New Control Strategy of Unified Power Quality Conditioner with Sliding Mode Approach

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Abstract—**This paper describes a novel sliding mode method with the fuzzy controller approach in the development of unified power quality conditioner (UPQC) for reactive power, harmonics and both symmetric and asymmetric sag and swell compensation. The UPQC consists of both shunt and series converter having a common dc link. The shunt converter eliminates current harmonics generated from the nonlinear load and the series converter suppresses the voltage sag and swell generated from the supply side .The dc link control strategy is based on fuzzy-logic controller where as sliding mode controller is used in the inner current control loop to dictate the gate signals for switching of the both converters. To determine the efficiency of UPQC model, it is implemented through MATLAB.The simulation results show the superior capability of the proposed approach in mitigating the effects of current harmonics and voltage sag and swell generated from the supply side.**

Index Terms— **Unified power quality conditioner (UPQC), reactive power compensation, sag and swell compensation, fuzzy-logic controller, sliding mode controller.**

I. INTRODUCTION

Power quality (PQ) issues have become one of the significant problems in recent years due to the high number of sensitive and nonlinear loads have come into wide use and generate several perturbations in the electric grid [1].Active power filter is one of the interesting proposals to mitigate the PQ problems[2].Many type of configurations, such as series ,shunt and hybrid have been used , out of which unified power-quality conditioner(UPQC) topology is one of the interesting device for improving the power quality problem. The UPQC, which has two inverters those share the common dc-link, can compensate harmonics current as well as voltage sag and swell in the power distribution system. A shunt converter can compensate for current harmonics and reactive power for unit power factor and series converter can compensate for voltage sag/swell for nonlinear sensitive load [3].Control techniques play an important role in the overall performance of the power quality .The rapid detection of the disturbance signal with high accuracy and fast processing of the signal is the important aspect of controller based on which a power conditioner performs. The UPQC control strategy actuates the reference signals for both current and voltage and therefore determines the switching pattern of inverter switches, such that it can achieve the desired performance. Several control methods, algorithms and techniques are available in the literature [4] those are easily applied to UPQC system. Other advanced control techniques have also been reported, such as state feedback controller, model predictive control, model reference adaptive controller[5], self tuning controller , sliding mode control and neural networks [6].As sliding mode controller has its natural way to control time-varying topologies, it has been widely used in power converter. The SMC is one of the robust control schemes 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 [7].

This paper discusses the sliding mode approach with fuzzy controller for development of UPQC for reactive power, current harmonics and both symmetric and asymmetric sag and swell compensation. The fuzzy-logic controller (FLC) of dc-link voltage is considered here because it improves the current total harmonic distortion (THD) in comparison to the conventional PI controller. Here SMC has been designed for generating switching pulses for controlling both shunt and series active power filter because it minimizes the effects of tracking error and parameter variation in the control action of UPQC.The efficiency of UPQC model is tested through simulation studies using MATLAB and the simulation results show the superiority of UPQC in terms of reactive power, current harmonics and voltage sag and swell compensation**.**

II.CONFIGURATION OF UPQC

The UPQC topology consists of two active power filters (Series and Shunt) those are connected back to back through common dc-link capacitor (C_{dc}) [8]. A simple block diagram of a UPQC is shown in Fig.1, in which series converter is connected through transformers between the source and load and shunt converter is connected in parallel with point of common coupling (PCC). It can be configured as either with the voltage source converter or current source converter, the series converter operates as a voltage source while the shunt converter as a current source [9].

A system configuration of UPQC using two voltage source converters connected back to back through a common dc-link capacitor is shown in Fig.2. Shunt coupling inductor L_{shf} is used for interfacing the shunt converter with the power line. It is also used to boost up the common dc-link voltage to the desired value [10]. The main objectives of the shunt converter are to regulate the dc-link voltage for both the converters and suppress the load current harmonics [11]. The power circuit of series converter is used for mitigating voltage sags and swell originating from the supply side .The ac filter inductor L_{sf} and capacitor C_f serves as a passive low-pass filter (LPF) are connected in each phase is helping to eliminate the high frequency switching ripple on generating converter output voltage. The transformers connected at the output of each leg of the converter provide isolation between power line and converter [12].The switching devices connected in both series and shunt converter are insulated gate bipolar transistors (IGBTs) with anti-parallel diodes. A three phase uncontrolled diode-bridge rectifier with resistive (R_L) and inductive (L_L) load is used as a nonlinear load.

