

## **FUZZY CONTROL OF A THREE-PHASE SHUNT ACTIVE FILTER FOR HARMONIC CURRENT COMPENSATION IN A WIND-DIESEL STANDALONE SYSTEM**

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*This paper presents the design of a fuzzy controller for a three-phase shunt active filter integrated in wind-diesel power system equipped with a wind turbine driving an induction generator. The goal for this controller is to maintain a good power quality under varying wind and load conditions. On the other hand, the controller should show acceptable closed-loop performance including stability and robustness. Active power filters as solutions to power quality problems have become more and more important nowadays. The modeling of the wind-diesel standalone system with control algorithm of the shunt active power filter (SAPF) to compensate the current harmonics and the power factor of nonlinear load is considered. A three-phase voltage source bridge inverter with a DC bus capacitor is used as an active filter.*

**Keywords:** SAPF, Diesel Generator (DG), Wind Turbine (WT), Power Quality (PQ), Fuzzy Logic

### **1. Introduction**

Power quality standards force to limit the total harmonic distortion (THD) within acceptable range caused by rapid usage of power electronic equipment. Therefore, the main purpose of this thesis is to widen the investigation of the quality problems in power system.

A hybrid power system is a combination of continuously available diesel power and locally available, pollution-free wind energy. Since the early eighties, the wind-diesel autonomous power system (WDAPS) has been accepted and widely used for power generating systems in remote areas.

Diesel generator is generally used to provide an uninterrupted energy on islands and remote areas. For these regions, the association of diesel generator (DG) and renewable energy sources, wind turbine (WT) generators. In recent

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years, wind turbines have been successfully interfaced to large grids and also to weak system usually consisting of diesel units [1]. However, one of the disadvantages is the intermittent nature of wind power generation. Diesel engine-driven synchronous generators operating in parallel with wind turbine must maintain a good voltage and frequency regulation against active and reactive load variations and wind speed changes [2,3]. It is necessary to improve the power quality of the distribution system reducing currents harmonics while compensating a reactive power and improving power factor.

All authors are treated filtering of this hybrid system by the conventional regulation, but in this paper, we have applied fuzzy logic to improve the filter dynamics to improve energy quality with robustness [5,6].

The design of fuzzy control techniques applied to a shunt active filter. The controller is designed to track a reference as current harmonics and reactive power. The shunt active power filter is modeled and investigated under non-linear load condition using MATLAB/Simulink. Various simulation results are presented to verify the improvement of performance by using shunt active power filter with hysteresis current controller for the distribution system.

## 2. System description

The proposed system consists of a wind turbine having an induction generator (IG), a diesel engine (DE), a synchronous generator (SG), a dumpload and shunt active filter (APF) and the system load. A three-phase dumpload is used with each phase consisting of seven transistor-controlled resistor banks. When wind-generated power is sufficient to serve the load, the DE is disconnected from the SG by electromagnetic clutch, and the synchronous generator acts as a synchronous condenser.

The wind-diesel autonomous power system (WDAPS) has three modes of operation: diesel only (DO), wind diesel (WD) and wind only (WO) [3].

High penetration wind-diesel system has three types of operating conditions: DO, WD and WO. In DO mode, the maximum power from the wind turbine generator (WTG) is always significantly less than the system load. In this case, the Diesel Generator (DG) operation never stops and supplies the active and reactive power demanded by the consumer load. But, the fuel consumption of DG can be reduced depending on how much power is supplied by the WTG (generally disconnected) and the particular characteristics of the diesel engine.

The SG (with/without diesel) is used for reactive power control, which is achieved by the excitation system used for voltage regulation. The SG also supplies the reactive power required by the induction generator.

The SAPF included in this system for compensating harmonics and reactive power is based on combination of three phase IGBT based inverter with

DC bus capacitor. Three-phase diode bridge rectifier with R-L load is taken as the nonlinear load.

