Power Quality Enhancement in Off-Grid Hybrid Renewable Energy Systems Using Type-2 Fuzzy Control of Shunt Active Filter

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Abstract Maintaining a clean, reliable and efficient electric power system has become more challenging than ever due to the widespread use of solid-state power electronic controlled equipment in industrial, commercial and domestic applications. Non-linear loads draw non-sinusoidal current and reactive power from the source causing voltage and current distortion, increased losses in the power lines and deterioration of the overall power quality of the distribution grid. Devices such as tuned passive filters are among the oldest and most widely used techniques to remove power line harmonics. Other solutions include active power filters which operate as a controllable current source injecting a current that is equal but with opposite phase to cancel the harmonic current. This chapter deals with the design of fuzzy control strategies for a three-phase shunt active power filter to enhance the power quality in a hybrid wind-diesel power system operating in standalone mode. The proposed control scheme is based on Interval Type 2 fuzzy logic controller and is applied to the regulation of the DC bus voltage to compensate for real power unbalances during variable load conditions. A simulation study is performed under Matlab/Simulink to evaluate the performance and robustness of the system under different wind speed conditions.

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1 Introduction

In recent years, renewable energy technologies have experienced considerable developments due to the world's expanding energy needs. Wind energy is among the fastest growing renewable energy technologies and has the potential to play a significant role in achieving the world's future energy targets [1].

In many developed and developing countries, off-grid hybrid energy systems are increasingly being utilized to connect remote areas to a source of electric power as an alternative to the conventional standalone diesel-generator system [2]. A Wind Diesel Hybrid System (WDHS) consists of Wind Turbine Generator(s) (WTG) and Diesel Generator(s) (DG) [3, 4]. The advantage of the WDHS is the association of the continuously available diesel power with locally available, pollution-free, but intermittent and fluctuating in nature, wind energy [5]. Fuel consumption savings are maximum in WDHS with high wind penetration, in which the DGs may be shut down during periods of high wind availability.

Electric power quality has become vitally important with the proliferation of nonlinear loads such as power electronic converters in electric power distribution systems. Nonlinear loads introduce harmonics into the power network which cause a number of disturbances such as distortion of the current and voltage waveforms, electromagnetic interference, overheating of power distribution components inducing losses and reducing their lifetime [6, 7]. The impacts are expected to become even more challenging with the increasing penetration of the dispersed generation, where power electronic converters are often used to connect the generation units, such as wind turbines, photovoltaics, fuel cells and micro-turbines, etc.

Passive filters, consisting of custom-tuned LC circuits, are the oldest and perhaps the most popular and widely adopted low-cost solution to the harmonic problem [8]. However, the passive filter scheme has a limitation since it provides a fixed harmonic frequency compensation and also the addition of a passive filter interferes with the system impedance and causes resonance with other networks.

Active Power Filters (APFs) also called Active Power Line Conditioners (APLCs) are a relatively new technology which offers a more flexible alternative and provides superior filtering performance characteristics and faster transient response as compared to conventional passive filters [9]. APFs are classified into three types: Shunt active power filters, series active power filters and hybrid active power filters.

The shunt active power filter (SAPF) is used to compensate current harmonics. Universal APF is used to compensate voltage harmonics as well as current harmonics. SAPF is connected in parallel at the Point of Common Coupling (PCC) between the source and the nonlinear load. It acts as a current source and inject compensating current at PCC to make the source current sinusoidal and in phase with the source voltage [10, 11]. The series active power filter was introduced at the end of 1980. It is usually connected in series with a line through a series transformer. This filter injects the compensating voltage in series with the supply voltage. Thus, it acts as a voltage source which can be controlled to compensate voltage sags. Series filters have their application mainly where the load contains voltage sensitive devices. In many cases series active power filters are used in combination with passive LC filters [12]. The hybrid active power filter or Unified Power Quality Conditioner (UPQC) is a combination of series and shunt active power filters. It consists of two converters connected back to back with same DC-link capacitor. One inverter is connected across the load and acts as shunt APF [10, 13]. It has the advantages of both series APF and shunt APF. In other words, it can compensate both voltage and current harmonics. Therefore, this filter can be applied to almost all types of power quality problems faced by a power system network [14].

APFs basically consist of a power electronic inverter and a control circuit. The performance of these filters systems depends mainly on the converter topology employed, the adopted reference current generation strategy for harmonic compensation as well as the controller for the regulation of the DC bus voltage. The regulation of the DC bus voltage consists of maintaining the voltage across the capacitor connected to the inverter at the desired level. The role of the capacitor voltage is to compensate for inverter losses and any transient fluctuations in real power between the AC and DC sides following load changes. Various DC bus voltage control strategies have been proposed in the literature ([6, 10, 12]).