The proposed UPQC system operates on two configuration modes such as

1) Series converter off and shunt converter on, in this case, PCC voltage is within its limit and shunt converter works as the current source. During this mode of operation ,two lower leg IGBT of each phase of series converter remains turned on and upper two IGBT remains turned off , hence the formation of short circuit occurs across the secondary winding of the series transformer through L_{sf} .Thus it eliminates the need of bypass switches across the transformer. At this time shunt converter suppresses the current harmonics and regulates the voltage across the dc-link capacitor.

2) Series converter on and shunt converter on ,in this mode of operation, series converter starts to mitigate both sag and swell by using the energy stored in dc-link capacitor and shunt converter continues to suppress the current harmonics and regulate the dc-link capacitor voltage.

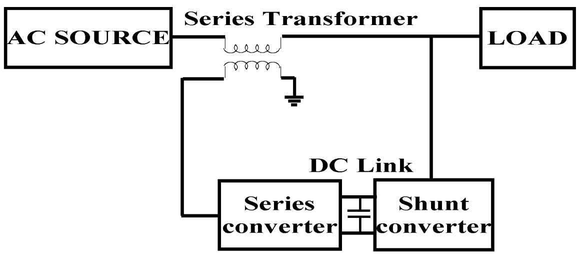


Fig.1. Block diagram of UPQC

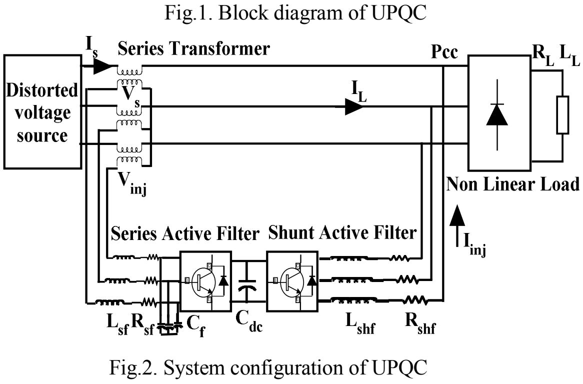


Fig.2. System configuration of UPQC

III. SLIDING MODE CONTROL OF UPQC

At this point, a sliding mode control can be designed for UPQC by considering both the shunt and series active power filter .The designer has to consider the following three main tasks for design of the controller.

3) Sliding surface selection.
4) Condition for existence of sliding mode and reaching Condition.
3) Control law determination.

A. Control structure for shunt active power filter

The schematic diagram of conventional single phase equivalent circuit of shunt active power is shown in Fig.3.We consider here the sliding mode control law based on switching function ‘ K ’. It is defined as when $K = 1$ either $S1$ or $D1$ is conducting and when $K = -1$ then either $S2$ and $D2$ is conducting .Thus the inductor current is defined as the

$$\frac{di_c}{dt} = \frac{v_{in}}{L} + K\frac{v_c}{2L} \tag{1}$$

The ripple due to compensating current can be written by considering the voltage across the capacitor.

$$\frac{dv}{dt} = -\frac{1}{2}[K\frac{i}{C} + K\frac{i}{C} + K\frac{i}{C}] \tag{2}$$

Where K_a, K_b, K_c are the switching variable and i_{ca}, i_{cb}, i_{cc} are the compensating current of the phase a,b and c respectively. To apply a sliding mode control strategy to the shunt active power filter, consider its control structure as shown in Fig. 4.The sliding surface or the trajectories is found out by using the reference current of the active power filter. These reference currents $i^*_{sa}, i^*_{sb}, i^*_{sc}$ are obtained by multiplying the unit vector U_{sa}, U_{sb}, U_{sc} with the peak source current $I_{\max}$ generated from the fuzzy controller used for stabilizing the dc-link capacitor voltage.

$$\begin{aligned} v_{sa} &= v_m \sin(\omega t) \\ v_{sb} &= v_m \sin(\omega t - 120^\circ) \\ v_{sc} &= v_m \sin(\omega t + 120^\circ) \end{aligned} \tag{3}$$

$$U_{sa} = \frac{v_{sa}}{v_m}, U_{sb} = \frac{v_{sb}}{v_m}, U_{sc} = \frac{v_{sc}}{v_m} \tag{4}$$

$$\begin{aligned} i^*_{sa} &= I_{\max} \times U_{sa} \\ i^*_{sb} &= I_{\max} \times U_{sb} \\ i^*_{sc} &= I_{\max} \times U_{sc} \end{aligned} \tag{5}$$