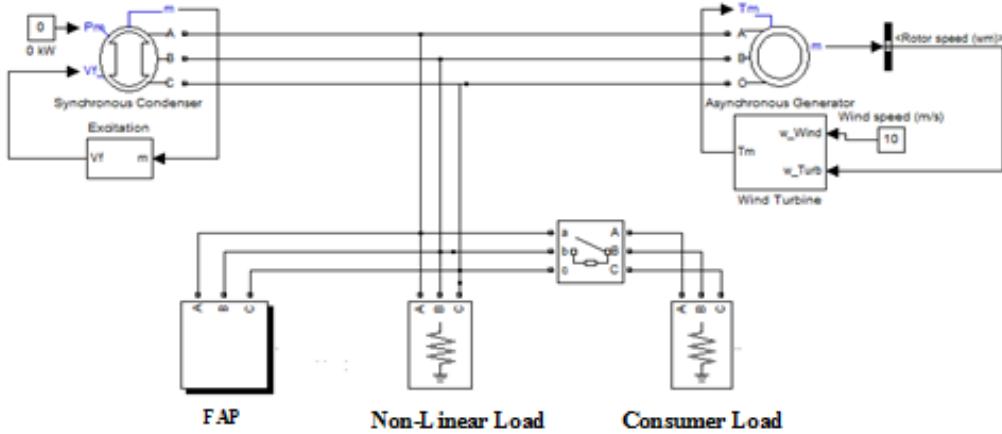


Fig. 1. System configuration

### 3. Modeling of the system

#### 3.1. Wind Turbine conversion system Modeling

The mechanical power ( $P_{tu}$ ) extracted from the wind is mainly governed by three quantities namely, the area swept by rotor blades ( $S$ ), the upstream wind velocity ( $V_0$ ) and rotor power coefficient ( $C_p$ ) [1].

$$P_{tu} = C_p P_{th} = C_p (\lambda, \beta) \frac{\rho S V_0^3}{2} \quad (1)$$

$C_p$ , the power coefficient of rotor, itself is a function of tip speed ratio ( $\lambda$ ) and pitch angle ( $\beta$ ). The wind turbine considered in this paper is ‘stall controlled’. So,  $\beta$  is kept out of (1) and  $C_p$  is function of  $\lambda$  only.

$\lambda$  is defined as the ratio of the tip speed of the turbine blades, and given by;

$$\lambda = \frac{\Omega R}{V} \quad (2)$$

Where  $\Omega$  is the angular speed of the rotor with the radius  $R$ . This function assumes a maximum for a certain value of  $\lambda$ . From the wind speed input  $V$  and the rotor speed  $\Omega$ , the operating point of the wind turbine can be determined. When the induction machine is generating, which corresponds to its operation in the vicinity of synchronous speed, the rotor speed is relatively constant.

### 3.2. Modeling of Induction Generator

The model of the induction generator is based on the standard Park's transformation that transforms all stator variables to a rotor reference frame described by a direct and quadrature (d-q) axis. The set of SG equations are based on the d-q axis as in [1], [2].

The electromagnetic torque equation is given by [3]:

$$T_{em} = \frac{3}{2} P (\lambda_{ds} i_{qs} - \lambda_{qs} i_{ds}) \quad (3)$$

The torque balance equation of mechanical motion of the induction generator side is given as [4]:

$$T_g = J \left( \frac{2}{P} \frac{d\Omega}{dt} \right) + T_{em} \quad (4)$$

With  $J$  is the inertia,  $P$  is the number poles of the induction generator and  $\Omega$  represents the rotor speed of induction generator.

### 3.3. Modeling of Synchronous Generator

A synchronous generator is used to model the diesel generator. Using Park's transformation, the electrical quantities like currents, voltages and flux linkages associated with stator and rotor are converted into a d-q reference frame. The diesel engine unit includes of a standard third order controller and actuator. The diesel engine model considered [6-8] consists of: a controller to check the steady-state error in speed and an actuator with gain  $K$ , time constant  $T_i$ , and integrator altogether to control the fuel rack position.

