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# Control of an Isolated Microgrid Including Renewable Energy Resources

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**Abstract:** It is now more then a choice to use small-distributed generators (DGs) based on renewable energy resources (RES) due to their benefits in minimizing environmental problems and simplifying power system planning and operation. The integration of DGs in the main grid or in forming a standalone microgrid (MG) is increasing day by day and became as an alternative solution to large conventional central power stations and as a key for the electrification of rural areas. This paper presents an overall comparison of controlling the MG system combining between different DGs in islanded mode. Energy management system (EMS) applied is mainly an essential task to maintain an ideal flow of energy in-between generation and consumption, many are strategies to do so, the artificial intelligence (AI) (highlighted) is one of the most advantages methods to help sizing, optimizing, and power energy managing.

To solve this problem in this paper we present a Fuzzy Logic Control of isolated MG in comparison with a classic PI control system to see the different influences in maintaining stability in voltage and frequency output especially in the standalone application. The considered HRES combines a wind turbine (WT) and photovoltaic (PV) and an energy storage system (ESS). Simulation results obtained from MATLAB/Simulink environment demonstrates the effectiveness of the proposed intelligent artificial algorithm.

**Keywords:** Micro-Grid, Fuzzy logic controller, Renewable Energy Sources, Wind-PV-Battery System, PI classical controller, Voltage Source Inverter, Energy Management System.

## 1 Introduction

With increasing concern of global warming and the depletion of fossil fuel reserves, many are looking at sustainable energy solutions to preserve the earth

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for future generations [1]. The increased environmental concerns after the Kyoto Protocol and the Copenhagen summit have also led to the development of renewable technologies [2]. The hybrid renewable energy system (HRES) is the perfect solution for problems presented in conventional classic distributed generators (DG) due to their environmental concerns about gas emissions and the global climate change coming from it [3]. The integration of RES in the architecture of HRES (Fig. 1) is the key to better performance in production of energy for a complementary operation [4]. The unpredictable variation in sources and the intermittency are the main features that characterize RES. The presence of different DG units operate in parallel based on RES can provide a stable microgrid (MG) system responding to the consumption of power demand despite the variation parameters. Nowadays, many research studies are focusing in optimizing and controlling HRES and their applications in standalone functioning mode or grid-connected one. The integration of RES in different configurations can improve the reliability of the electrical power system presenting an enhanced quality of energy to the load with less dissipation-adding resiliency to the main power network.

Applications for MG in an isolated approach can be the ideal solution to supply power for rural areas located far away from the conventional electrical grid. In the literature, many studies showed an overview of MG related to rural electrification [5 – 7]. The use of one or multiple RES in one MG architecture demands an optimization and energy management algorithm to maintain sustainable energy production in any mode of operation [8 – 10].

An efficient control system has an important role to maintain a continuous supply of energy in all conditions, including when the MG integrate into the main grid to ensure stability in frequency and voltage values, responding to the peak load. Adding to that, the energy management system (EMS) takes many strategies in whom have proved their effectiveness in all situations. In the literature, we can find many numbers of studies reviewing different kinds of topologies, beginning with sizing and optimization, which allow us to understand the flow of energy from and to DG units. Hina and Palanisamy presented in their paper [11] an overview of various hybrid systems and many optimization methods and applications witch being employed in their operation. Similarly, Gamarra and Guerrero [12] reviewed optimization techniques applied to MG with computational sizing methods. In [3] Sinha and Chandel presented diverse methods for the design and development of solar photovoltaic wind hybrid system, an overview of sizing methodologies is showed. However, an EMS is well conducted in papers, Arul et al gives in their article [13] a review of standalone and grid-connected HRES, explaining the appropriate configuration and the interfacing power converters to the AC bus. Moreover in [14] Nejabatkhah and Wei showed the most EMS strategies in AC/DC MG with different coupling structures in both steady-state a process and transient circumstances. In [15] Das et al gives a control algorithm of power architecture for fuel cell (FC) in ESS. A comparison of FC technology with wind and solar technology discussed in this paper.

The previous paragraph presented several numbers of papers that addressed optimization sizing and EMS implemented and used. Besides addition, the literature includes many other papers that consider discussion for various aspects related to HRES [16 – 19].

Therefore, in this paper, we present a Fuzzy Logic Controller (FLC) of isolated HRES to maintain stability in voltage and frequency output in the standalone system. The HRES combines a wind turbine (WT) and photovoltaic (PV) panels as primary energy sources and an energy storage system (ESS) based on battery. Simulation results obtained from MATLAB/Simulink environment demonstrate the effectiveness of the proposed intelligent artificial algorithm (FLC).