The trajectory for sliding surface is obtained by subtracting the measured source current i_{sabc} from the reference source current i^*_{sabc} . Thus the standard form of sliding surface is chosen by

$$v_x = i_{sabc} - i^*_{sabc} \tag{6}$$

It should assure that the system maintains on the sliding surface by maintaining the $\dot{s}(v_x, t) = 0$ .Therefore the switching law must ensure the stability condition for the system in sliding mode by $s(v_x,t)\ \dot{s}(v_x,t) < 0$ at all the time , where as K is the natural control's bounds of the physical system for $\dot{s}(v_x,t) = 0$, then it ensures the convergence of the system trajectories to the sliding surface , by setting $s(v_{x,t)=0}$ and $s(v_y,t) = 0$. The equivalent control law can be found by writing a single phase expression for active power filter.

$$\dot{s}(v_x,t) = (i_{sa} - i_{sa}^*)$$
$$= (i_{la} + i_{ca} - i_{sa}^*)$$
$$= [i_{la} + \frac{v_{sn}}{L} + (K_x)(\frac{v_c}{2L}) - i_{sa}^*] \tag{7}$$

Solving the equation (7) to zero, the equivalent control can be found by

$$v_{eq} = (\frac{di_{sa}^*}{dt} - \frac{di_l}{dt} - \frac{v_{sn}}{L})(\frac{2L}{v_c}) \tag{8}$$

Recalling the limit of the natural control law equal to $-1 < v_{eq} < 1$, and $s(v_x,t)\ \dot{s}(v_x,t) \le 0$, the discontinuous control law can be seen by considering the following relation.

5) If $s(v_x,t) > 0$ and $\dot{s}(v_x,t) < 0$, then K will decrease towards zero.

6) If $s(v_x,t) < 0$ and $\dot{s}(v_x,t) > 0$, then K will increase towards zero.

Thus the existing condition of the switching law for shunt active power filter is

$$v_k = \begin{cases} 1 & for\ s(v_x,t) > 0 \\ -1 & for\ s(v_x,t) < 0 \end{cases} \tag{9}$$

The capacitor voltage control of the proposed method is obtained from FLC, that determines the maximum value of the source current for stabilizing the capacitor voltage .In this case v_{dc-err} is obtained from the difference of capacitor set value

