Moreover, In SAPF, three phase voltage source inverter is the key element as it injects current proportional to the harmonica and improves the regulation. That is solely depends upon the proper control strategy. In this paper, FSMC is proposed to get improved regulation, harmonics reduction, improved power factor and higher stability.in this section, the Modelling of DGS is dealt first, secondly design of SAPF is presented.

2.1 Modelling of DGS with load

DGS can be mathematically modelled as voltage source with series inductance having finite value because of the intermittent nature of DES and dependency of power conditioning circuit (DC/DC converter in the case of PV and Fuel cell and AC/AC converter in the case of Wind)[1]-[3]. Due to the presence of source inductance on the supply leads to degradation of its quality [2] which is Shown in Fig.7a that distorted voltage and current waveforms of supply and load. It is evident that quality depends upon the source inductance. In case of CES, the voltage is pure sinusoidal because of the negligible source inductance. When it is connected with the load such as motor, power electronics based recent inventions, residential appliances, it can be act as a harmonic current source in parallel with the fundamental impedance as eqn.(12). Whenever the nonlinear load connected with the utility, the voltage and current profile of the utility get distorted. Due to this, it is not only reducing power quality but it will also ruin the other load which are connected to the same grid. By considering the system model, In general, we can express the Fourier series of the line currents as follows:

$$i_a(t) = i_{a0} + \sum_{k=1}^{\infty} i_{ak} \cos(k\omega t - \theta_{ak}) \quad (1)$$

$$i_b(t) = i_{b0} + \sum_{k=1}^{\infty} i_{bk} \cos\left(k\left(\omega t - 120^o\right) - \theta_{bk}\right) \quad (2)$$

$$i_c(t) = i_{c0} + \sum_{k=1}^{\infty} i_{ck} \cos\left(k\left(\omega t + 120^o\right) - \theta_{ck}\right) \quad (3)$$

Due to the interconnection of DGS, the line voltages can be expressed as follows:

$$v_a(t) = v_{a0} + \sum_{k=1}^{\infty} v_{ak} \cos(k\omega t - \theta_{ak}) \quad (4)$$

$$v_b(t) = v_{b0} + \sum_{k=1}^{\infty} v_{bk} \cos\left(k\left(\omega t - 120^o\right) - \theta_{bk}\right) \quad (5)$$

$$v_c(t) = v_{c0} + \sum_{k=1}^{\infty} v_{ck} \cos\left(k\left(\omega t + 120^o\right) - \theta_{ck}\right) \quad (6)$$

If the load is unbalanced and nonlinear, then the line current and voltage may contain AC & DC harmonics of all order, including even and triplen harmonics

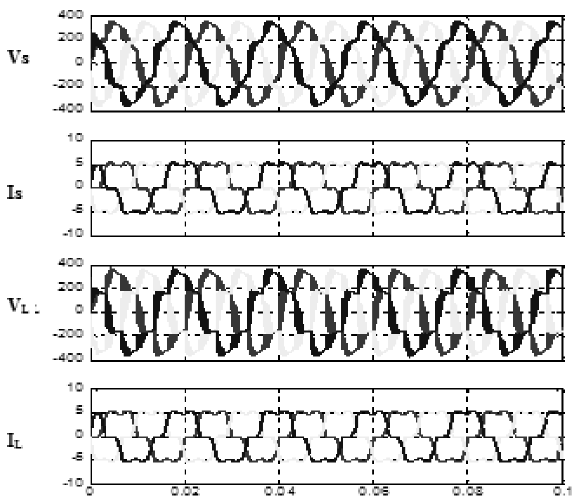


Fig. 2. Observed system waveforms of DGS under nonlinear load to high nonlinear load change

causes the abnormal increase in the RMS current which causing the PFC capacitor as well as the insulation to fail and finally leads to poor power quality. The design aspects of control strategy to meet out the above objective will cover in the next section.

2.2 Shunt Active Power filter (SAPF)

Shunt Active Power Filter (SAPF) can be realized by a three single phase half-bridge inverter together with the controller. It is connected to PCC as shown in Fig. 1. It injects the filter current in to the PCC which is proportional to the harmonics introduced by the nonlinear load in to the DGS.

2.2.1 Modelling of Inverter

The topology proposed [5-7] is highly suitable for high power application because of the fact that the output voltage is twice that of the half-bridge inverter and requires less number of switches when compared to full bridge version. For the sake of simplicity, single phase leg A is taken in to consideration [15]. by considering conventional three phase Voltage source inverter with high series inductance ,Then the filter current as function of switching action is modelled as,

$$i_{fa} = \frac{V_{dc}}{Z_{fa}}\left(Q_1(t) - Q_4(t)\right) \quad (7)$$

$$i_{fb} = \frac{V_{dc}}{Z_{fb}}\left(Q_3(t) - Q_6(t)\right) \quad (8)$$

$$i_{fc} = \frac{V_{dc}}{Z_{fc}}\left(Q_5(t) - Q_2(t)\right) \quad (9)$$

The Dynamic analytical model of the SAPF is obtained by using state variable concept. Let us define the following state variables $X_1 = i_{f1}; X_2 = V_{dc}; X_3 = \cos(\omega t)$