Finally the production of  $T_{mech}$  is represented by conversion of fuel-flow to torque after a time-delay  $T_D$ . The equation used or the conversion is expressed by:

$$T_{mech}(s) = e^{-sT_D} \Phi(s) \quad (5)$$

The diesel engine is a complex device and has many nonlinear components affecting the generation unit performance [9].

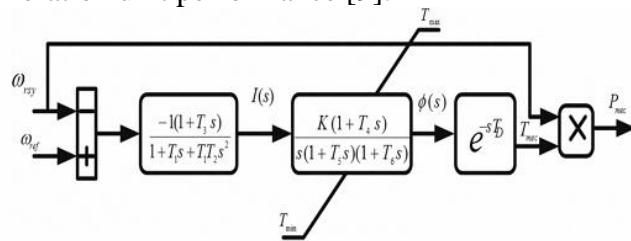


Fig. 2. Model of diesel engine

### 3.4. Modeling of Active Power Filter

The aim of the SAPF is to inject a current with the same magnitude but opposite phase shift with harmonics current. The harmonics are compensated by a voltage source converter. Though several control strategies had been developed for harmonics compensation, but still two control theories, the instantaneous active and reactive currents ( $i_d - i_q$ ) method and instantaneous active and reactive power (p-q) methods are the most popular [5].

#### 3.4.1. Instantaneous real and reactive power method (p – q)

The generalized theory of the instantaneous reactive power in three-phase circuits, namely the p-q theory has been proposed by Akagi et al. in 1983. The active filter currents are achieved from the instantaneous active and reactive powers p and q of the non-linear load [10].

Fig..3 depicts the overall configuration of a SAPF.

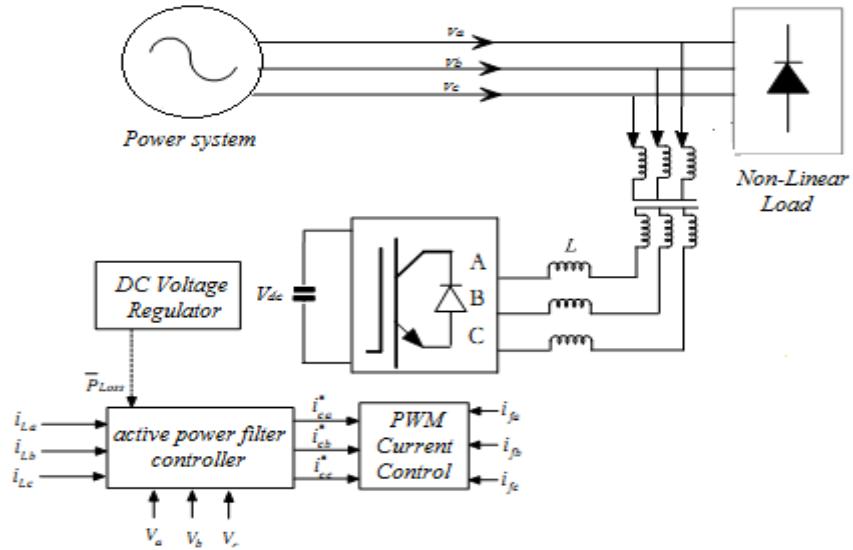


Fig. 3. SAPF configuration

This theory consists in the algebraic transformation of the current and voltage of the system from the abc system to  $\alpha\beta0$  system using Clarke's transformation as in "Eq. (6)" and "Eq. (7)".

$$\begin{bmatrix} V_0 \\ V_\alpha \\ V_\beta \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \\ 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} V_1 \\ V_2 \\ V_3 \end{bmatrix} \quad (6)$$

$$\begin{bmatrix} I_0 \\ I_\alpha \\ I_\beta \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \\ 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} I_{S1} \\ I_{S2} \\ I_{S3} \end{bmatrix} \quad (7)$$

The instantaneous power for the three-phase system is as follows:

$$\begin{bmatrix} p \\ q \end{bmatrix} = \begin{bmatrix} V_\alpha & V_\beta \\ -V_\beta & V_\alpha \end{bmatrix} \begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} \quad (8)$$

Where  $p$  is the instantaneous real power and  $q$  is the instantaneous reactive power.

