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Research Article

Fuzzy Sliding Mode Based Series Hybrid Active Power Filter for Power Quality Enhancement

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This paper contributes an innovative gating signal generation technique based on fuzzy sliding mode pulse width modulation (FSMPWM) with a Series Hybrid Active Power Filter (SEHAPF) for reducing the total harmonic distortion (THD). Hybrid filters are used for compensating reactive power on the load side and mitigate harmonics for the growth of power quality under variable source and load conditions in the utility system. The objective of the paper is to eradicate the various power quality (PQ) problems with development in power factor and reducing distortion in transmission and distribution line due to harmonics. With the implementation of FSMPWM of the proposed filter, the gating pulses are generated by implementing a Mamdani fuzzy rule with sliding surfaces. For producing a fixed pulse the presented method reduces the chattering reaction by controlling the narrow boundary coating on the sliding surface. The results of the projected technique are analyzed and compared with the traditional hysteresis band current controller (HCC). The overall proficiency and results are examined with the help of MATLAB/SIMULINK environment.

1. Introduction

In the present scenario, wide use of power electronic devices generates huge quantities of harmonics in the utility network [1–3]. Due to the presence of harmonics, The load end characteristics behave abruptly. These harmonics are nothing but integer multiples of sinusoidal components of voltage and current. Due to the existence of nonlinear loads [4], different levels of consumers get affected hardly. Current or voltage harmonics and reactive power [5, 6] are the main sources for reducing the quality of power in the distribution system. To overcome these effects, traditionally passive LC filters [7] have been used, but in spite of several advantages still they are ineffectual due to certain conditions like tuning problem, bulky size, and resonance problems. Hence, many researchers conducted analysis with different custom power devices [8] to advance the quality of the power system. Current development in switching appliances has led to focus on a different arrangement of active power filter (APF). This APF is helpful in compensating voltage and current harmonics as well as compensation in unbalanced voltage with other power quality problems. Out of the different configuration of hybrid active filters [9–13], the SEHAPF [14] is the widely used one. This arrangement is linked in series between supply and load. The proposed configuration can mitigate PQ disturbances, like sag and swell insource and load voltage, three-phase imbalance voltage, and many more such that regulation in voltage is maintained perfectly on the load side. SEHAPF is able to supply the voltage harmonics in the utility system with equal magnitude and opposite phase with respect to the nonlinear load. The operation of these custom power devices is determined upon reference current technique and the controlling process used to supply the essential current or voltage compensation into the grid. For better compensation, fast sensing of distorted signal and quick extraction process are highly required.

Several research papers are analyzed based on HCC [15–20] for controlling voltage source inverter (VSI) of active filters. This controller performs a bang-bang type controller, which in turn affects the voltage compensation of APF

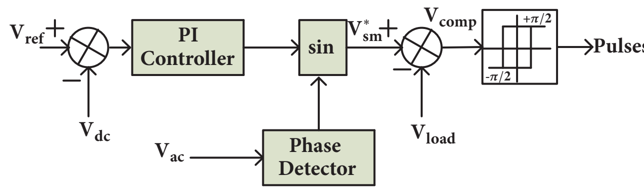


Figure 1: Control strategy of HCC.

and follows its estimated reference signal within a specific tolerance limit. The control strategy is depicted in Figure 1. For generating the gating signal to the VSI, the obtained reference voltage signal is related to actual voltage and the error between them is determined to HCC. This controller is employed individually for individual phase and produces the gating signals for the PWM-VSI. But the above controlling techniques are not suitable for tracking the reference signal during distortion in supply and load side.

Sliding mode controllers (SMC) [21, 22] have been utilized widely because of constancy, toughness, and fast switching action with respect to variable load conditions. Despite several merits still this technique suffers from chattering difficulties, in turn, producing a variable switching frequency causing severe losses in power and switching signal.

To overcome this problem, a slight modification has been made with the SMC using fuzzy based method [23] to produce a fixed switching technique. Because of using fuzzy controller the particular mathematical model of the system is not required. Fuzzy controller can perform with indefinite inputs and controls nonlinearity and is dynamic compared to other controllers. This arrangement [24–26] is able to hold power quality issues. A pulse width modulation based fuzzy SMC is presented for better compensation of SEHAPF by tracking accurately the reference signal during uncertainty conditions.

Projected FSMPWM technique eradicates several complications such as voltage harmonics, imbalance in the load, sag and swell in voltage, and distortion in voltage that are found in the utility system. The primary focus of the paper is to lower harmonics by reducing the percentage in THD and managing the reactive power using FSMPWM controlling techniques employed in SEHAPF.

The projected technique produces a constant switching signal in which the loss in power and EMC noise gets reduced. Moreover, it also makes very simple and easy-to-design passive LC filter. Consequently, the applied technique nullifies the mathematical operations and quite effectively to the external disturbances and uncertainties of the concerned system. The proposed scheme is analyzed under different source and load conditions. The result of the projected technique is examined using MATLAB/SIMULINK environment and the results are compared with the conventional HCC. In this paper, the subsequent sections are organized in the following pattern. Section 2 describes the systematic arrangement of the proposed SEHAPF. The control scheme for the SEHAPF using FSMPWM and unit vector is depicted in Section 3. Simulation results analysis is described in Section 4. Section 5 draws the conclusion.