Fuzzy systems have evolved for more than four decades and have proved to be a powerful technique in dealing with uncertainties, parameter variation and especially where the system model is complex or not accurately defined for the designed control action. They have been successfully implemented in many real world applications mainly focusing on quantitative modeling and control [15]. Fuzzy logic controllers (FLCs) [7, 16, 17] have also been very popular for their applications to APFs.

This chapter presents a simplified design approach of an Interval Type-2 fuzzy logic controller (IT2FLC) [18, 19] for the regulation of the DC bus voltage of the SAPF connected to WDHS. The simulation results provide the validation of the p-q theory-based SAPF system to meet the IEEE Standard 519 which is the recommended harmonic standard for different rated nonlinear loads under balanced supply conditions.

The rest of the chapter is organized as follows: Sect. 2 present a description and detailed mathematical modeling of the hybrid power system. Section 3 presents the design steps of the proposed control strategy for the DC voltage. In Sect. 4, the overall system performance is evaluated in a series of simulation scenarios and the results are presented and discussed. Finally, Sect. 5 presents the conclusions of this contribution.

2 Hybrid Wind-Diesel Power System Configuration

The WDHS has three operation modes: Diesel Only (DO), Wind Diesel (WD) and Wind Only (WO) [4, 20]. In DO mode the DGs supply the active and reactive power demanded by the consumer load (WTGs are disconnected). In this case, the DGs operate continuously and the maximum power from the WTG is always significantly less than the system load. In WD mode, in addition to DG(s), WTG(s) also supply

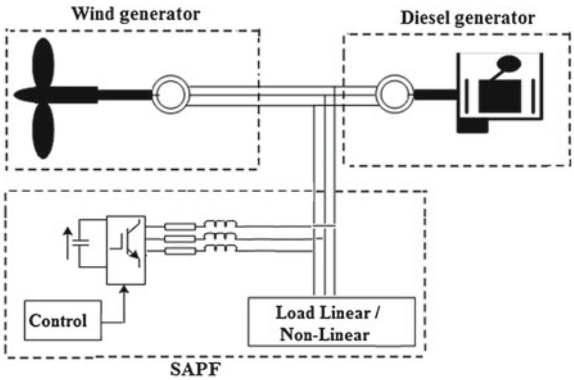


Fig. 1 WDHS and SAPF configuration

active power. In this case, the WTG power is approximately the same as the consumer load and in addition to DG(s), WTG(s) also supply active power. In WO mode, the DGs are not running, and only the WTs are supplying active power therefore no fuel is consumed in this mode.

Figure 1 shows the basic structure of a WDHS system supplying a local isolated load. The system essentially consists of a vertical axis wind turbine driving an induction generator connected to a synchronous generator driven by a diesel engine. The synchronous generator is equipped with a voltage regulator and a static exciter and the shunt active filter (SAPF).

The SAPF included in the system for compensating harmonics and reactive power consists of a three phase IGBT-based inverter connected to a DC bus capacitor. The nonlinear load is simulated with a three-phase diode bridge rectifier with R-L load.

2.1 Wind Turbine Model

The WT converts the kinetic energy of the wind into electric energy. The model complexity of the WT depends merely on the type of control objectives imposed. In order to study the dynamic response of multiple components and aerodynamic loading complex simulators are required. Generally, the impact of dynamic loads and interaction of large components are verified by the aero elastic simulator. However, for designing a WT controller, a simplified mathematical model is usually sufficient [3, 21]. In this work, the WT model is described by the set of nonlinear ordinary differential equation with limited degree of freedom.

The aerodynamic power captured by the rotor is given as:

$$P_a = C_p\left(\lambda, \beta\right)\frac{\rho S v^3}{2} \tag{1}$$

From Eq. (1), it is clear that the aerodynamic power (P_a) is directly proportional to the cube of the wind speed. The power coefficient C_P is a function of blade pitch angle (β) and tip speed ratio (λ). The tip speed ratio is defined as the ratio between the linear tip speed and the wind speed.

$$\lambda = \frac{\Omega R}{v} \tag{2}$$

where Ω is the angular speed of the rotor with the radius R. This function assumes a maximum for a certain value of λ. From the wind speed input v and the rotor speed Ω, 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.

The models of the generators are based on the standard Park's transformation that converts all stator variables to a rotor reference frame described by a direct and quadrature (d-q) axis [2, 3, 22].