Where  $\bar{p}$  and  $\bar{q}$  denote the average portion and  $\tilde{p}$  and  $\tilde{q}$  indicate the oscillating portion of  $p$  and  $q$ , respectively.

For balanced voltage sources, the oscillating powers  $p$  and  $q$  represent the undesirable powers due to harmonic components in the load current. In some situations  $q$  is an undesirable power as well [12 -14].

The currents, voltages and powers in the  $\alpha$ - $\beta$  system can be decomposed in mean and alternating values, corresponding to the fundamental and harmonic components, as in “Eq(9)”.

$$\begin{cases} p = \bar{p} + \tilde{p} \\ q = \bar{q} + \tilde{q} \end{cases} \quad (9)$$

$\bar{p}$  is the continuous part related to the fundamental component of the current active,  $\bar{q}$  is the continuous part related to the fundamental reactive current component, while  $p$  and  $q$  fluctuating parts are related to the sum of interfering components of current and voltage

The power required to be compensated by the APF are calculated as in “Eq. (10)”.

$$\begin{bmatrix} P \\ Q \end{bmatrix} = \begin{bmatrix} \bar{V}_\alpha & \bar{V}_\beta \\ 0 & 0 \end{bmatrix} \begin{bmatrix} I_\alpha \\ I_\beta \end{bmatrix} + \begin{bmatrix} 0 & 0 \\ -V_\beta & V_\alpha \end{bmatrix} \begin{bmatrix} I_\alpha \\ I_\beta \end{bmatrix} \quad (10)$$

Taking into account that the three-phase parallel active filter must compensate reactive power and the oscillating component of real power, the reference currents are calculated in the coordinates  $\alpha\beta 0$  using reactive power and the oscillating part of real power using the relation .

$$\begin{bmatrix} i_{c\alpha} \\ i_{c\beta} \end{bmatrix} = \frac{1}{V_\alpha^2 + V_\beta^2} \begin{bmatrix} V_\alpha & -V_{s\beta} \\ V_\beta & V_{s\alpha} \end{bmatrix} \begin{bmatrix} p - p_{\text{loss}} \\ q \end{bmatrix} \quad (11)$$

Signal  $P_{\text{loss}}$  creates balance of energy inside the parallel active filter. The sign  $\sim$  indicate the oscillation component of real power. To determine the reference currents in the coordinate abc, inverse Clarke's transformation is used.

$$\begin{bmatrix} i_{ref1} \\ i_{ref2} \\ i_{ref3} \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & 0 \\ -\frac{1}{2} & \sqrt{\frac{3}{2}} \\ -\frac{1}{2} & -\sqrt{\frac{3}{2}} \end{bmatrix} \begin{bmatrix} \tilde{I}_\alpha \\ \tilde{I}_\beta \end{bmatrix} \quad (12)$$

### 3.4.2. Fuzzy logic controller

Robustness or sensitivity can be conceived as a fundamental property of a logical system stating that the conclusions are not essentially changed if the assumed conditions varied within reasonable parameters. It is a relevant research area with important contributions. Nevertheless, robustness can be guaranteed only by sophisticated design techniques such as Fuzzy Logic.

Among the various controllers, the most promising is the fuzzy logic controller. Fuzzy control involves four stages: fuzzification, knowledge base, inference mechanisms, and defuzzification. The knowledge base is designed to provide a good dynamic response under uncertainty in process parameters and external disturbances [11, 15]. In our application, the fuzzy controller acts by processing the voltage error and its variation as shown in Fig. 4.