2. System Configuration

The proposed scheme is presented in Figure 2. It comprises active series filter with passive LC filter. The SEHAPF guards the load end from the distorted source voltage, having imbalance characteristics, and delivers cost effective compensation method especially for heavy range of applications. It inserts the compensated voltage to the grid system at the point of common coupling through the coupling transformer. The voltage across the capacitor is maintained at a certain level, which is considered as reference values. The active power difference in the grid system gets affected during deviation of load. The DC link capacitor compensates the power differences. Out of the several configurations of hybrid filters, the series hybrid filter suits the best one which contains a small rating of series active filter with tuned passive LC filters. Series active filters allow the passive filters to tune exactly to reduce harmonics current at load end and to improve the power factor.

3. Control Strategy

3.1. Reference Signal Generation for SEHAPF. The control arrangement for reference voltage generation for SEHAPF is shown in Figure 3. This arrangement provides a fixed frequency pulse width modulation wave for the VSI of SEHAPF. At first a sliding surface is defined and for that a control strategy is designed for compensating the voltage reference. For realizing the value, the required real power can be obtained from the product of three-phase load voltages and three-phase source currents:

$$\begin{aligned} V_{La} &= V_m \sin\left(\omega_1 t + \varphi\right) \\ V_{Lb} &= V_m \sin\left(\omega_1 t - 120^\circ + \varphi\right) \\ V_{Lc} &= V_m \sin\left(\omega_1 t + 120^\circ + \varphi\right) \end{aligned} \tag{1}$$

$$\begin{aligned} I_{Sa} &= I_m \sin\left(\omega_1 t + \varphi\right) \\ I_{Sb} &= I_m \sin\left(\omega_1 t - 120^\circ + \varphi\right) \\ I_{Sc} &= I_m \sin\left(\omega_1 t + 120^\circ + \varphi\right) \end{aligned} \tag{2}$$

where V_m, I_m, and u are, respectively, defined as source magnitude voltage, current, and phase angle.

Now, RMS value of 3-phase load current is shown as

$$I_{Lx} = \sum_{n=1}^{\infty} I^{+}{}_{xn} + \sum_{n=1}^{\infty} I^{-}{}_{xn} + \sum_{n=1}^{\infty} I^{0}{}_{xn} \tag{3}$$

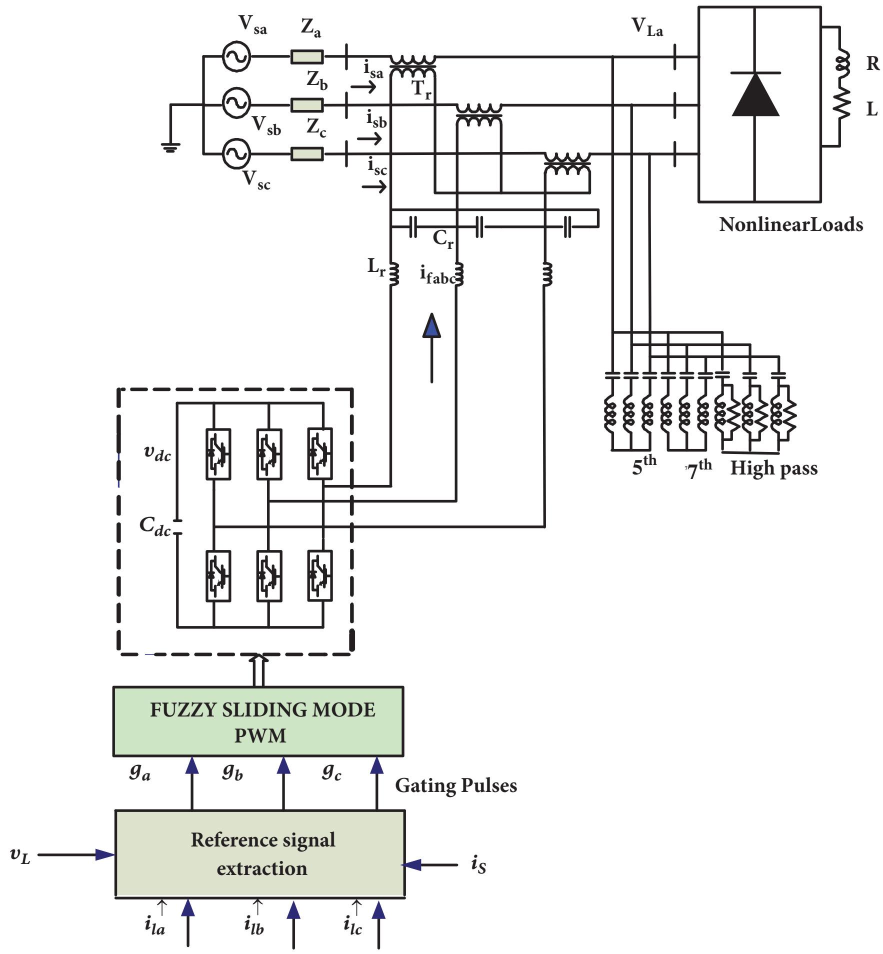


Figure 2: Circuit configuration of SEHAPF.