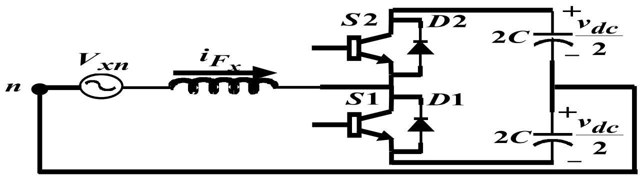


Fig.3 Single phase converter Equivalent Circuit

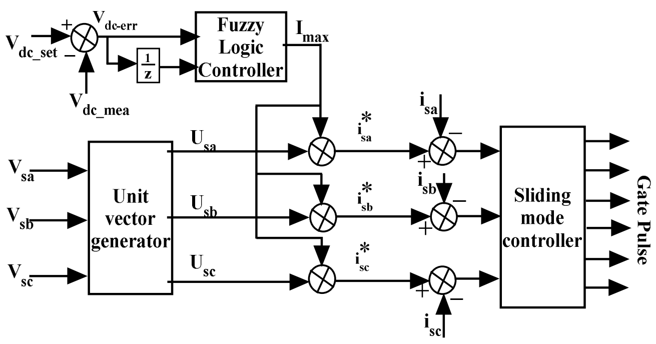


Fig.4 Control Algorithm of SAPF using sliding mode scheme

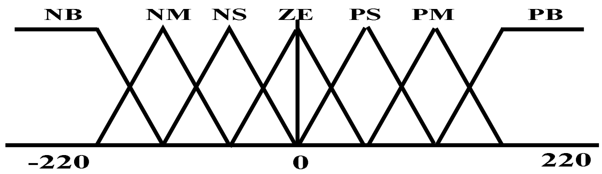


Fig.5 Input variables v_{dc-err} and Δv_{dc-err}

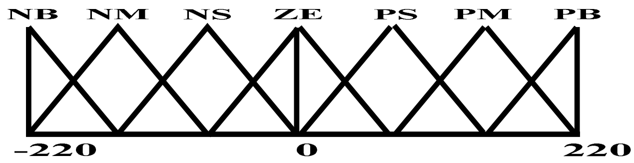


Fig.6 Output variables I_{max}

Table I Rule based table

e / Δe	PB	PM	PS	ZE	NS	NM	NB
PB	PB	PB	PB	PM	PM	PS	ZE
PM	PB	PB	PB	PM	PS	ZE	NS
PS	PB	PM	PS	PS	ZE	NS	NM
ZE	PM	PS	PS	ZE	NS	NM	NM
NS	PM	PS	ZE	NS	NM	NM	NB
NM	PS	ZE	NS	NM	NM	NB	NB
NB	ZE	NS	NM	NM	NB	NB	NB

v_{dc-set} and measured capacitor voltage v_{dc-mea} .The input of the FLC is the v_{dc-err} and its rate of change Δv_{dc-err} .

$$v_{dc-err} = v_{dc-set} - v_{dc-mea} \tag{10}$$
$$\Delta v_{dc-err} = v_{dc-err}(m) - v_{dc-err}(m-1) \tag{11}$$

Both the input signals are processed through thefuzzycontroller and IF..THEN rule is used for converting these variables into linguistic variables.

Here membership functions are selected as symmetrical membership functions and the two inputs i.e. v_{dc-err} and Δv_{dc-err} are converted into each seven membership functions, five triangular and two trapezoidal membership functions as shown in Fig.5.That makes 49 rules based table . The rule base stores the linguistic variables for rule evaluation for producing the set of modified control output of linguistic variables. Membership functions and rules based are obtained by understanding the system behavior based on this. Defuzzification is designed by considering seven triangular membership functions as shown in Fig.6.The centroid method is used for its defuzzification process to get the crisp output because this method is simple and it provides high accuracy in defuzzification process. The output of the fuzzy controller estimates the magnitude of peak reference current I_{max} .

B. Control structure for series active power filter

Control structure for series active power filter for designing trajectory of SMC is shown in Fig.7. The proposed control strategy is used to maintain the desired load voltage under specific level for compensation of both symmetric and asymmetric sag/swell on the load side. To achieve this goal , the following desired three-phase load voltage of (12)-(14) must be multiplied with the source current of (15)-(17) for generating the required power P_a, P_b and P_c .

$$v_{la} = v\sin(\omega_1 t + \phi_1) \tag{12}$$

$$v_{lb} = v\sin(\omega_1 t - 120^\circ + \phi_1) \quad (13)$$

$$v_{lc} = v\sin(\omega_1 t + 120^\circ + \varphi_1) \quad (14)$$

$$i_{sa1} = I_{m1}^{+}\sin(\omega_1 t + \phi_1) \quad (15)$$

$$i_{sb1} = I_{m1}^{+}\sin(\omega_1 t - 120^\circ + \phi_1) \quad (16)$$

$$i_{sc1} = I_{m1}^{+}\sin(\omega_1 t + 120^\circ + \phi_1) \quad (17)$$

Where I_{m1}^{+} and ϕ_1 are the source current magnitude and the phase angle of the positive-sequence component. Under the condition that the load active power is supplied by the source,it is required to determine the load voltage magnitude V from the sequential instantaneous current and real power components supplied to the load. According to the symmetrical-component transformation of the three-phase instantaneous rms load current can be expressed as

$$i_k = \sum_{n=1}^{\infty} i_{kn}^{+} + \sum_{n=1}^{\infty} i_{kn}^{-} + \sum_{n=1}^{\infty} i_{kn}^{\circ} \quad (18)$$

Where k is the phase sequence $(a,b.c)$ and 0, +, - stand for zero, positive and negative-sequence components respectively and n represents the fundamental (i.e. , $n = 1$) and harmonic components, therefore positive sequence active power consumed by the load can be expressed by

$$p_{l1}^{+} = \frac{1}{T}\int_0^T \sum_{k\in k} V_{lk} i_{k1}^{+} dt = \frac{3VI_{m1}^{+}}{2} \quad (19)$$

Where as $p_{l1}^{+} = p_{s1}^{+}$

p_{l1}^{+} p_{l1}^{+} is the positive sequence active power consumed by the load and p_{s1}^{+} is the positive sequence active power supplied by the source. The fundamental source currents are input to the positive sequence component detector that includes a phase-locked-loop function, where the positive sequence fundamental currents are determined by (18). The positive sequence active power, the output of the low pass filter is fed to the divider block and the output of the divider block gives rise to reference voltage V_{kref} after multiplication with unity vector generated from the positive sequence calculator block.