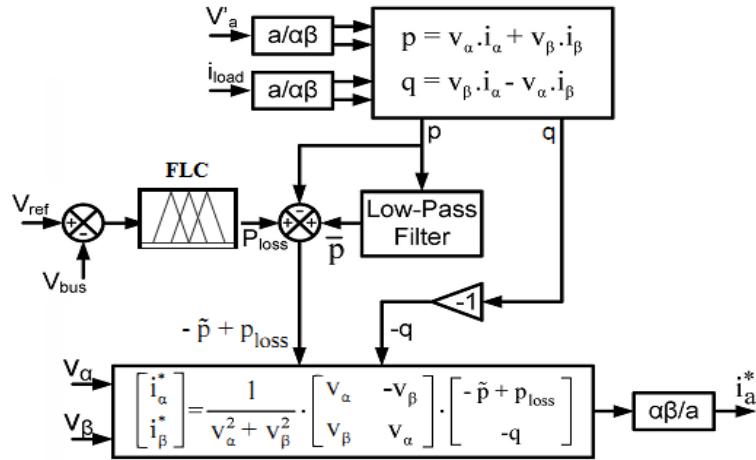


Fig. 4. Control strategy of the SAPF

The input and output variables are converted into linguistic variables using three fuzzy subsets, N (Negative), EZ (Equal Zero) and P (Positive). In this paper, the min-max inference method was used and the centroid method was used to defuzzify the fuzzy control variables. The membership functions used for the input and output variables are shown in Fig. 5, the fuzzy rule base is given in the Table 1 [16].

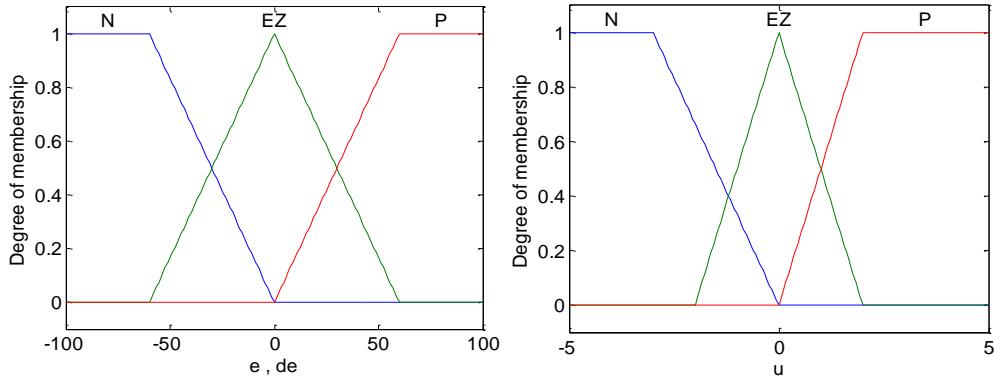


Fig. 5. Membership function for the inputs and output variables

Table 1

Fuzzy control rule				
de	e	N	EZ	P
N		N	N	EZ
EZ		N	EZ	P
P		EZ	P	P

#### 4. Simulation results

The performance of the proposed fuzzy logic control strategy is evaluated through simulation using Simulink and SimPowerSystems toolboxes. The model parameters used for these simulations are listed in Table 2.

Table 2

The Parameters of system

System parameters	Values
wind turbine (WT)	$P_n=37\text{ kW}$ , $L_s=0.087 \Omega$ , $V_n=480\text{ V}$ , $R_r=0.228 \Omega$ , $F_r=50\text{ Hz}$ , $L_r=0.8\text{ mH}$ , $L_m=34.7\text{ mH}$ , $2P=4$ ,
diesel generator (DG)	$R_s=0.087 \Omega$ , $J=0.4\text{ kg.m}^2$ , $S_n(\text{kVA})=37.5$ , $X_{1'}=0.09$ , $X_d=3.23$ , $T_{d0}=4.4849$ , $X_d'=0.21$ , $T_{d0'}=0.0681$ , $X_d''=0.15$ , $T_{q0''}=0.1$ , $X_q=2.79$ , $R_s(\text{pu})=0.017$
Consumer Load	Main load( $\text{kW}$ )= $10\text{ kW}$ , Non-linear load $R=35 \Omega$ , $L=20\text{e-}3$
Active filter	$C=22000\mu\text{F}$ , $L_f=3 \text{ mH}$ , $V_{dc}=1200 \text{ V}$

Fig. 6 shows the supply voltage with the source current and its harmonic currents spectrum before filtering.