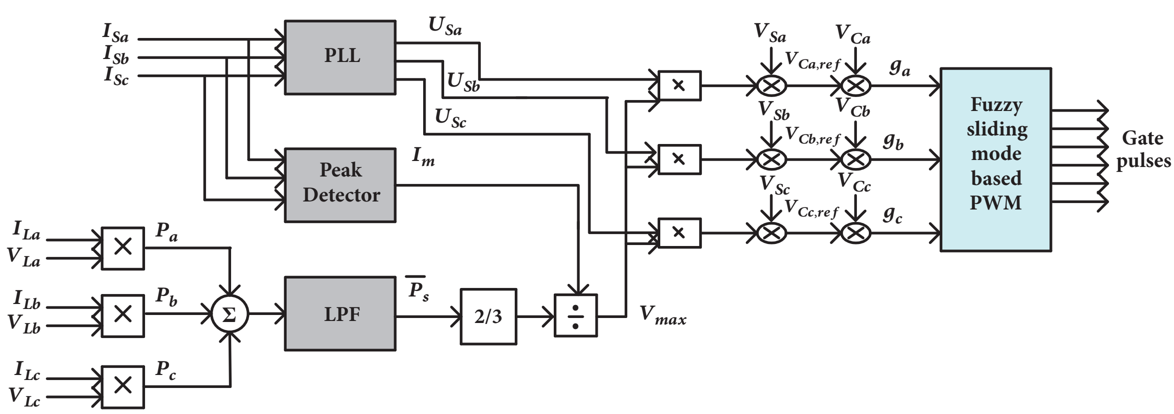


Figure 3: Control strategy of series filter using FSMPWM technique.

where $x, +, -, 0$ are, respectively, the sequence in phase, positive, negative, and zero sequence and n denotes number of harmonic components.

∴ the actual power absorbed by the load in positive sequence is expressed as

$$p^{+}{}_{n} = \frac{1}{T}\int_0^T \sum_{x\epsilon k} V_{Lx} I_{Lx}\,dt = \frac{3V_{max}I_{max}}{2} \tag{4}$$

And $p^{0}{}_{l1} = p^{+}{}_{S1}$.

In the aforementioned part, $p^{+}{}_{l1}$ and $p^{+}{}_{S1}$ are, respectively, the actual power absorbed by the load in positive sequence and real power supplied by the grid in positive sequence. Now for obtaining the maximum voltage of the load both the values of low pass filter and maximum value of supply current is used and is shown in (5), and the voltage reference is obtained from the product of

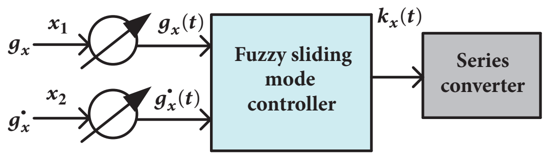


Figure 4: Block diagram of FSMC of series converter.

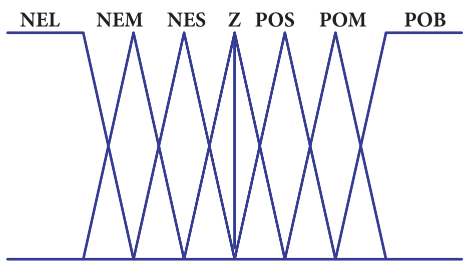


Figure 5: Membership function for fuzzy rule base.

maximum load voltage and unit sine vector as shown in (6):

$$V_{max} = \frac{2p^{+}{}_{l1}}{3I_m} = \frac{2\overline{p_S}}{3I_m} \quad (5)$$

$$V_{xref} = V_{max} * U_{Sx} \quad (6)$$

The compensation value of voltage reference in sliding surface is obtained by removing the supply reference voltage from the supply voltage as shown in

$$V_{Cxref} = V_{Sx} - V_{xref} \quad (7)$$

4. FSMPWM Control of SEHAPF

Block diagram of FSMPWM of series converter is revealed in Figure 4, where $u_c(V_{dc}/2)$ and I_f represent, respectively, the voltage and current along filter side, while, V_{ef}, L_{ef} and V_C, L_{sf}, respectively, represent voltage and current across the capacitor on ac side and at grid side.