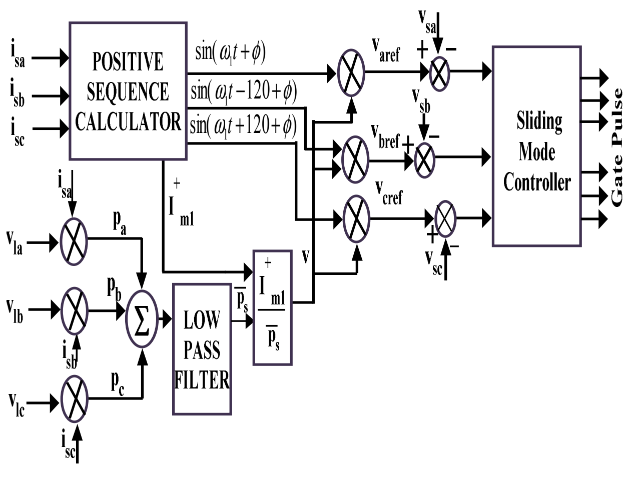


Fig.7 Control Algorithm of series active filter using sliding mode scheme

$$V = \frac{2p_{l1}^{+}}{3I_{m1}^{+}} = \frac{2\overline{p}_s}{3I_{m1}^{+}} \quad (20)$$

$$v_{aref} = V * \sin(\omega_1 t + \phi)$$

$$v_{bref} = V * \sin(\omega_1 t - 120^\circ + \phi) \quad (21)$$

$$v_{cref} = V * \sin(\omega_1 t + 120^\circ + \phi)$$

The determined unity positive-sequence current components and the magnitude of voltage are then used for computing the desired reference voltage v_{aref} , v_{bref} , v_{cref} (21) for compensation of sag and swell occurred in the distribution line . The trajectories for sliding surface are obtained by subtracting the measured source voltage vs_{abc} from the reference source voltage v_{kref} . Thus the standard form of sliding surface is chosen by (22).

$$g_x = v_{kref} - v_{sk} \quad (22)$$

Once the sliding surface is obtained , then the existence of sliding mode is determined by the condition $S(g_x, t) = 0$ .Also it should maintain on the sliding surface , the control system should guarantee $\dot{s}(g_x, t) = 0$ .Therefore, the switching law must be insured the stability condition for the system on sliding mode by equation (23).

$$s(g_x, t)\dot{s}(g_x, t) < 0 \quad (23)$$

The fulfillment of this discontinuous control law ensures that the convergence of the system trajectories has following switching law (24).

$$\delta(t) = \begin{cases} 1 & for \ \ s(g_x, t) < 0 \\ -1 & for \ \ s(g_x, t) > 0 \end{cases} \quad (24)$$

This discontinuous control law will satisfy(23).To apply the control of (24) to the series active power filter as a pulse width-modulated (PWM) signal, based on that the converter can inject the series compensation voltage for compensating both symmetrical and unsymmetrical sag /swell.