The supply current obtained before filtering is completely distorted and its current Harmonic Distortion (THD) is 28.53 %. This value is higher than the international standard (THD<5%).

The supply current sinusoidal waveform and its THD equal to 3.2% are shown in Fig. 7(a) and (b). Fig. 7(c), illustrated the results response of DC-voltage. In This wave is obtained from our proposed PI controller.

In the case of fuzzy logic controller FLC. The supply current sinusoidal waveform and its THD equal to 2.8 % are shown in Fig. 8(a) and (b). It is also observed that the dc bus voltage of SAPF is maintained at the reference value under all disturbances is shown in Fig. 8(c).

The ability of the active to compensate for the harmonic current of the load filter is demonstrated by the reading of the current harmonic spectrum of wind-diesel standalone system after filtering. The results obtained demonstrate the effectiveness of the SAPF based on a FLC controller.

These results are very good and very encouraging compared to those obtained by the PI controller

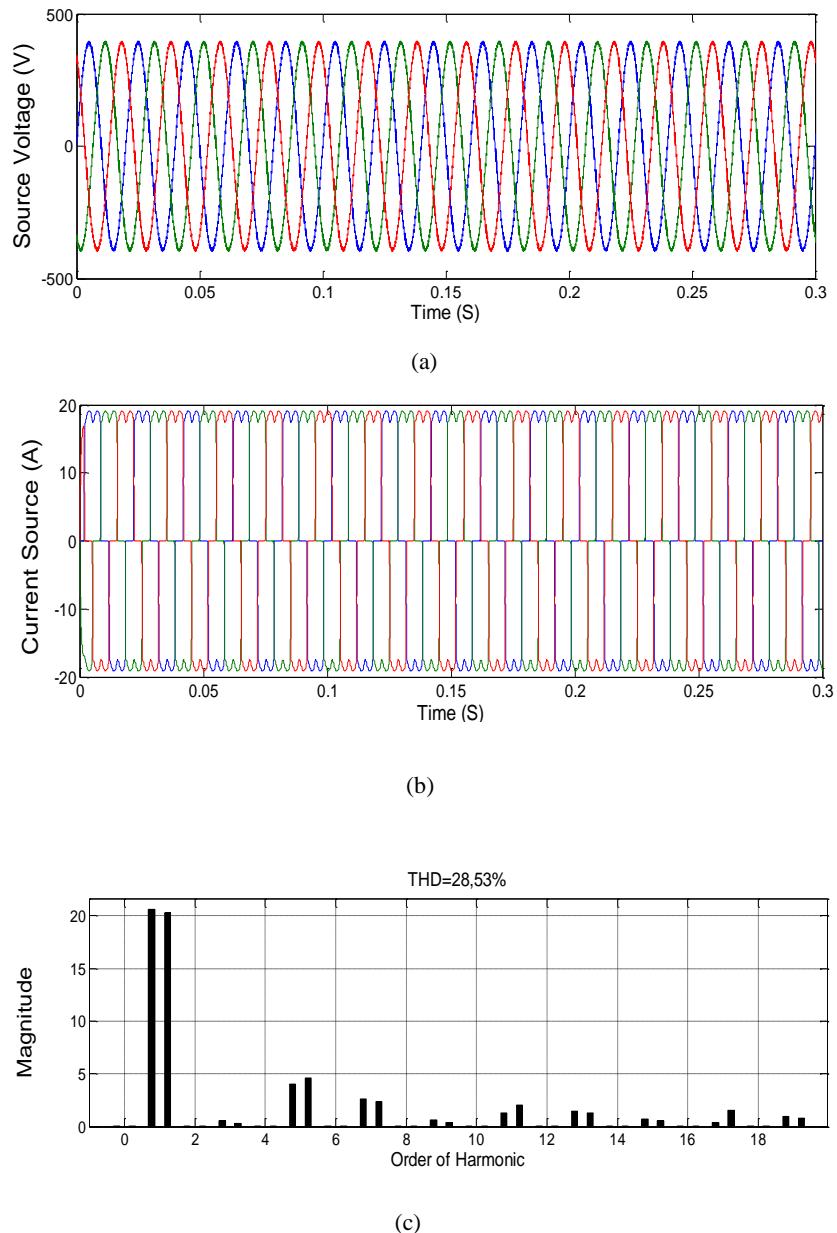


Fig. 6. Supply voltage and current waveforms and its harmonic currents spectrum of the wind-diesel standalone system before filtering