The model of GAS is composed of two electrical differential equations and a mechanical differential equation. The electrical equations, expressed in direct (d) quadrature (q) coordinate are given by [23]:

$$\begin{cases} U_{ds} = R_s i_{ds} - L_s \frac{di_{ds}}{dt} + L_m \frac{di_{dr}}{dt} \\ U_{qs} = R_s i_{qs} - L_s \frac{di_{dq}}{dt} + L_m \frac{di_{qr}}{dt} \end{cases} \tag{3}$$

$$\begin{cases} U_{dr} = R_r i_{dr} + L_r \frac{di_{dr}}{dt} + L_m \frac{di_{ds}}{dt} + P\omega_g \left(L_r i_{qr} + L_m i_{qs}\right) \\ U_{qr} = R_r i_{qr} + L_r \frac{di_{qr}}{dt} + L_m \frac{di_{qs}}{dt} + P\omega_g \left(L_r i_{dr} + L_m i_{ds}\right) \end{cases} \tag{4}$$

where R_s, R_r are stator and rotor resistances L_s, L_r are stator and rotor inductances, L_m is magnetizing inductance between the stator and rotor, P is the number of machine poles and ω_g is the angular speed of the generator.

The electromagnetic torque equation is given by:

$$T_{em} = \frac{3}{2} P \left(\lambda_{ds} i_{qs} - \lambda_{qs} i_{ds}\right) \tag{5}$$

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

$$T_g = J \frac{2}{P} \frac{d\Omega}{dt} + T_{em} \tag{6}$$

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

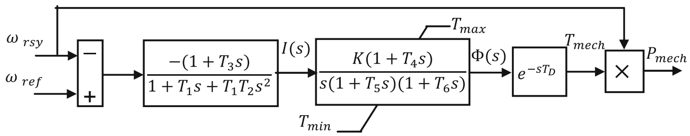


Fig. 2 Model of diesel engine

2.1.1 Modeling of Diesel Generator

The DG consists of a diesel engine (DE) and a synchronous generator (SG). The SG generates the voltage of the isolated power system and its automatic voltage regulator maintains the system voltage within prescribed levels during the three modes of operation. The DE provides mechanical power to the SG and its speed governor (speed regulator and actuator) controls the DE speed. In this work, the DE speed control is isochronous, so the diesel speed governor adjusts the fuel rate to make the DE run at a constant speed [23].

The DE is a complex device and has many nonlinear components affecting the generation unit performance. The DE model considered here [20–24] consists of a controller to monitor the steady-state speed, a first order actuator with gain K and time constant T_i to control the fuel rack position (Fig. 2).

Finally, the mechanical torque produced T_{mech} is represented by the conversion of fuel-flow to torque with a time-delay T_D.

$$T_{mech}(s) = e^{-sT_D}\Phi(s) \tag{7}$$

where s denotes the Laplace transform operator and $\Phi(s)$ represents the fuel flow.

3 Shunt APF Configuration and Control Scheme

3.1 Shunt AFP Configuration

The APF concept is to use an inverter to produce specific currents or voltages harmonic components to cancel the harmonic components generated by the load. The most commonly used APF configuration is the Shunt APF (SAPF) which injects current harmonics into the point of common coupling (PCC). Figure 3 illustrates the basic principle of SAPF.

3.2 Control Scheme of the SAPF

The SAPF control strategy is implemented in three basic stages: The first is the harmonic detection method to identify harmonic level in the system. The second part