The current and voltage at the terminal of the SEHAPF is given as (assume, $V_{ef} = V_C$)

$$\frac{dI_F}{dt} = \frac{V_{dc}}{2L_{sef}} u_c - \frac{R_{sef}}{L_{sef}} I_F - \frac{1}{L_{sef}} V_{ef} \quad (8)$$

$$\frac{dV_{ef}}{dt} = \frac{dV_C}{dt} = \frac{1}{C_{ef}} I_F - \frac{1}{C_{sef}} I_{sf} \quad (9)$$

The path of fuzzy sliding surface for SEHAPF is acquired as

$$S_x(t) = \dot{g}_x \quad (10)$$

[which is obtained from $(V_{Cxref} - V_{Cx})$], where "x" is a sequence of phase.

∴ the Error function is stated as

$$g_x(t) = \left(V_{Cxref} - V_{Cx}\right) \quad (11)$$

For the SEHAPF, $\dot{S}(t)$ is written as

$$\dot{S}(t) = \ddot{g}(t) \quad (12)$$

$$\therefore \dot{s}_x(t) = \left(\ddot{V}_{Cxref} - \ddot{V}_{Cx}\right) \quad (13)$$

Utilizing value of dV_C/dt the value from (13) becomes

$$\begin{aligned} \dot{s}_x(t) &= \left(\dot{V}_{Cxref} - \frac{1}{C_{ef}} \dot{I}_{Fx} + \frac{1}{C_{ef}} \dot{I}_{sFx}\right) \\ &= \frac{1}{C_{ef}} \left(-\frac{V_{dc}}{2L_{sef}} u_{cx} + \frac{R_{sef}}{L_{sef}} I_{Fx} + \frac{1}{L_{sef}} V_{efx}\right) \\ &\quad + \frac{1}{C_{ef}} \dot{I}_{sFx} + \ddot{V}_{Cxref} \end{aligned} \quad (14)$$

By setting $\dot{s}(t) = 0$ the equation can be written as

$$\begin{aligned} u_{eqcx} = \Bigg(& \frac{2R_{sef}}{V_{dc}} I_{Fx} + \frac{2V_{efx}}{V_{dc}} + \frac{2L_{sef}}{V_{dc}} \dot{I}_{sfx} \\ & + \frac{\ddot{V}_{Cxref}}{V_{dc}} 2C_{ef} L_{sef} \Bigg) \end{aligned} \quad (15)$$

$s(\dot{g}_x, t)$ decides the presence of sliding mode.

∴ the switching law is expressed in

$$s\left(\dot{g}_x, t\right) \dot{s}\left(\ddot{g}_x, t\right) < 0 \quad (16)$$

It is evident from the equation that the corresponding equation is linear with regard to u_c subject to

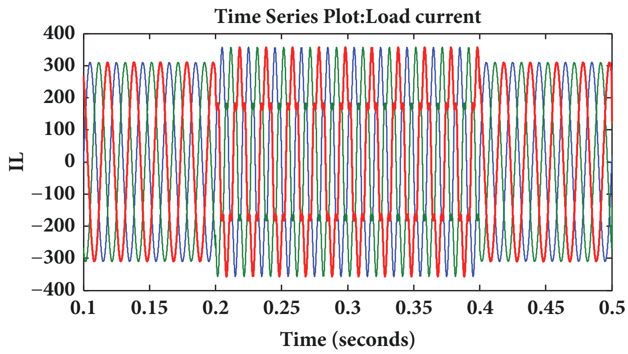
$$\begin{gathered} u_c < u_{eqsx}; \\ \dot{s}\left(\ddot{g}_x, t\right) > 0 \\ u_c > u_{eqsx}; \\ \dot{s}\left(\ddot{g}_x, t\right) < 0 \end{gathered} \quad (17)$$

and u_c, controlling signal of Series APF.

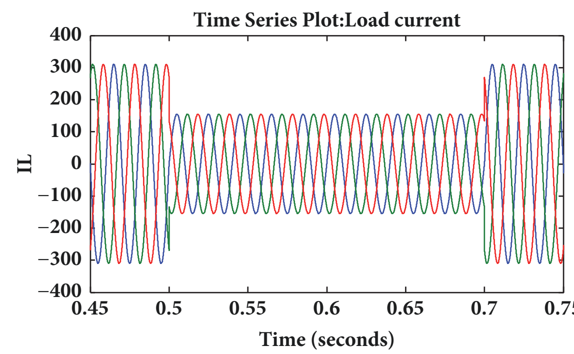
Therefore, corresponding control is reserved by the natural bounds of Series APF, and it is found that

$$\begin{gathered} u_c = -1; \\ \dot{s}\left(\ddot{g}_x, t\right) > 0 \\ u_c = 1; \\ \dot{s}\left(\ddot{g}_x, t\right) < 0 \end{gathered} \quad (18)$$

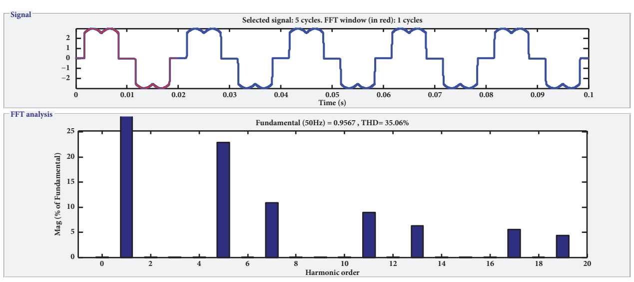
The real error functions are scaled which relates to their time domain variables, implemented to the fuzzy controller, presented in Figure 5, and $k(t)$ fuzzy controller output, which is arranged from -1 to 1.