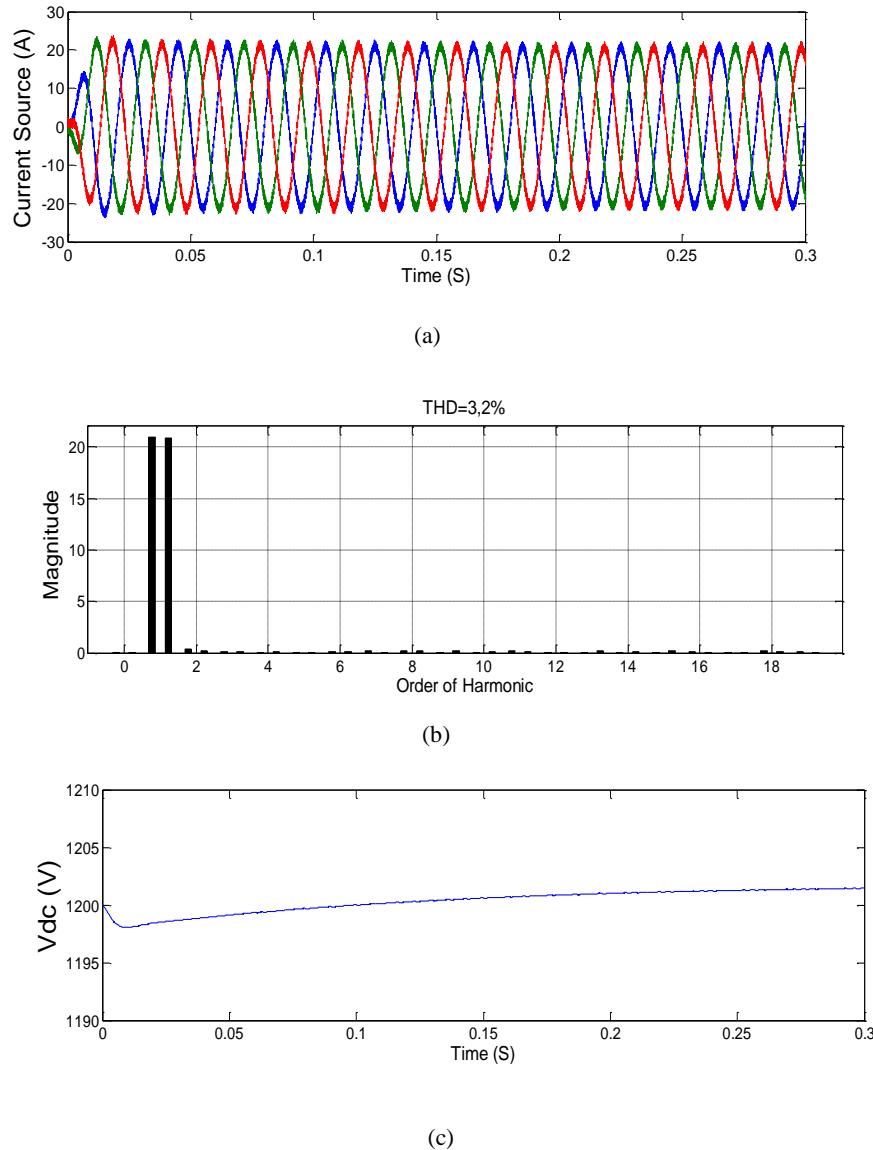


Fig.7. Simulation results for PI-controlled SAPF (a) Source currents, (b) Total harmonic distortion (THD) spectrum and (c)DC bus voltage ( $V_{dc}$ )