The state space model of the SAPF is given by

$$\begin{bmatrix} \dot{X}_1 \\ \dot{X}_2 \\ \dot{X}_3 \\ \cdots \\ \dot{X}_{n+3} \\ \cdots \\ \dot{X}_{k+3} \end{bmatrix} \begin{bmatrix} \frac{1}{2L_s}X_2 + \frac{V_m}{L_s}X_4 \\ \frac{2}{C}X_3 \\ -\omega\sqrt{1-X_4{}^2} \\ \cdots \\ (n+3)\,\omega\sqrt{1-X_{n+3}{}^2} \\ \cdots \\ -(k+3)\,\omega\sqrt{1-X_{k+3}{}^2} \end{bmatrix} + \begin{bmatrix} \frac{1}{2L_s}X_3 \\ \frac{1}{C}X_1 \\ 0 \\ \cdots \\ 0 \\ \cdots \\ 0 \end{bmatrix} \quad (10)$$

The State vector is given by

$$X = \begin{bmatrix} i_{f1} \\ V_{dc} \\ \cos\omega t \\ \cos\left[(n+3)(\omega t + \phi_{n+3})\right] \\ \cdots \\ \cdots \\ \cos\left[(k+3)(\omega t + \phi_{k+3})\right] \end{bmatrix} u(t)$$

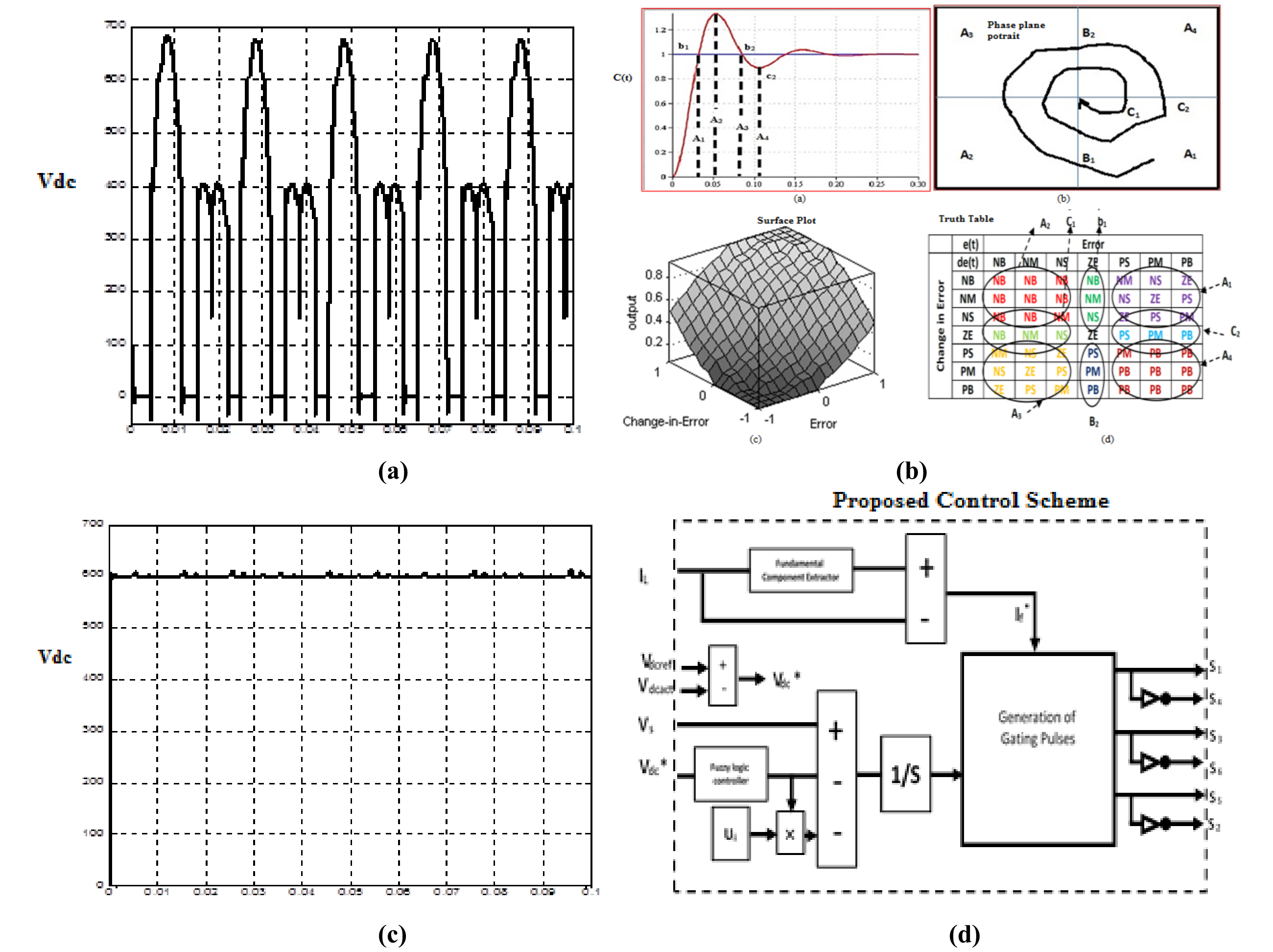


Fig. 3. (a) DC Voltage profile under SMC (b) Fuzzy controller design elements (c) DC Voltage profile under FSMC d) Detailed block diagram of proposed control Scheme.

2.3 Design of Sliding Mode Control (SMC)

As for as the design of SAPF concerned, there are 3 steps involves, namely Reference current generation, Actual filter current extraction and Switching signal generation.