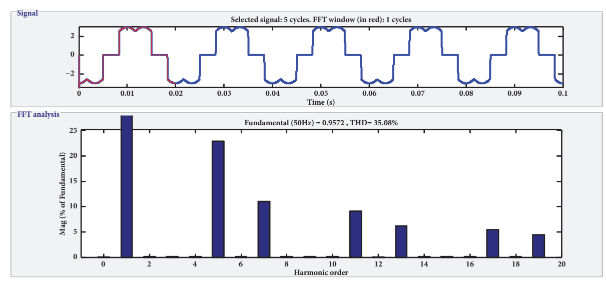
(a) Voltage swell



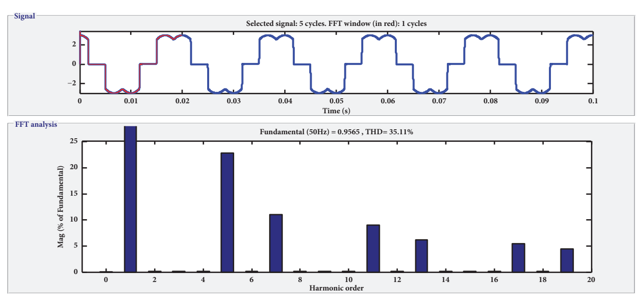
(b) Voltage sag



(c) THD of phase a



(d) THD of phase b



(e) THD of phase c

Figure 6: Load voltage and THD during distortions and without connecting SEHAPF.

For controlling the series part of hybrid filters the fuzzy controller obeys the fuzzy set theory as shown in Figure 4, and it is expressed as

$$\begin{aligned} \dot{g}(t) &= \{NEL, NEM, NES, Z, POS, POM, POB\} \\ \ddot{g}(t) &= \{NEL, NEM, NES, ZE, POS, POM, POB\} \\ k(t) &= \{NEL, Z, POB\} \end{aligned} \tag{19}$$

where $NEL, NEM, NES, Z, POS, POM, POB$ are the membership functions in fuzzy set as shown in Table 1.

The Fuzzy rule is designed [13] by using

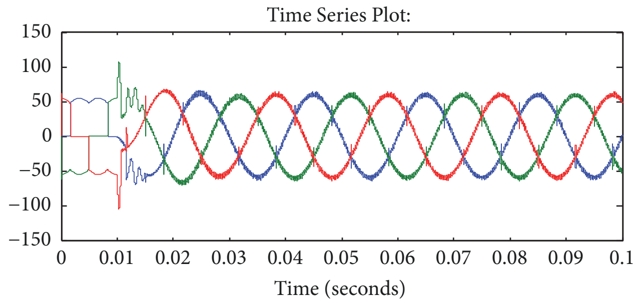
$$u_{cx} = \begin{cases} 1, & s\left(\dot{g}_x, t\right) > 0 \\ 0, & s\left(\dot{g}_x, t\right) = 0 \\ -1, & s\left(\dot{g}_x, t\right) < 0 \end{cases} \tag{20}$$

Finally, the FSMPWM produces PWM signal depending upon fuzzy rule as shown in Table 1 which is helpful for compensating the power quality problems.

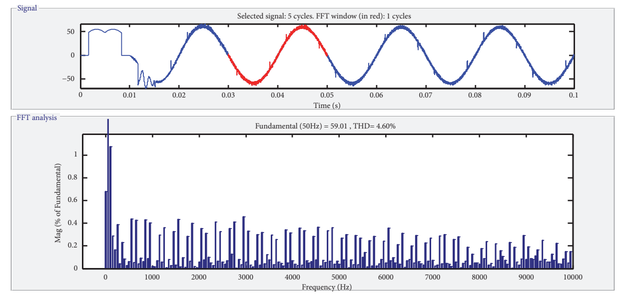
5. Results and Analysis

The modelling and simulation of SEHAPF controlled by a PI controller using HCC and FSMPWM are presented. The system performance is examined using MATLAB/SIMULINK tool. Design of SEHAPF with FSMPWM is employed to remove the voltage harmonics in the power system. The realization of SEHAPF connected through FSMPWM has been examined and the results are compared with the classical HCC using unit vector theory. The data of variable parameters are described in Table 3. The realization of SEHAPF is analyzed by simulating the circuit using the "Power System Block set" simulator.