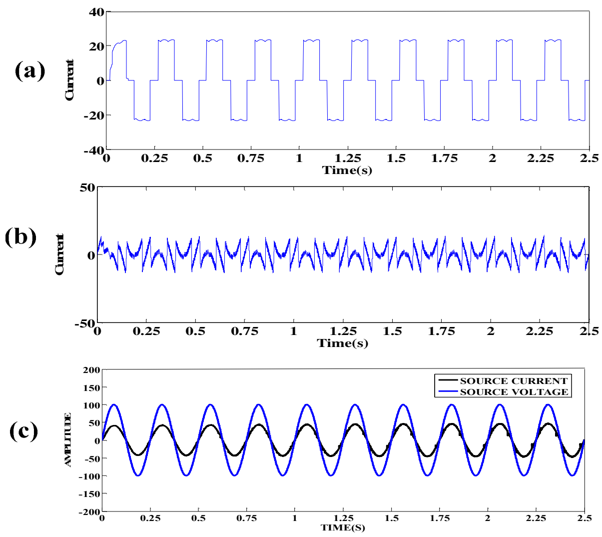
VI. SIMULATION RESULTS AND DISCUSSIONS

The power quality improvement capability of the UPQC has been tested using MATLAB. A three phase diode bridge rectifier feeding R , L load is considered as a nonlinear load with total harmonic distortion (THD) of 32% .The series converter is able to compensate up to more than 40% of voltage sag/swell under normal voltage condition. In this simulation study we consider 20% variation of three phase voltage for symmetrical sag/swell and 20% to 30% variation of three phase voltage for asymmetrical sag/swell condition. The parameters used in the simulation are shown in Table II, where R_{shf} and L_{shf} correspond to the link inductor model for shunt active power filter, C_{dc} is the capacitance of dc bus, V_{dc-set} is the reference dc bus voltage, R_{sf} , L_{sf} , C_f are the resistance,inductance and capacitance of filter circuit respectively for series active power filter and V_{rms} is the RMS value of the source voltage.

Table II. Simulation parameter

$v_{rms} = 100v$	$V_{dc\_set} = 220v$	$R_L = 6.8\Omega$	$R_S = 0.1\Omega$
$L_L = 20mH$	$L_S = 10mH$	$C_{dc} = 3000\mu f$	$R_{sf} = 23\Omega$
$R_{shf} = 0.5\Omega$	$L_{sf} = 7mH$	$L_{shf} = 2.3mH$	$C_f = 4000\mu f$

Here we first analyzed the harmonics suppression capability of shunt converter , by overcoming the load current harmonics with the control algorithms shown in Fig.4.The nonlinear load contains higher and lower order harmonics with the THD of 32% that is shown in the load current harmonic spectrum.Fig.8 shows the waveform of load current (i_{la}),compensating current(i_{ca}),and source current after compensation(i_{sa}) and dc-link capacitor voltage V_{dc}.The result shows the successful elimination of harmonics from the supply current with an approximation of 4% THD , that is shown in Fig.8(f). Next we consider the case of symmetric sag of 20% between 0.75s<t<1.75s. Fig.9(a) shows the source voltage during the voltage sag condition. The compensating voltage V_{ca} , load voltage V_L after compensation and dc-link capacitor voltage V_{dc} during sag condition are presented in Fig.9(b),(c) and (d) respectively. Fig.10(a) shows the source voltage under symmetrical swell condition . There is 20% of swell occurred between t=0.75s to t=1.75s. The compensating voltage V_{ca} ,load voltage V_L after compensation and dc-link capacitor voltage V_{dc} during swell condition are represented in Fig.10(b),(c) and (d) respectively.



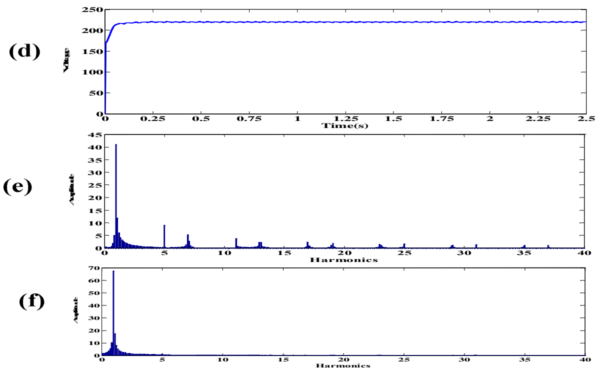


Fig.8 (a)Load current waveform,(b)Compensating current waveform,(c)Source voltage and source current after compensation,(d) Capacitor voltage waveform,(e) Source current spectrum before compensation,(f) Source current Spectrum after compensation for Shunt Active Filter

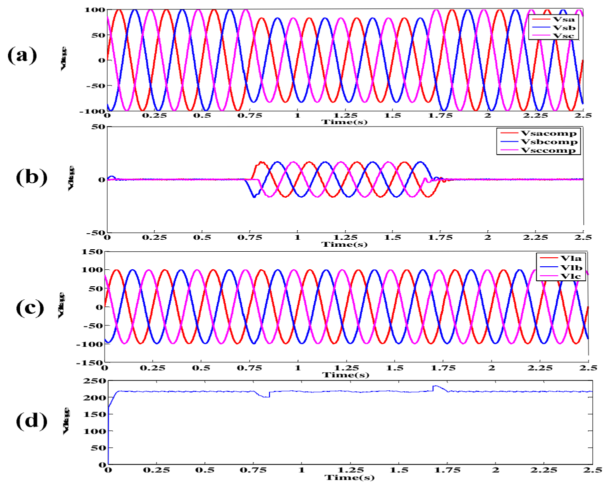


Fig.9 (a) Source voltage with sag, (b) Compensating Voltage, (c) Load voltage after compensation, (d) capacitor voltage waveform in Series Active Filter with Symmetrical sag condition