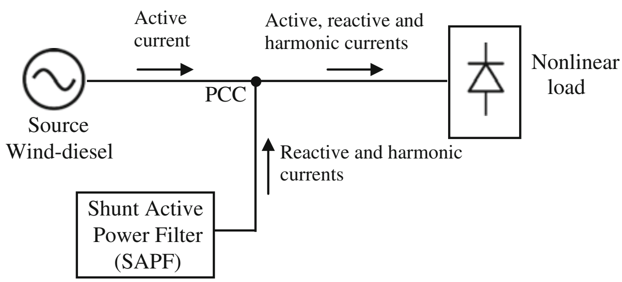


Fig. 3 Basic principle of a SAPF

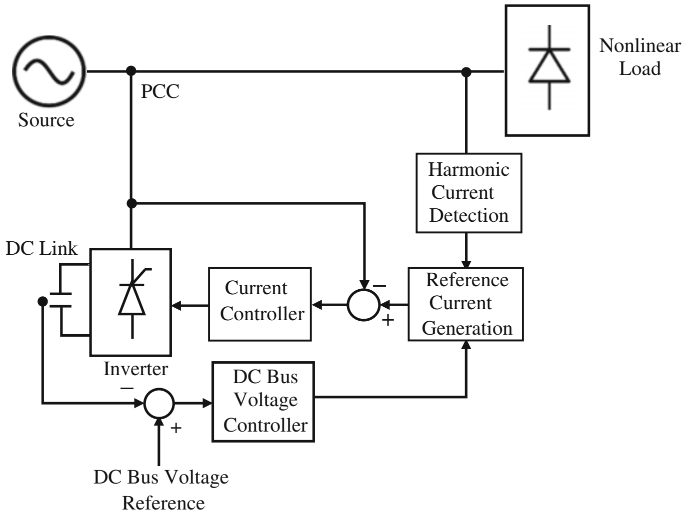


Fig. 4 SAFP control system implementation

is to derive the compensating currents and the third one is the control technique of the inverter for injecting these currents into the power system. The overall control system of the SAFP is depicted in Fig. 4.

There are different methods for generating the current reference for the shunt APF in he frequency domain. In this paper, the current reference for the active power filter is generated using the p-q theory.

3.2.1 p-q Control Strategy

This theory, derived in time-domain, also known as "instantaneous power theory" was proposed in 1983 by Akagi et al. [10, 15] to control APFs. It is based on instantaneous values in three-phase power systems with or without neutral wire, and is valid for steady-state or transitory operation, as well as for generic voltage and current power system waveforms allowing to control the APFs in real-time. Another important characteristic of this theory is the simplicity of the calculations, which involves only algebraic calculation.

This concept is based on the theory of instantaneous reactive power in the α-β reference frame. In this method, a set of voltages (v_a, v_b, v_c) and currents (i_a, i_b, i_c) from phase coordinates are first transferred to the α-β coordinates using Clark's transformation [12].

$$\begin{bmatrix} V_0 \\ V_\alpha \\ V_\beta \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \\ 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} V_1 \\ V_2 \\ V_3 \end{bmatrix} \tag{8}$$

$$\begin{bmatrix} I_0 \\ I_\alpha \\ I_\beta \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \\ 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} I_{s1} \\ I_{s2} \\ I_{s3} \end{bmatrix} \tag{9}$$

For simplicity, the zero-phase sequence component voltage and current signals are eliminated in (8) and (9). The instantaneous active power (p) and the instantaneous imaginary power (q) in a three-phase circuit are defined as:

$$\begin{bmatrix} p \\ q \end{bmatrix} = \begin{bmatrix} V_\alpha & V_\beta \\ -V_\beta & V_\alpha \end{bmatrix} \begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} \tag{10}$$

Writing p and q in the following form:

$$\begin{cases} p = \bar{p} + \tilde{p} \\ q = \bar{q} + \tilde{q} \end{cases} \tag{11}$$

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.

Using (10) load current in α-β frame can be calculated as:

$$\begin{bmatrix} i_{c\alpha} \\ i_{c\beta} \end{bmatrix} = \frac{1}{V_\alpha^2 + V_\beta^2} \begin{bmatrix} V_\alpha & -V_{s\beta} \\ V_\beta & V_{s\alpha} \end{bmatrix} \begin{bmatrix} p \\ q \end{bmatrix} \tag{12}$$

The compensating current signals in α-β frame can be transferred to a-b-c frame using inverse Clark's transformation as:

$$\begin{bmatrix} I_{ref1} \\ I_{ref2} \\ I_{ref3} \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & 0 \\ -1/2 & \sqrt{3/2} \\ -1/2 & -\sqrt{3/2} \end{bmatrix} \begin{bmatrix} \tilde{I}_\alpha \\ \tilde{I}_\beta \end{bmatrix} \tag{13}$$

This method does not take into account the zero sequence components, and hence, the effect of unbalanced voltages and currents. The instantaneous reactive power (p-q) theory is widely used for three-phase balanced non-linear loads, such as rectifiers [28].

3.2.2 DC Link Voltage Regulation with Fuzzy Type 2 Controller

Fuzzy Type 2 control is basically an adaptive and non-linear controller that gives robust performance for a linear or non-linear plant with parameter variations [18, 25]. Any given linear control can be achieved with a fuzzy controller for a given accuracy.

The capacitor that powers the active filter acts as voltage source and its voltage must be kept constant to ensure that the performance of the filter is maintained and the voltage fluctuations of the semi-conductors do not exceed the limits prescribed. The Interval Type 2 Fuzzy Logic Controller (IT2FLC) is implemented as shown in Fig. 5.