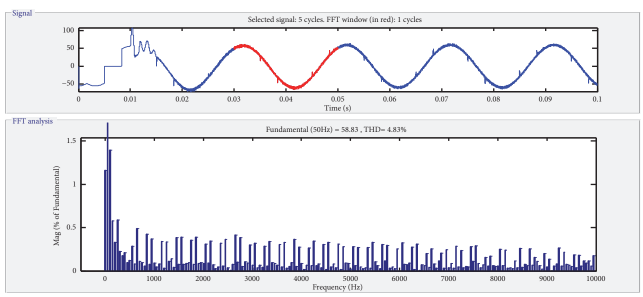
Initially the system is performed in the absence of SEHAPF and connecting unbalance nonlinear loads. It shows that there is a distortion in voltage signal at load end, which



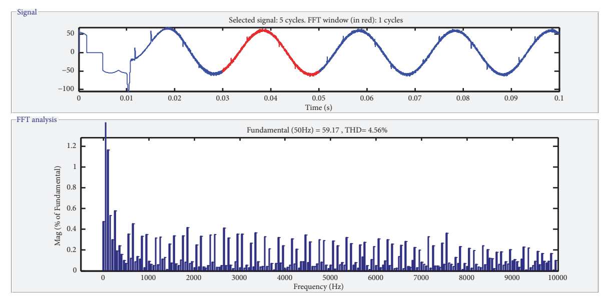
(a) Three-phase load voltage



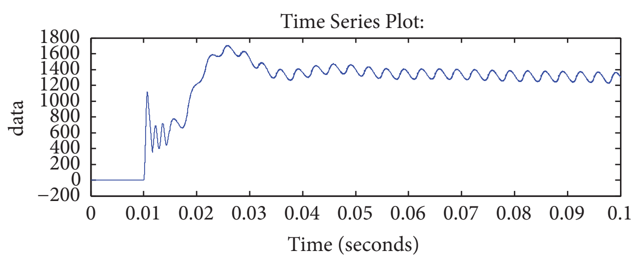
(b) THD for Phase a: 4.60%



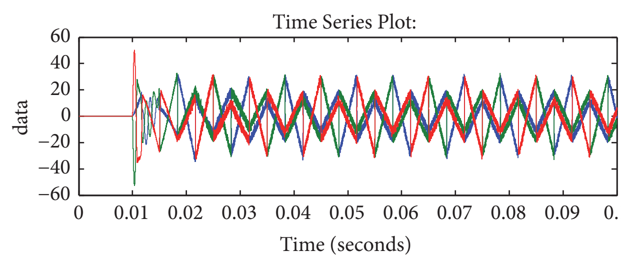
(c) THD for Phase b: 4.83%



(d) THD for Phase c: 4.56%



(e) Dc link voltage



(f) Compensated voltage

Figure 7: Performance of load voltage and THD values of three-phase voltages and dc bus voltage and compensation voltage using HCC.

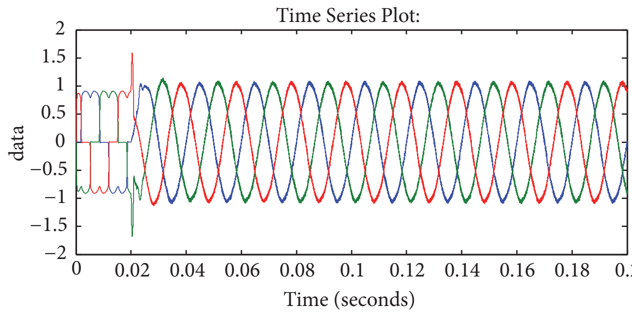
Table 1: Fuzzy rule.

				$\dot{g}$			
$\Delta\ \dot{g}$	NEL	NEM	NES	Z	POS	POM	POB
NEL	NEL	NEL	NEL	Z	POB	POB	POB
NEM	NEL	NEL	NEL	Z	POB	POB	POB
NES	NEL	NEL	NEL	Z	POB	POB	POB
Z	NEL	NEL	NEL	Z	POB	POB	POB
POS	NEL	NEL	Z	Z	POB	POB	POB
POM	NEL	Z	Z	POB	POB	POB	POB
POB	Z	Z	Z	POB	POB	POB	POB

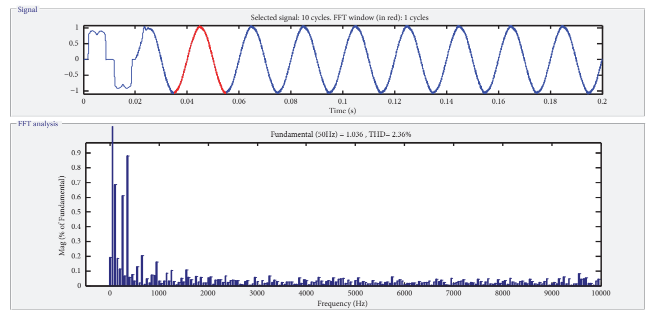
provides sag and swell characteristics of the voltage. From simulations it is observed that voltage swell is found to be present from 0.2 Sec to 0.4 Sec. Similarly, from 0.5 Sec to 0.7 Sec, voltage sag is noticed. The output results are presented in Figures 6(a) and 6(b). It shows that the three-phase load voltages are affected in the sag and swell. THD value in phases a, b, and c is attained to be 35.06%, 35.08%, and 35.11%, respectively, and illustrated in Figures 6(c), 6(d), and 6(e).