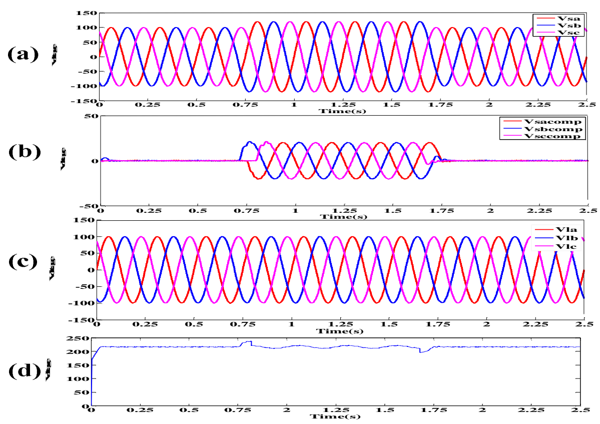


Fig.10 (a) Source voltage with swell, (b) Compensating Voltage, (c) Load voltage after compensation, (d) Capacitor voltage waveform in Series Active Filter with Symmetrical swells condition

Fig.11 displays the waveforms unsymmetrical sag/swell condition. This sag/swell varies between 20% to 30% from the peak value of supply voltage and it is exiting in between t=0.75s to t=1.75s . The injected voltage by series APF and the load voltage after compensation are given in Fig.11 (b) and (c) respectively. The waveforms of the same in swell condition are displayed in Fig.12.

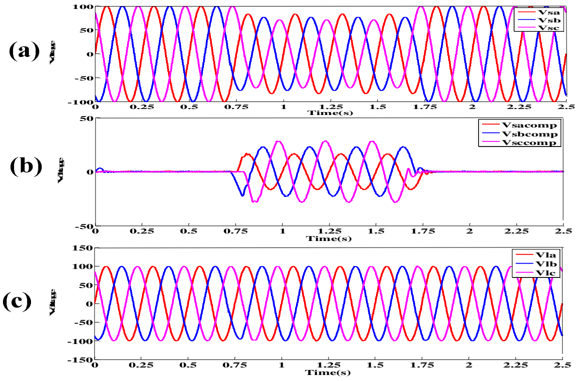


Fig.11 (a) Source voltage with sag, (b) Compensating Voltage, (c) Load voltage after compensation in Series Active Filter with Unsymmetrical sag condition

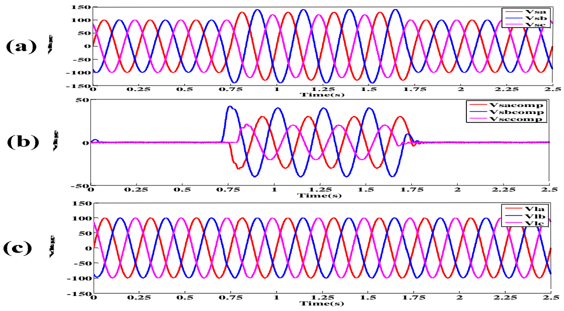


Fig.12 (a) Source voltage with swell, (b) Compensating Voltage, (c) Load voltage after compensation in Series Active Filter with Unsymmetrical swell Condition

V.CONCLUSIONS

A novel controller for the UPQC is introduced and analyzed by using both shunt and series converter based on sliding mode control algorithm and dc-link voltage regulation with a fuzzy logic controller. The SMC algorithm used here is simpler than other control algorithms with minimum amount of mathematical operands. The control scheme of UPQC has been validated for compensation for current harmonics, reactive power, symmetrical and unsymmetrical sag/swell conditions. The simulation results demonstrate the perfect harmonics control of the Sliding Mode Control algorithm by eliminating the harmonics present in the load current and making the power factor unity. It can also be observed that use of SMC to the series APF can compensate the both symmetrical and asymmetrical sag and swell in terminal voltages and make the load voltage free from any voltage fluctuations.

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