Type-2 fuzzy logic systems, are an extension of ordinary Type-1 fuzzy logic systems introduced by Zadeh (1975), are characterized by fuzzy membership functions represented by fuzzy sets in [0, 1]. Unlike a Type-1 fuzzy which have crisp membership functions, T2FLC consists of five components including fuzzifier, rule base, fuzzy inference mechanism, type-reducer and defuzzifier as depicted in Fig. 6.

In an IT2FLC at least some of the fuzzy sets used in the antecedent and/or consequent parts and each rule inference output are type-2 fuzzy sets. Generally speaking, in a T2FLC, the crisp inputs are first fuzzified, usually into Type-2 fuzzy sets. The fuzzified Type-2 fuzzy sets then activate the inference engine and rule base to yield output Type-2 fuzzy sets by performing the union and intersection operations of Type-2 fuzzy set and compositions of Type-2 relations. Then a type-reduction process is applied to these output sets in order to generate Type-1 fuzzy sets (called type-reduced sets) by combining these output sets and performing a centroid calculation. Finally, the type-reduced Type-1 set is defuzzified to produce crisp output [19, 26].

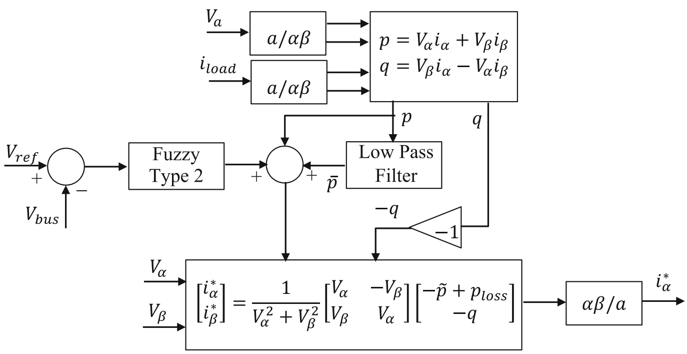


Fig. 5 Implementation of IT2FLC controller for the SAPF

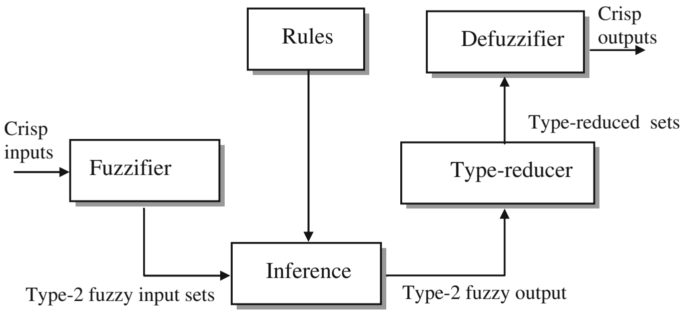


Fig. 6 Interval Type-2 fuzzy system (IT2FLS)

Table 1 Type 2 fuzzy control rules

de	e		
	N	EZ	P
N	N	N	EZ
EZ	N	EZ	P
P	EZ	P	P

A generalized rule for Type-2 fuzzy system is:

$$IF \quad x_1 \; is \; \bar{A}_{k1} \; and \; x_2 \; is \bar{A}_{k2} \; and \; \ldots \; and \; x_n \; is \; \bar{A}_{kn}$$

$$THEN \quad u_k = \sum_{i=1}^{n} p_{ik} x_i + b_k \tag{14}$$

where x_k and u_k are the input and output linguistic variables respectively; $\bar{A}_{ki}$ are Type-2 fuzzy sets for the kth rule and ith input; p_{ki} and b_k are consequent parameters of the rules which are Type-1 fuzzy sets.

The fuzzy controller inputs (DC bus voltage error (e) and change of error (de)) are implemented using Gaussian membership functions as shown in Fig. 7. The fuzzy labels are negative (N), environ zero (EZ), positive (P).

The control rules are given in Table 1.

4 Simulation Results

A series of simulation scenarios have been performed to evaluate the performance of the proposed control methods of the SAPF on the current harmonics under variable load and wind speed conditions. The parameters values used in the simulation are listed in the Appendix.