2.3.1 Reference current generation

This section derives the net harmonics introduced by the nonlinear load in the utility supply by observing the load current. Then extraction of its harmonic content is obtained by subtracting with the filter current which will be discussed in the next section. The harmonic components, so extracted, are adjusted for polarity and used as reference commands for the current controller. The instantaneous nonlinear load current i_L can be written by applying Fourier transform as

$$i_L = \sum_{k=1}^{\infty} i_{Lh} \cos\left(k\left(\omega t + \theta_n\right)\right) \tag{11}$$

and

$$i_L = i_L \cos\left(\omega t\right) + \sum_{k=2}^{\infty} i_{Lh} \cos\left(k\left(\omega t + \theta_n\right)\right) \tag{12}$$

The equation (12) can be simplified as

$$i_L = i_{Lf} + i_{Lh} \tag{13}$$

and

$$i_L = i_{LfP} + i_{LfQ} + i_{Lh} \tag{14}$$

As in (14), fundamental component of Load current, is decomposed in to two major component into real (i_{LfP}) and reactive (i_{LfQ}) power component and harmonic component (i_{Lfh}).First term deals with the power converted into useful and Second term considered as a useless power mainly due to i_{Lfp}, i_{Lfq} the switching action, the reactive parameters and etc., Third term i_{Lh} is the key part is to be eliminated since it deteriorate the supply quality.

By applying KCL at PCC

$$i_s = \beta V_s = i_L + i_f \tag{15}$$

From (15), the reference filter current (i_f) is extracted as

$$i_f = \left(\beta V_s - \left(i_{LfP} + i_{LfQ}\right)\right) - i_{Lh} \quad (16)$$

Let, compensation current (i_c) for the regulation of DC capacitor

$$i_c = \left(\beta V_s - \left(i_{LfP} + i_{LfQ}\right)\right) \quad (17)$$

and $$i_f = i_c - i_{Lh} \quad (18)$$

2.3.2 Actual filter current extraction

Applying KVL at the PCC gives the following expression

$$\frac{di_f}{dt} = \frac{1}{L_s}\left(v_s - V_{dc} u_i\right) \quad (19)$$

$$\frac{dv_{dc}}{dt} = \frac{1}{C}\sum_{i=1}^{3} i_{fi} \quad (20)$$

u_i = Switching state if $u_i = 1$, then Switch is "ON" & Switch is "OFF" otherwise. Eqn. (19) represents the actual instantaneous filter current of the SAPF. In this proposed control scheme, both the DC voltage and Supply Voltage is taken into consideration. So this proves that both harmonic elimination and power factor improvement and be done.

2.3.3 Switching signal generation

The switching signal for SAPF is generated by comparing reference filter current with the actual filter current and it is given to bang-bang controller to inject the current into PCC so as to improve power quality and power factor. This makes the power system must be stiff irrespective of any variation due to DGS, load and reactive component. To realize the above approach, parameters are sampled as per (16) & (19). Then it is compared and the error signal is allowed to pass through bang-bang current controller (BCC). The BCC will generate the gate pulse for the individual phase le of 3 Φ inverter as per (21)

$$u_i = \begin{cases} 1 \text{ if } \varepsilon \geq H_b \\ 0 \text{ if } \varepsilon < H_b \end{cases} \quad (21)$$

3. Control Scheme

The required functioning of SAPF depends upon the proper control scheme so that to reduce the harmonics and reactive power requirement in the supply to ensure maximum utilization of the supply. In this connection, fuzzy sliding mode based control (FSMC) scheme is discussed here and the performance comparison has been made with the available control schemes in the literature.

3.1 Hysteresis current mode control

Generally it is called as two-level current control in which the gate signal is generated in such a manner that the error filter current tracks a harmonic reference within a specified hysteresis band. Generally hysteresis controllers are preferred to control the switching of the inverter because of its quick dynamic response, improved stability and wide command-tracking bandwidth. This method controls the switches in an inverter asynchronously to ramp the current through an inductor up and down so that it tracks a reference current signal. One disadvantage is that there is no limit to the switching frequency, ripples in the DC input voltage of the inverter. But additional circuitry can be used to limit the maximum switching frequency.

3.2 Sliding mode control (SMC)

Sliding Mode Control (SMC) is a robust control scheme based on the concept of changing the structure of the controller in response to the changing state of the system in order to obtain a desired response. A high speed switching control action is used to switch between different structures of the controller and the trajectory of the system and is forced to move along a chosen switching manifold in the state space. SMC is basically an adaptive technique in which output response is forced to track the desired response. Sliding mode control offers several advantages, such as stability, even for large supply and load variations, robustness, good dynamic response and simple implementation [11 &15]. SMC is proposed to accomplish the underlying idea of the current mode control. The controller focuses on injecting the filter current proportional to the harmonics in the system.
Consider the system

TABLE I
SYSTEM PARAMETERS

Element	Parameter	Values
Power Grid	Source Voltage Vs (V) = 415 V; Supply frequency f (Hz) = 50 Hz;	
Transmission line	Frequency (Hz) = 50; Positive- and zero-sequence resistances (Ohms/km) [r1 r0] = [0.01273 0.3864]; Positive- and zero-sequence inductances (H/km) [l1 l0] = [0.9337e-3 4.1264e-3]; Positive- and zero-sequence capacitances (F/km) [c1 c0] = [12.74e-9 7.751e-9] Line length (km) = 10	
Three phase Load	Configuration = Y (grounded); Active power P (W) = 10e3; Inductive reactive power QL (positive var) = 100;	
Passive filter	Nominal reactive power (var) = 2000; Tuning frequencies [Fr1 (Hz) Fr2 (Hz)] = [3*f 5*f] & [7*f 9*f]; Quality factor (Q) = 16	
Active filter	Resistance (Ohms)= 10; Inductance (H) = 1e-3;	

$$\dot{\gamma} = f(\gamma) + g(\gamma)U_{smc} \tag{22}$$

$$u_{smc} = \begin{cases} u^{+}_{smc} & \text{if } \sigma(\gamma) < H_b \\ u^{-}_{smc} & \text{if } \sigma(\gamma) > H_b \end{cases} \tag{23}$$

Where $\gamma \in \Re^n$, f and g are continuous vector fields and $\sigma(\gamma)$ is a sliding function such that $\dot{\sigma} = \frac{\partial \sigma(\gamma)}{\partial \gamma}\dot{\gamma}$ with U^{+}_{smc} and U^{-}_{smc}, take 0 or 1 respectively in case of inverters. In [16], it is proved that, if the system trajectory evolves on the sliding surface $\dot{\sigma} = 0$. Moreover, the stability analysis is carried out to prove that SMC yielding good results.