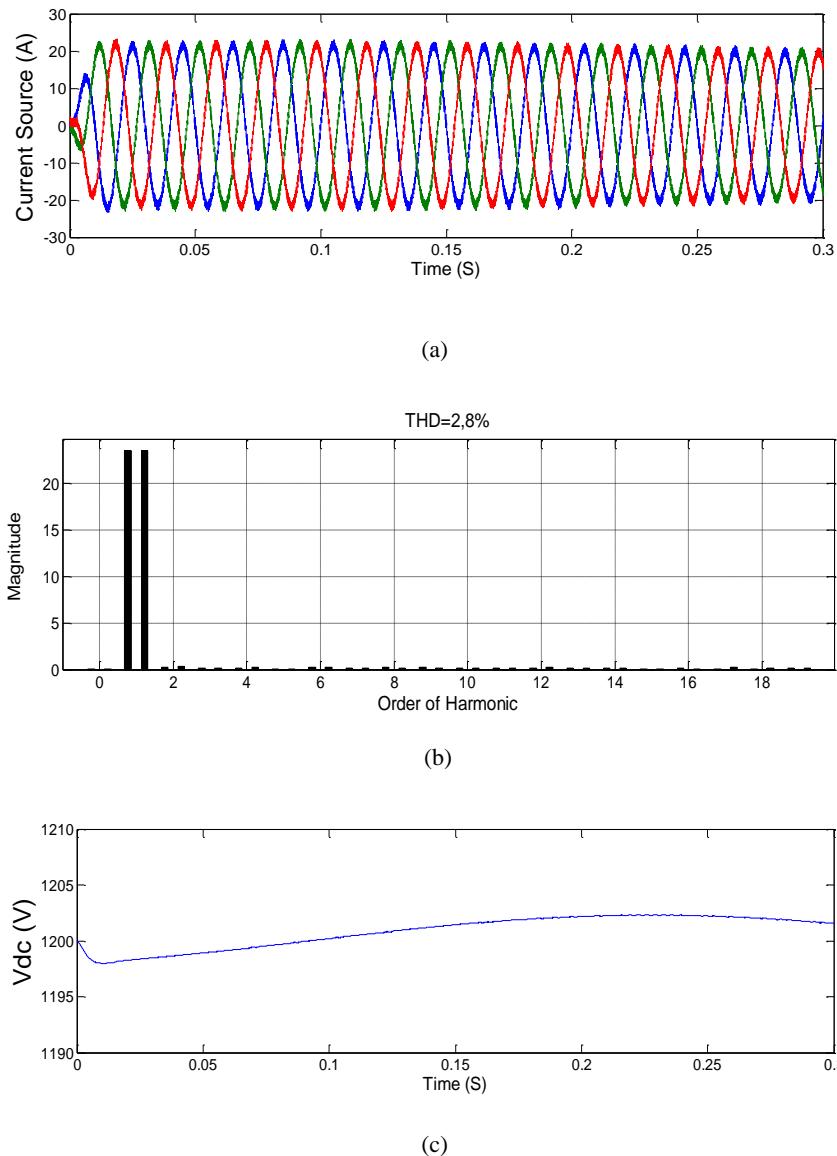


Fig 8. Simulation results for FLC-controlled SAPF (a) Source currents, (b) Total harmonic distortion (THD) spectrum and (c)DC bus voltage ( $V_{dc}$ ) .

## 5. Conclusions

In the present paper, we proposed an instantaneous active and reactive power control strategy with of three-phase shunt active filter for harmonic current compensation for the wind-diesel standalone system under Matlab/simulink environment. This control strategy is capable to suppress the harmonics in the system during balanced sinusoidal, un-balanced sinusoidal and balanced non-sinusoidal conditions with the supply voltage and the very reduced harmonic distortion achieved with the FLC controller (2.8%) compared to that obtained by the PI (3.2%). These results confirm with the international standard which imposed by the IEEE-519-1992 recommendations of harmonic standard limits. Overall the system performance is quite good not only under balanced condition but also under un-balanced and non-sinusoidal condition using p-q control strategy with a fuzzy logic controller.

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