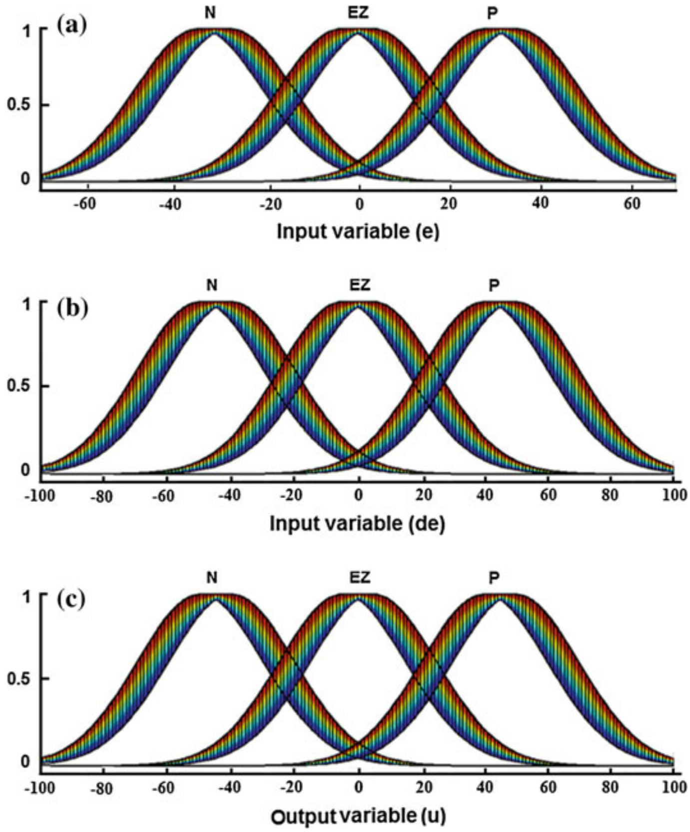


Fig. 7 The membership functions for **a** error and **b** change of error and **c** output (u)

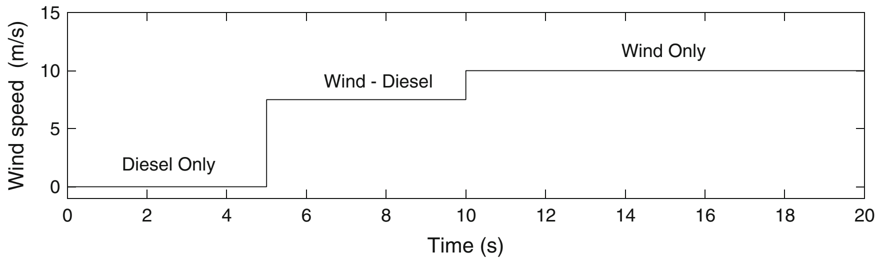


Fig. 8 Wind speed profile

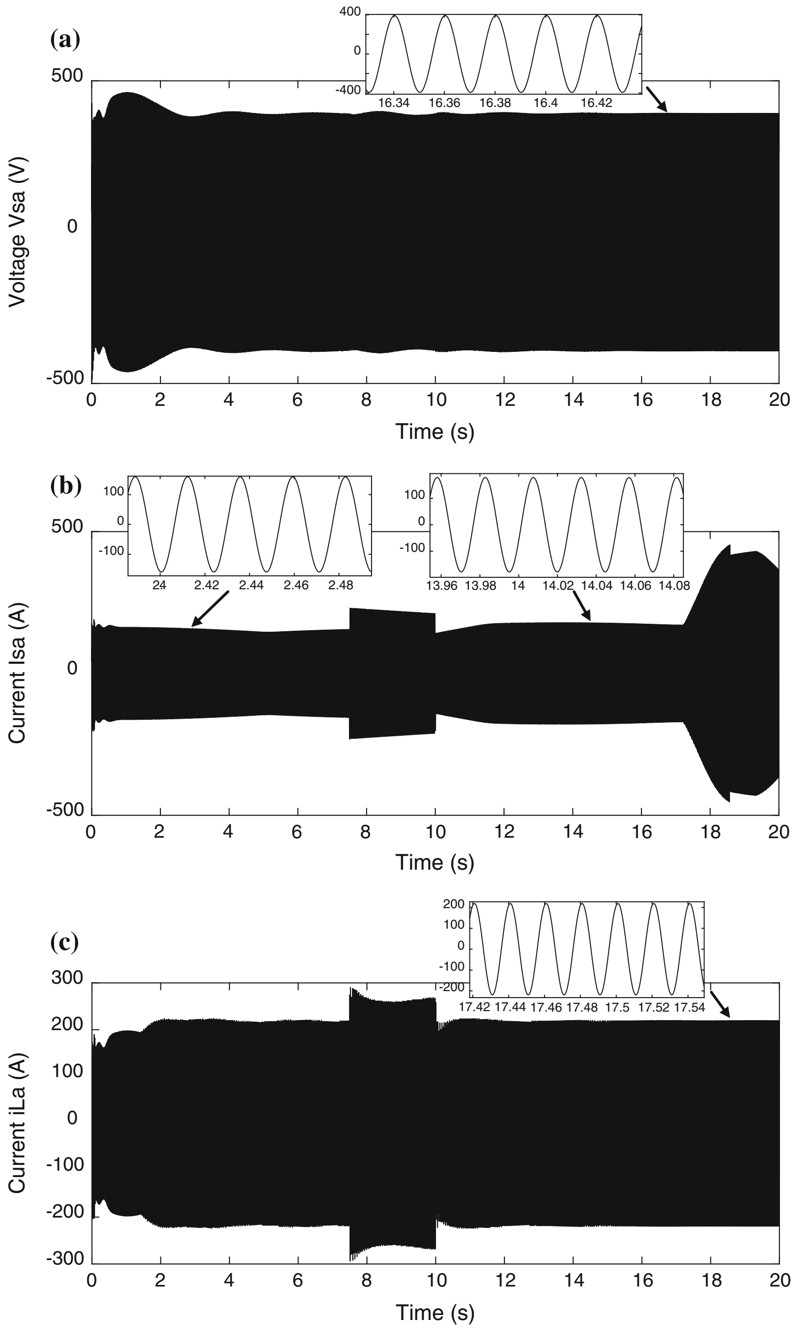
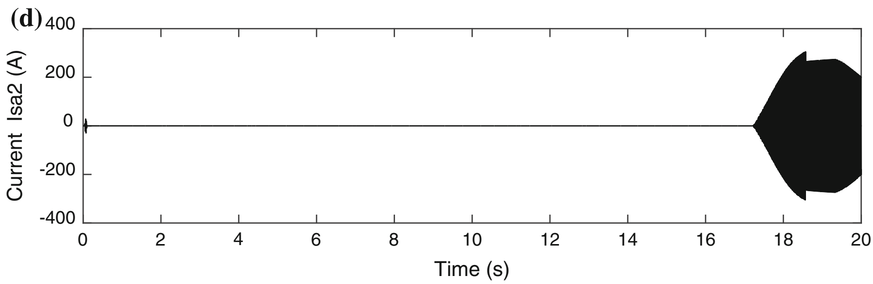