3.2.1 Stability analysis

As far as the design of sliding mode is concerned, there are three steps one is proposing a sliding surface, second is testing for the sliding mode existence and final is performing stability analysis of the surface. In order to control the output current of the inverter, suitable sliding surface is to be chosen, which is directly affected by switching law. In order to guarantee the sliding mode existence, $\sigma.\dot{\sigma} < 0$ must be fulfilled and this fact guarantees the attraction of the system to the surface. The proposed Sliding surface (S) is a linear combination of state variables and the references:

$$\sigma(X) = \dot{X}_1 - X_1 \tag{24}$$

$$\dot{X}_1 = \left(I_c X_4 - \sum_{n=2}^{k} I_{Ln} X_{n+3} \right) \tag{25}$$

$$\sigma(X) = \left(I_c X_4 - \sum_{n=2}^{k} I_{Ln} X_{n+3} \right) - X_1 \tag{26}$$

$\dot{\sigma}(X) = 0$ is obtained from (27)

$$\dot{\sigma}(X) = \frac{1}{2L_s}\left(\begin{array}{l} X_2 - 2V_m X_4 - 2L_s \omega I_m \sqrt{1 - X_4^2} \\ + \ldots \qquad \ldots \\ 2L_s \omega I_{Ln} k \sqrt{1 - X_{k+3}^2} + \frac{1}{2L_s} X_3 u \end{array} \right) \tag{27}$$

The general form of the proposed control law is:

$$U = U_{eq} + U_n \tag{28}$$

$$\text{Where} \quad U_n = -sig(\sigma) \tag{29}$$

The first term U_{eq} is valid only in the sliding surface and the second term U_n assures the sliding mode existence. The existence of the equivalent control is a necessary condition for the existence of the sliding mode,

With (29) and (30) in $\dot{\sigma}(X)$ is expressed as:

$$\overset{*}{\sigma}(X) = \frac{1}{2L_s}\left\{ \begin{array}{l} \left(X_2 - 2Vm X_4 - 2L_s w I_{cm} \sqrt{1 - X_4{}^2} \right) + \\ + \ldots + 2L_s w I_L n \sqrt{1 - X_{(n+3)}{}^2} + \ldots + 2L_s w I_L k \sqrt{1 - X_{(n+k)}{}^2} \\ + \frac{1}{2L_s} X_3 u_{eq}) + \frac{1}{2L_s} X_3 u_n \end{array} \right\} \tag{30}$$

Then, the equivalent control is given by

$$u_{eq} = \frac{1}{X_3}\left[\begin{array}{l} (-X_2 + 2Vm.X_4 + 2L_s w I_{cm} \sqrt{1 - X_4{}^2} \\ -\ldots - 2L_s w I_L n \sqrt{1 - X_{(n+3)}{}^2} \\ -\ldots - 2L_s w I_L k \sqrt{1 - X_{(k+3)}{}^2} \end{array} \right] \tag{31}$$

and to guarantee the sliding mode existence

$$\left[\sigma \overset{*}{\sigma} = \frac{1}{2L_s} X_3 [-\sigma sig(\sigma)] < 0 \right] \tag{32}$$

Must be satisfied. Due to the fact that the term $-\sigma sig(\sigma)$ is always negative, the above condition is reduced to $\frac{1}{2L_s} X_3 > 0 \quad et \quad Vc > 0$ (33)

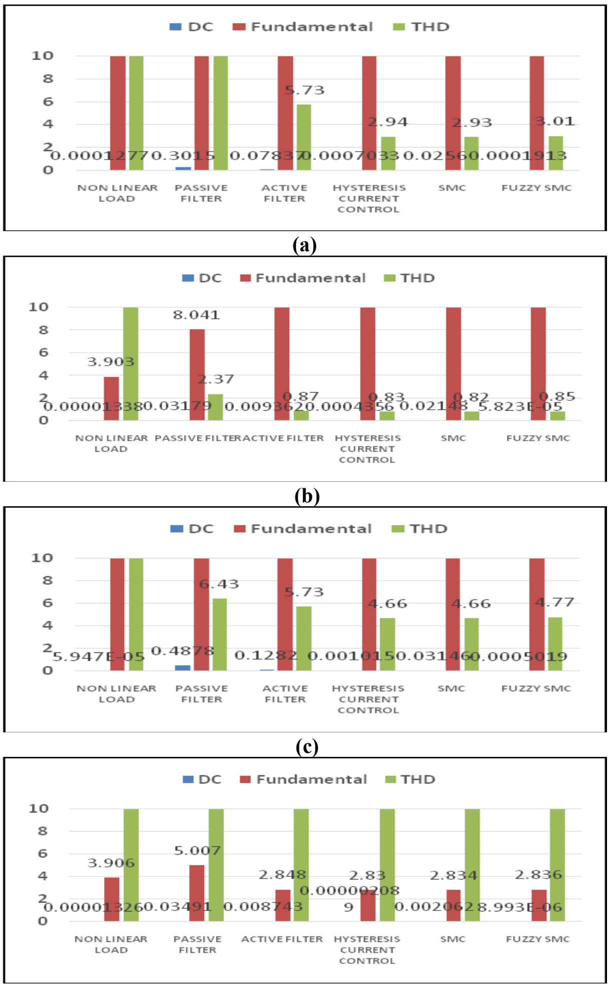
Since the sliding surface and switching does not depend on system operating point, load, circuit parameters, or power Supply, the converter dynamics, operating in sliding mode, is robust and stable.