5.1. Load Voltage after Compensation Using Hysteresis Current Controller. In this section, SEHAPF configurations based on the hysteresis current controller using unit vector theory are analyzed. The hybrid filters implementing series active filters are performed and simulation results are illustrated in Figure 7(a), and the corresponding THD values of three-phase voltages V_a, V_b, V_c are presented in Figures 7(b), 7(c), 7(d), and 7(e), respectively. The THD value observed from the simulation for three-phase load voltage is found to be 4.60%, 4.83%, and 4.56%, respectively. Figures 7(e) and 7(f) provide the simulation output of the DC bus value and compensation voltage of the SEHAPF using hysteresis controller.

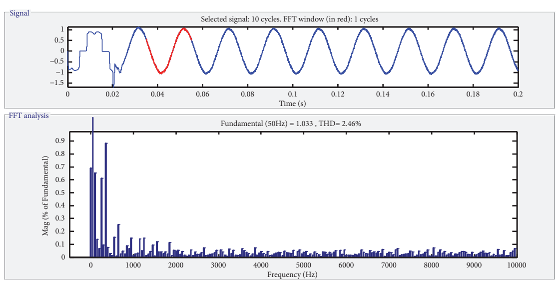
5.2. Load Voltage after Compensation Using FSMPWM. This category represents the performance of the system using the SEHAPF configurations based on FSMPWM. The hybrid filters implementing series filters are performed and simulation results are presented in Figure 8(a), and the corresponding THD values of three-phase voltages V_a, V_b, V_c are illustrated in Figures 8(b), 8(c), and 8(d), respectively. By implementing FSMPWM, a noticeable improvement was found in the THD value 2.36%, 2.46%, and 2.39%, respectively, of phase a, phase b, and phase c. Figures 8(e) and 8(f) provide the simulation



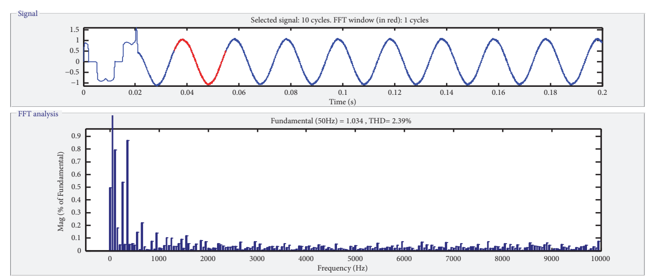
(a) Three-phase load voltage



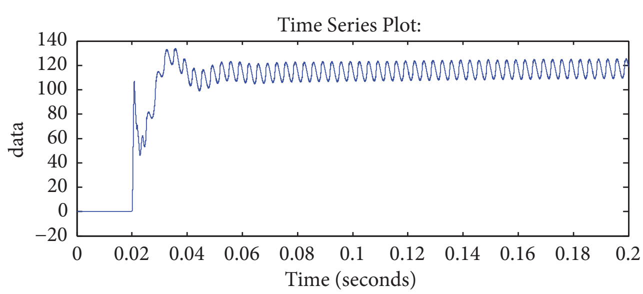
(b) THD for Phase a: 2.36%



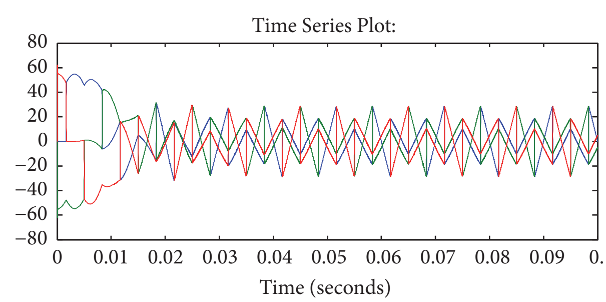
(c) THD for Phase b: 2.46%



(d) THD for Phase c: 2.39%



(e) Dc link voltage



(f) Compensated voltage

FIGURE 8: Performance of load voltage and THD values of three-phase voltages and dc bus voltage and compensation voltage using FSMPWM.

TABLE 2: Comparison of THD % analysis of load voltages between FSMPWM and HCC used in SEHAPF.

Load Voltages	%THD Without SEHAPF	%THD HCC	%THD FSMPWM
Phase a	35.06	4.60	2.36
Phase b	35.08	4.83	2.46
Phase c	35.11	4.56	2.39

output of the dc link value and compensation voltage of SEAPF using FSMPWM.

Table 2 describes a comparative result of the percentage THD between HCC and FSMPWM

TABLE 3: Parameters in the system.