Fig. 9 Waveforms of **a** source voltage, **b** source current, **c** dump load current, **d** load current and **e** network frequency



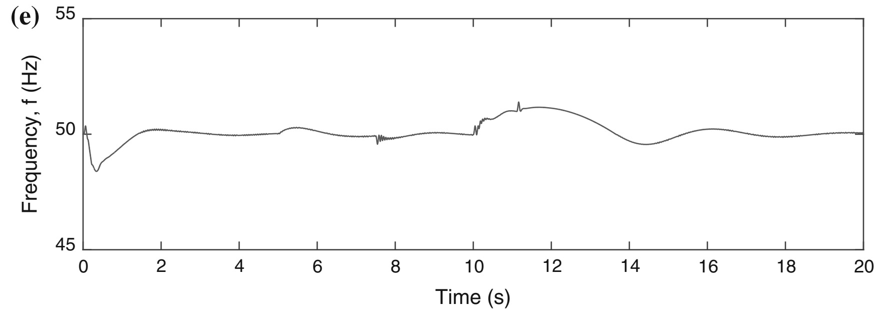


Fig. 9 (continued)

4.1 Linear Load

Initially, the overall wind-diesel power system is simulated with a linear load variation of 50 % applied at $t = 7$ and 10 s. The wind speed profile considered in this simulation is shown in Fig. 8.

The corresponding waveforms of the voltage source (v_{sa}), current source (i_{sa}), the main load current (i_{La}), the secondary load current (i_{sa2}) and the system frequency (f) are shown in Fig. 9.

It can be noted that in the case of linear load, the load current remains sinusoidal throughout the simulation time and the voltage and frequency are stable.

4.2 Nonlinear Load with SAPF and Fuzzy Type 2 Controller

Figure 10 shows the source voltage ($\boldsymbol{v_1}$), source current ($\boldsymbol{i_{sa1}}$), load current ($\boldsymbol{i_{ca}}$), filter current ($\boldsymbol{i_1}$) and the DC bus voltage ($\boldsymbol{V_{dc}}$) and Fig. 11 show the harmonic spectrum without and with the SAPF filter respectively.

The application of the APF with Fuzzy Type 2 control, has resulted in a reduction of the THD which has dropped from 28.53 to 1.9 %.