3.3 Fuzzy based nonlinear Control (FSMC) Scheme

Generally Fuzzy control [12] is preferred because it does not require any mathematical model because its control action is obtained by evaluating set of simple linguistic rules. Also the rules have been framed based on the thorough understanding and to obtain stability of the application to be controlled. In this scheme the rules are framed in order to obtain the fast response and high stable condition by taking typical Step response trajectory as shown in Fig. 3b (a & b) and the surface plot and its Rule matrix is shown in Fig. 3b (c) & (d). In this proposed scheme, it combines both SMC and FSMC in which fuzzy control is used to control the capacitor voltage in order to have a constant DC voltage regulation. Whereas Sliding mode control is also used to control the SAPF as shown in Fig. 3d.

4. Verification by Simulation

As discussed in previous section, the proposed control scheme is simulated, tested and compared with its counterparts under linear and nonlinear load with the help of MATLAB-SIMULINK software package. A three phase radial distribution system whose parameters are depicted in Table 1 is built as shown in Fig.1. It is then tested and performance is analyzed in open loop mode and with closed loop controllers such as hysteresis current mode based control, sliding mode based control and proposed fuzzy sliding mode based control. In all simulations studies, enough care is take in such a way that the sampling rate is higher enough to avoid the problem of aliasing [21]. Steady state analysis has been carried out and its dynamic



(d)

Fig. 4. Estimated DC, Fundamental and THD values of (a) Source Voltage, (b) Source Current, (c) Load Voltage, and (d) Load Current under different control strategies adopted for the SAPF.

characteristics are being discussed in the forthcoming section.

4.1 Uncompensated distributed radial line

When the system is supplying for a linear load, the power factor is around 0.98 in the supply side where as it is unity in the load side but harmonics are introduced in the supply. At the same time when the line is loaded with RL load, the real and reactive power flow from the source side get increases from 7490 W to 9422 W and from 1261 VAR to 3206 VAR respectively. The Power factor of source side is reduced from .98 to .95 which is mainly due to increase in reactive power flow. At the same time the real and reactive power flow from the load side get increases from 7435 W to 9285 W and from 0 VAR to 46.42 VAR respectively. The Power factor at the load side is maintained at unity due to small contribution of reactive power flow. Apart from that, the power quality disturbance in both source and load side becomes negligible. In addition, its effect on DC, Fundamental and THD values in the Source Voltage, Source Current, Load Voltage, and Load Current is shown in Fig. 4 (a, b, c & d) respectively.

3.2 Passive filter

In order to reduce the harmonics, doubled tuned filters are designed to inject the 3rd, 5th, 7th & 9th order harmonics current at the PCC. It has been observed that the real and reactive power flow from the source side get increases from 9422W to 11267W and reduces from 3206VAR to 1788VAR respectively. The Power factor of source side increases from .95 to .98 which is mainly due to reduction in reactive power flow. At the same time the real and reactive power flow from the load side get increases from 9285W to 10889W and from 46.42 VAR to 54.45 VAR respectively. The Power factor at the load side is maintained at unity due to small contribution of reactive power flow. Apart from that, the power quality disturbance in both source and load side becomes negligible. In addition, its effect on DC, Fundamental and THD values in the Source Voltage, Source Current, Load Voltage, and Load Current is shown in Fig. 4 (a, b, c & d) respectively.

3.3 Active filter

Due to limitation of passive filter stated in [4]-[6], inverters are proposed to act as an active filter to enhance the power quality in power grid. In this case a three phase inverter is designed and operated at 180^{O}conduction mode by allowing a dead band between switching of positive and negative group switches in order to avoid shoot through fault [22]-[23]. It has been observed that the real and reactive power flow from the source side get reduces from 11267 W to 7104 W and increases from 1788 VAR to

5551 VAR respectively. The Power factor of source side is reduces from .98 to .79 which is mainly due to increase in reactive power flow. At the same time the real and reactive power flow from the Load side get reduces from 10889 W to 5162 W and reduces from 54.45 VAR to 25.81 VAR respectively. But the Power factor at the load side is maintained at unity due to reduction and small contribution of reactive power flow. Apart from that, the power quality disturbance in voltage and current rated in THD for both source and load side becomes 23 %, 8% and 39 %, 39 % respectively which is against the maximum permissible value of THD in the Power Grid [3]. In addition, its effect on DC, Fundamental and THD values in the Source Voltage, Source Current, Load Voltage, and Load Current is shown in Fig. 4 (a, b, c & d) respectively.