Parameters	Value
Line voltage and Frequency	440V, 50 Hz
Line and Load impedance	Ls= 0.25 mH, Lac= 1.05 mH, C,DC = 2000 μF, RL=30 Ω, L=20 μF (R1 =3 Ω, R2 =6 Ω, R3 =9 Ω)
Passive Filter	Cf5= 50 μF Lf5 =8.10 mH Cf7= 20 μF Lf7 = 8.27 mH Cf11= 20 μF Lf11=8.270 mH
Ripple Filter	CRF = 50 μF, LRF =0.68 mH
Active Filter side	CD = 2000 μF VD =800V
Filter coupling inductance	3 mH
Controller gain	K_P=0.032, K_I=0.00004, for Series PF

6. Conclusions

This paper presents a distinct and dynamic strategy of SEHAPF where the switching signals are controlled by using FSMPWM. The performance of the projected model is analyzed under unbalance load conditions. The simulation results show the improvement in three-phase load voltages with compensating voltage sag and swell. Improved results in THD are also found to be compared with conventional hysteresis controller. The output results with its THD value are shown in Figures 7 and 8, which shows FSMC is the better one and also follows the IEEE-519 standard.

Data Availability

No data were used to support this study.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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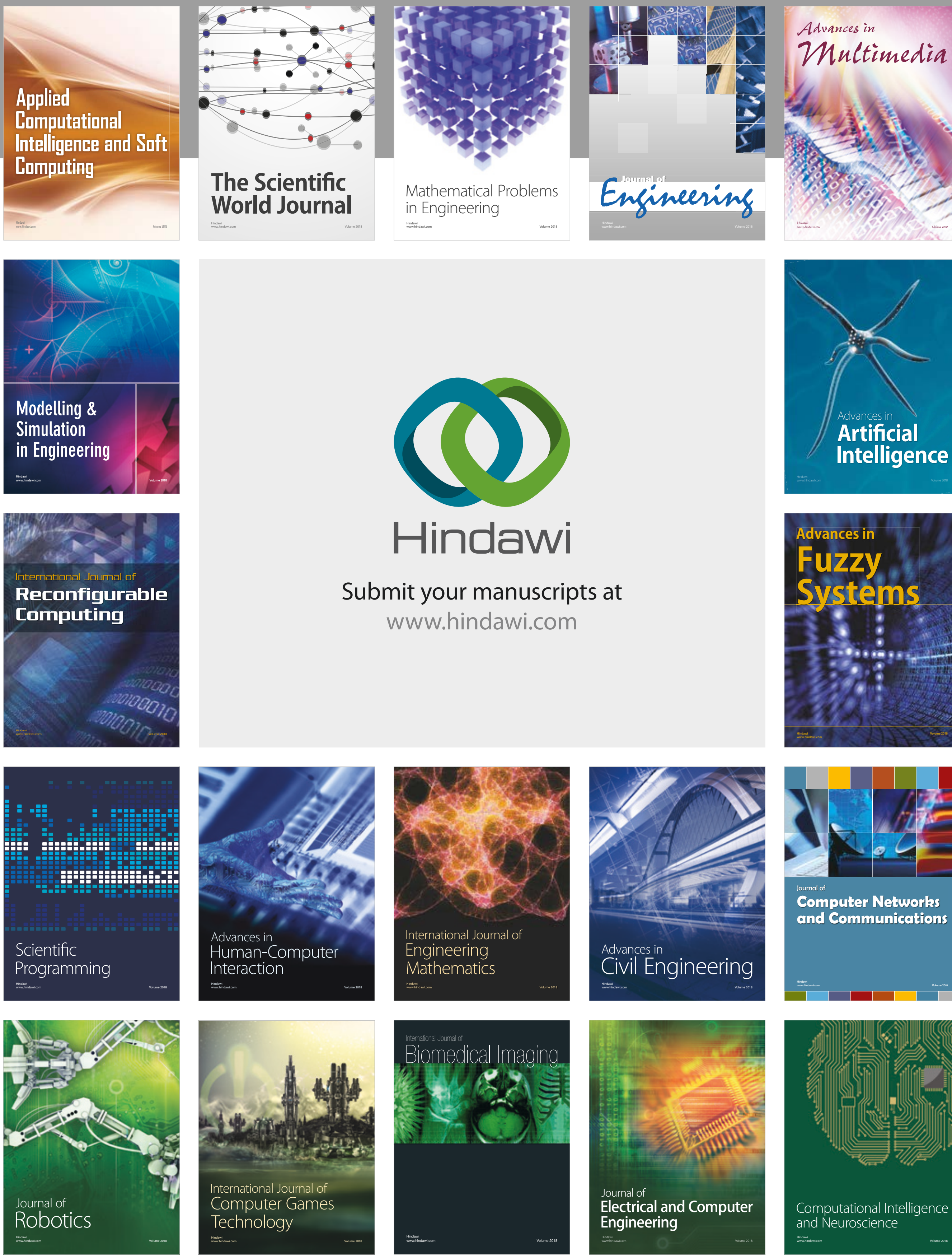
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