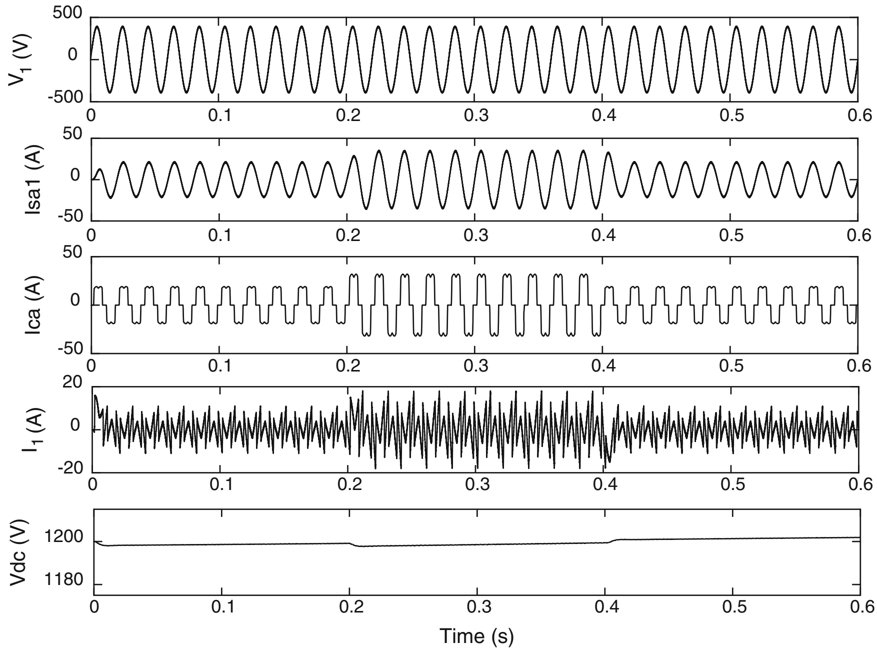


Fig. 10 Waveforms of the source voltage, source currents, load current, filter current and DC bus voltage (V_{dc})

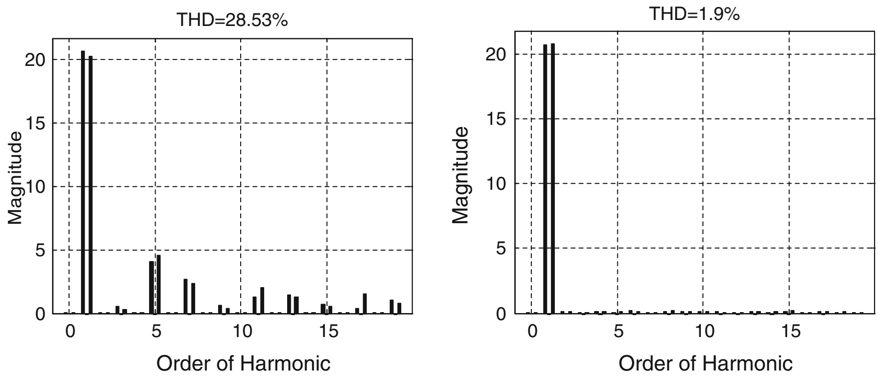


Fig. 11 Total harmonic distortion (THD) spectrum without and with APF

5 Conclusions

A control approach is presented for a three-phase shunt active power filter for the mitigation of harmonics introduced by nonlinear loads in an off-grid hybrid win-diesel power system. The control of the DC bus voltage of the shunt active power filter is based on Type-2 fuzzy systems. Improved dynamic current harmonics and reactive power compensation has been achieved.

The results show that with the proposed control scheme, the supply current waveforms were almost perfectly sinusoidal and in-phase with the supply voltage and the harmonic distortion achieved with the proposed controller (1.9 %) was well below the limit imposed by the IEEE-519-1992 recommendations of harmonic standard limits.

Appendix

Model parameters values used in the simulations.

System parameters	Values
Wind turbine (WT)	$P_n = 37\,\text{kW}, L_s = 0.087\,\Omega, V_n = 480\,\text{V}, R'_r = 0.228\,Omega,$ $f = 50\,\text{Hz}, L'_r = 0.8\,\text{mH}, L_m = 34.7\,\text{mH}, 2P = 4,$ $R_s = 0.087\,\Omega, J = 0.4\,\text{kg.m}^2$
Diesel generator (DG)	$S_n\ (kVA) = 37.5, X'_1 = 0.09, X_d = 3.23, T_{d0} = 4.4849,$ $X'_d = 0.21, T''_{d0} = 0.0681, X''_d = 0.15, T''_{q0} = 0.1,$ $X_q = 2.79, R_s(pu) = 0.017$
Consumer load	Mainload $= 100\,\text{kW}$ Nonlinearload $R_1 = 35\,\Omega, R_2 = 35\,\Omega, L = 10^{-3}H$
Active filter	$C = 2000\,\mu\text{F}, L_f = 3\,\text{mH}, V_{dc} = 1200\,\text{V}$

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