3.4 Hysteresis Current Mode Control HCMC

In this case, three phase inverters are used as an active filter and their switches can be controlled by Hysteresis Current Mode Control (HCMC) in which load current (iL)is compared with the source current (iS) and the error between them is fed to the hysteresis comparator where small value of hysteresis band +δ & - δ is introduced. When the error exceeds the value of + δ, the positive group switches are turned on to supply required reactive power to enhance the power quality. When the error exceeds the value of - δ, the negative group switches are turned on to absorb the excessive reactive power to maintain the power quality. It has been observed that the real power flow from the source side reduces from 7104 W to 5337 W while the reactive power flow increases from 5551 VAR to 6994 VAR. The Power factor of source side reduces from .79 to .60 mainly due to decrease in real power flow and increase in reactive power flow. At the same time the real and reactive power flow from the load side get decreases from 5162 W to 1732 W and reduces from 25.81 VAR to 11.15 VAR respectively. But the Power factor at the load side is maintained at unity due to reduction and small contribution of reactive power flow. Apart from that, the power quality disturbance in voltage and current rated in THD for both source and load side becomes 32 %, 6% and 31 %, 28 % respectively which is against the maximum permissible value of THD in the Power Grid [3] and also its effect under nonlinear load is also given in Table II. In addition, its effect on DC, Fundamental and THD values in the Source Voltage, Source Current, Load Voltage, and Load Current is shown in Fig. 4 (a, b, c & d) respectively.

3.5 Sliding Mode Controller (SMC)

In this case, sliding mode controller is used to

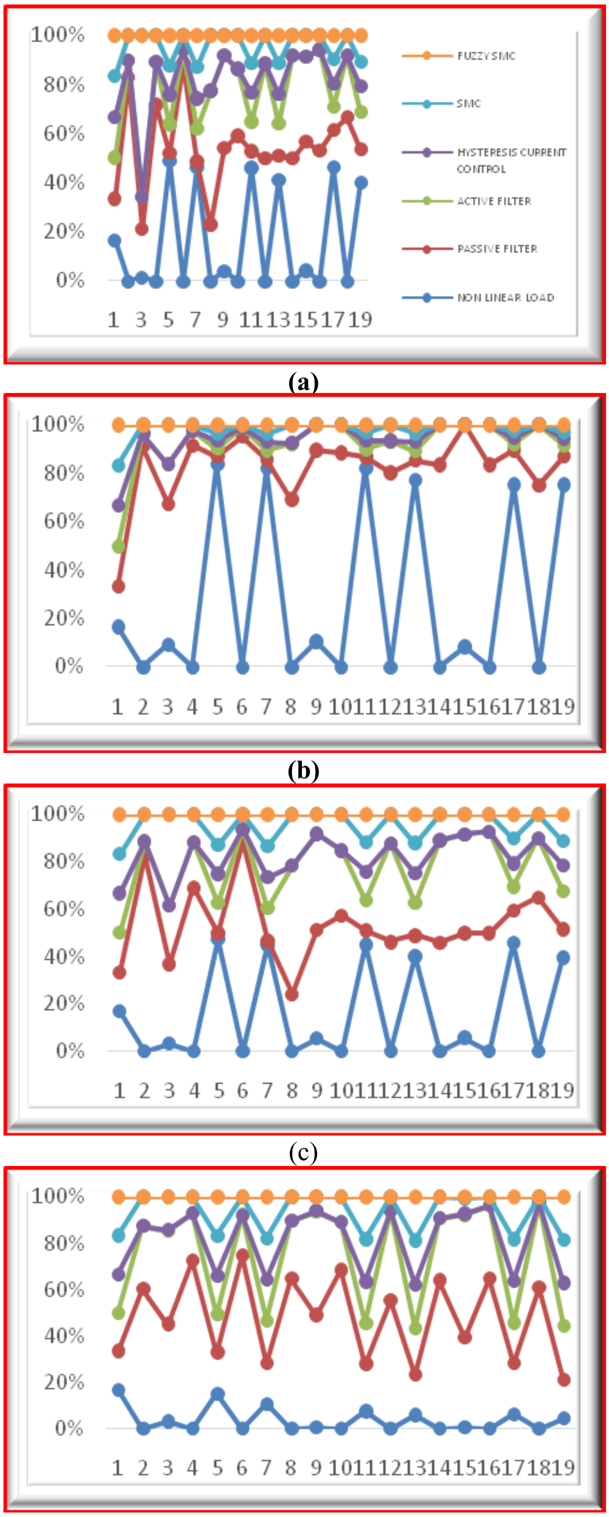
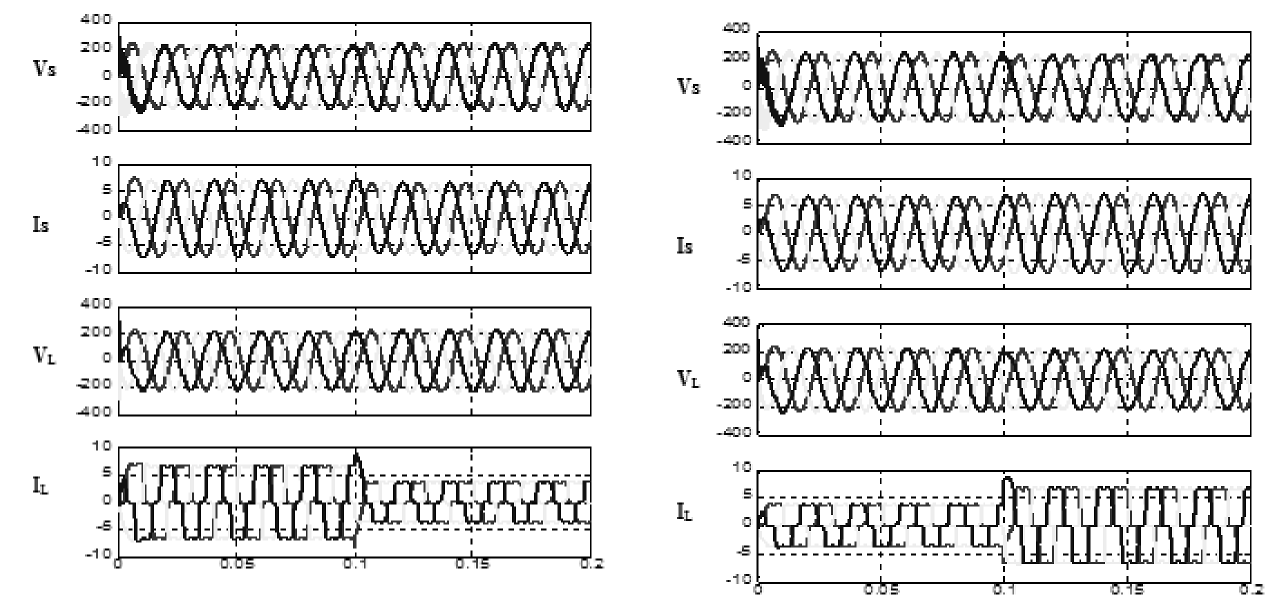


Fig. 5. Estimated Error graph of Individual Harmonics level of (a) Source Voltage, (b) Source Current, (c) Load Voltage, and (d) Load Current under different control strategies adopted for the SAPF.

control the inverter. It has been observed that the real and reactive power flow from the source side get increases from 5337 W to 7895 W and reduces from 6994 VAR to 5208 VAR respectively. The Power factor of source side is increases from .6 to .83 which is mainly due to reduction in reactive power flow. At the same time the real and reactive power flow from the Load side get increases from 1732 W to 5373 W and increases from 11.15 VAR to 27.12 VAR respectively. But the Power factor at the load side is maintained at unity due to small contribution of reactive power flow. Apart from that, the power quality disturbance in voltage and current, rated in THD, for both source and load side becomes 17.42 %, 3.52% and 24 %, 23 % respectively which is against the maximum permissible value of THD in the Power Grid [3]. At the same time this control shows a significant improvement in power quality than the previous one and also its effect under nonlinear load is also given in Table II. In addition, its effect on DC, Fundamental and THD values in the Source Voltage, Source Current, Load Voltage, and Load Current is shown in Fig. 4 (a, b, c & d) respectively.

3.6 Fuzzy Sliding Mode Controller (FSMC)

Even though some improvement in the real, reactive power flow and Power factor is obtained by SMC, but still it exceeds the maximum permissible level particularly in THD profile in voltage and current of source and load side. In order to bring the THD under 5% according to IEEE-519-1992 recommendation, one of the Soft computing techniques particularly fuzzy logic can be applied to enhance the power quality in the GRID. It has been observed from the table II such that the real and reactive power flow from the source side get increases from 7895 W to 9096 W and reduces from 5208 VAR to 4291 W respectively. The Power factor of source side is increases from .83 to .9 which is mainly due to reduction in reactive power flow from the source side. At the same time the real and reactive power flow from the Load side get reduces from 5373 W to 3290 W and reduces from 27.12 VAR to 2e-6 VAR respectively. Moreover the Power factor at the load side is maintained at unity due to very small contribution of reactive power flow. Apart from that, the power quality disturbance in voltage and current rated in THD for both source and load side becomes 0.45 %, 0.45% and .46 %, .46 % respectively which is within the maximum permissible value of THD in the Power Grid [13]. This performance of FSMC proves that it agrees with our proposed scheme by enhancing the power quality in the GRID when it is supplied to the load and also its effect under nonlinear load is also given in Table II. In addition, its effect on DC, Fundamental and THD values in the Source Voltage, Source Current, Load Voltage, and Load Current is shown in Fig. 4 (a, b, c & d) respectively. From the above discussions, the proposed control scheme offers Low value of THD in the source, load voltage and current waveforms which are given in Fig. 7 b. that represents the detailed individual harmonics level in the system waveform under different control strategies. Fig. 7b. Shows that the source and load waveforms under proposed control scheme. From this it clearly shows that the proposed control scheme offers simple



(a) (b)

Fig. 6. Observed system waveforms (a) Under high to low nonlinear load (b) Under Low to high nonlinear load

control scheme and increased real and reduced reactive power flow and improved power factor with better DC voltage regulations.

5. **Performance Evaluation**

The advantages of the proposed control scheme over the available one are that it can compensate for the variations in harmonic currents and unbalances in nonlinear currents together with power factor correction. In this connection, speed of response and its stability will be checked out by observing the dynamic characteristics. This can be done by, subjecting the proposed scheme under two different operating conditions, namely high to low nonlinear load current condition and low to nonlinear load current conditions are simulated in the following section whose values are specified in Table I. Fig. 6 a & b Shows the source, load voltage and current waveforms for two different load conditions respectively.

5.1 Case 1: Low to High nonlinear load

In this case, a load change is allowed (Low to high nonlinear load) at 0.1s in the system is simulated while the power flow between them made constant. It is desired that the changes in the supply voltage is taken care off by the controller. The system response is shown in Fig. 6a. It can be seen that the supply voltage, supply current and load voltage profile remain undisturbed except the load current waveform concerned with. This makes us to conclude that the proposed controller show a stable system operation in the event of load changes. For the realization of Low to high nonlinear load condition, a three phase uncontrolled rectifier is used whose details are shown in Table. I. When it is connected to the system after t=0.1S, the real and reactive power flow from the source side get increase from 9170 W to 9202 W and reduces from 3850 VAR to 3405 VAR respectively. The Power factor of source side is increases from .92 to .94 which is mainly due to reduction in reactive power flow. At the same time the real and reactive power flow from the Load side get reduces from 2309 W to 1366 W and reduces from 106 VAR to 51 VAR respectively. But the Power factor at the load side is maintained at unity due to small contribution of reactive power flow. Apart from that, the power quality disturbance in voltage and current rated in THD for both source and load side reduces from 4 % to 3 %, 1.3% to 1 %, 7.9 % to 4.7 %, but it increase from 23 % to 26% respectively. This shows that other than load current, all must lies within the maximum permissible value of THD in the Power Grid [3].

5.2 Case 2: High to Low nonlinear load

In this case, a load change is allowed (High to low nonlinear load) at 0.1s in the system is simulated while the power flow between them made constant. It is desired that the changes in the supply voltage is taken care off by the controller. The system response is shown in Fig. 6b. It can be seen that the supply voltage, supply current and load voltage profile remain undisturbed except the load current waveform concerned with. This makes us to conclude that the

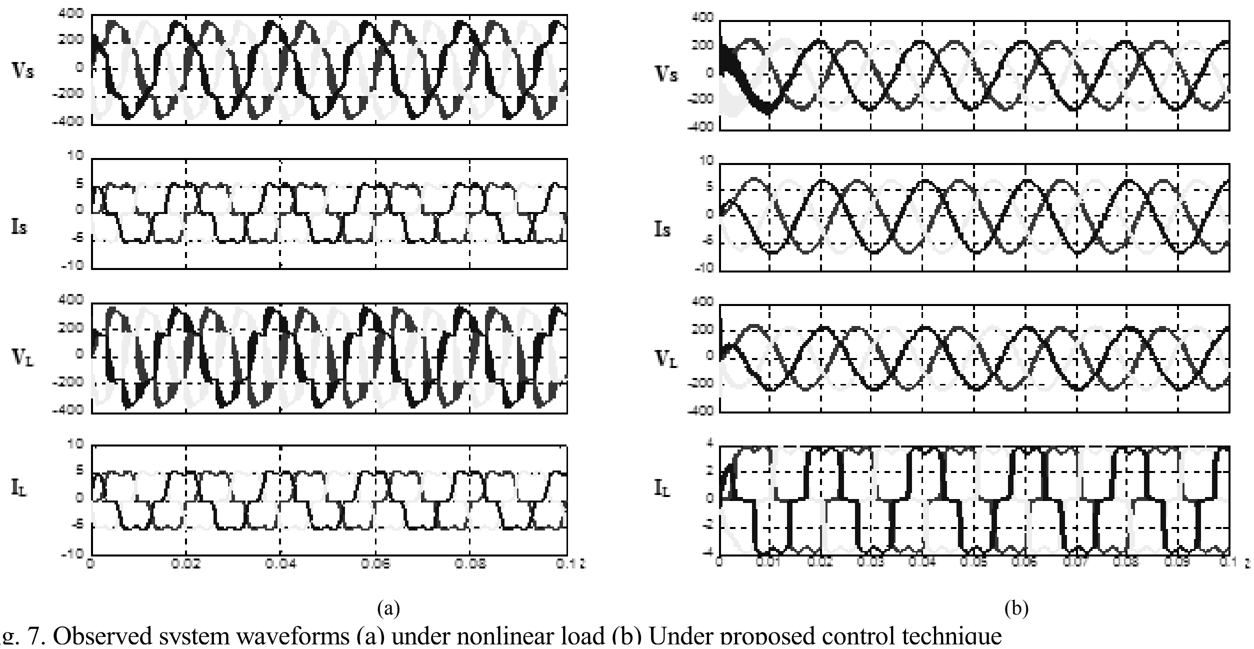


Fig. 7. Observed system waveforms (a) under nonlinear load (b) Under proposed control technique

proposed controller show a stable system operation in the event of load changes. For the realization of high to low nonlinear load condition, same three phase uncontrolled rectifier with modified load values are chosen whose details are shown in Table. I from the above discussion, it can be seen that the proposed controller takes approximately less than 2 ms.

5.3 DC Voltage Regulation

The Value of the DC voltage at the input side of SAPF must be constant with less ripples. Because ripples reduces the performance of SAPF by injecting additional harmonics in the filter current [21]. Under proposed control scheme, the settling time of DC voltage profile is less when compared to [21]. The DC voltage profile of SAPF under SMC & FSMC is shown in Fig. 3 (a) & (c) respectively.

6. Conclusion

A new control algorithm is proposed in this manuscript for Shunt active power filter to eliminate the harmonics in the utility supply both voltage and current and improve the power factor of the system. The control design is based on the both fuzzy and sliding mode control which will inject the filter current into the PCC which is Proportional to compensate the reactive power, thereby improves the power factor, harmonics introduced by the load and balance the symmetrical load. In order to achieve the above, it uses a unique approach for estimating the reference current based on Kirchhoff's law. It features fast response over a wide range of voltage variations. In which fuzzy is used to improve the DC voltage profile of SAPF. SMC is used to generate control signal for it. It can compensate for the balanced, unbalanced nonlinear load current. The obtained results demonstrates that the applicability of the proposed control scheme yield good performance. Also the steady state and dynamic behaviour have been presented to verify its performance. Moreover to demonstrate the superiority of the proposed scheme comprehensive comparison was conducted and it is presented by adopting various control schemes. It clearly proved that the proposed scheme offers simple control and implementation. The Stability of the proposed control scheme is also presented to emphasize its applicability in real time. The speed of response is very high because it takes only 20 % of half cycle of the input supply. However, the proposed scheme needs to be validated by adopting different load condition such as motor load and experimental verification. Finally these simulation results and performance verification serve as fundamental setup toward the hardware implementation of it in real time.

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