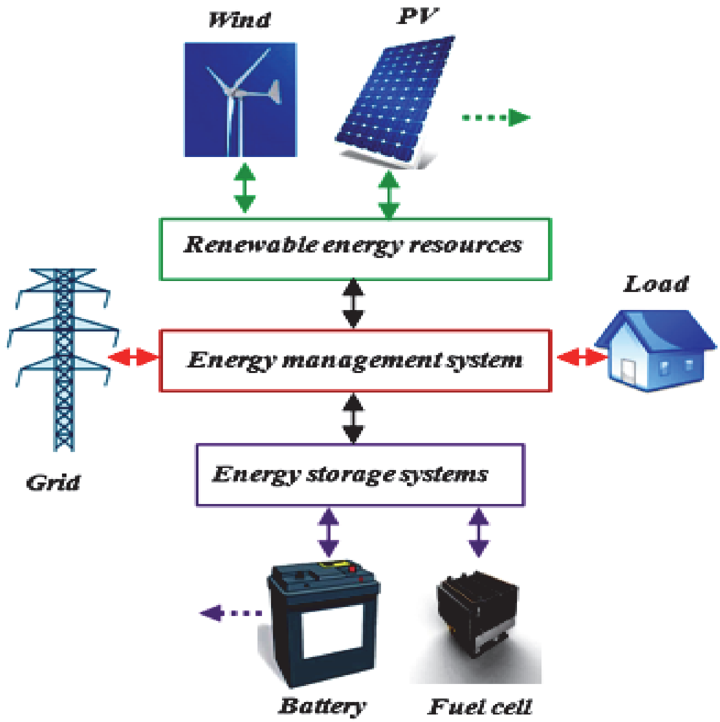


**Fig. 1** – *General configuration of HRES.*

## 2 Structure and optimization of Isolated Micro-grid

The cost of a configuration for HRES is higher than diesel engine generator of similar size, but the operating and maintenance costs are always lower than that for a diesel engine generator [11]. The lifetime of operation for different components of HRES is important to know to realize an optimization and sizing studies to minimize power generation cost and to maximize the useful life for DGs RES units with the application of the appropriate algorithm. An ESS is an important element in most configurations. It must be considered into account to guarantee a stable and efficient operation of the entire system [8, 20] and play as a backup source. The system configuration of the PV/wind hybrid power system studied in this paper shown in Fig. 2. The hybrid power system consists of a PV station of 10 kW rating, WT of 7 kW, and ESS of 9 kW. The system integrates voltage source inverter (VSI) via CC-bus to ensure continuous delivery of power generated from PV array and WT via AC-DC converter for improved system performance. The power in the output of VSI used to feed the load. The PV array is equipped with the DC/DC boost converter to step up an array output voltage. A battery controller used to maintain firstly the management power in the hybrid system by combining between the different sources of power production, the charge and discharge of the battery, and secondary the control of the DC/DC converter to maintain a desirable voltage DC-bus in the input of VSI.

In recent years, many studies have adopted artificial intelligence (AI) methods to ensure proper energy management system. Problems associated with developing a mathematical model for each DG unit make the AI the perfect tool to manage an EMS for HRES linked in control tasks. One of the control methods operates in terms of dispatching energy is the fuzzy logic controller (FLC). It is an efficient tool to deal with non-linear concepts, without the need for a mathematical projection model; with less sensitivity to variation in parameters then the conventional controllers do. FLC technique operate based on rules describing conditions among various inputs to establish certain objectives outputs. In [21] Hasanien et al proposed an FLC for standalone DG unit applied on voltage source converter (VSC). In this work, FLC is created to control voltage, doing a comparaison between voltage reference values with the actual load voltage signals. Inputs in this case are the error signal and the change of error, output signal generates pulses controlling the VSC. In [22] AlBadwawi and al isvestigated on FLC applied to control power flow in islanded AC microgrid, in this work FLC proposed to manage energy for a PV, and battery and micro gas turbine units, it is implemented to keep battery SOC in their limits. A second supervisory droop controller using bus frequency is activated in parallel with EMS, to accelerate rapid response for the auxiliary gas turbine unit when the frequency drooped from its nominal value.

Two FLC subsystems created in this contribution, first one responsible for preventing the battery from overcharging, where their inputs are $\Delta SOC1$ and $\Delta P$ charge, the second responsible for keeping the battery from over-discharging with $\Delta SOC2$ and $\Delta P$ discharge as inputs. Outputs are positive and a negative change in frequency respectively, causing the activation and non-activation of a gas turbine unit to produce power. Validation of results implemented via Matlab software environment and experimentally.

In this paper, we present a comparison study between a classic PI controller and FLC to maintain a constant frequency and sinusoidal AC voltage in AC load. The principle of the FLC, in this case, consists of generating three control signals for a pulse with modulation (PWM) of VSI. The energy management system (EMS) for HRES used to satisfy the load demand under variable weather conditions. It uses the power generated by wind and PV system to satisfy the load demand in this case the battery is in charging mode when the power required by the load is greater than power generation; the battery is starting to discharge.

In the simulation, we analyze under different power input scenarios the quality of active power delivered by HRES using both methods of control.

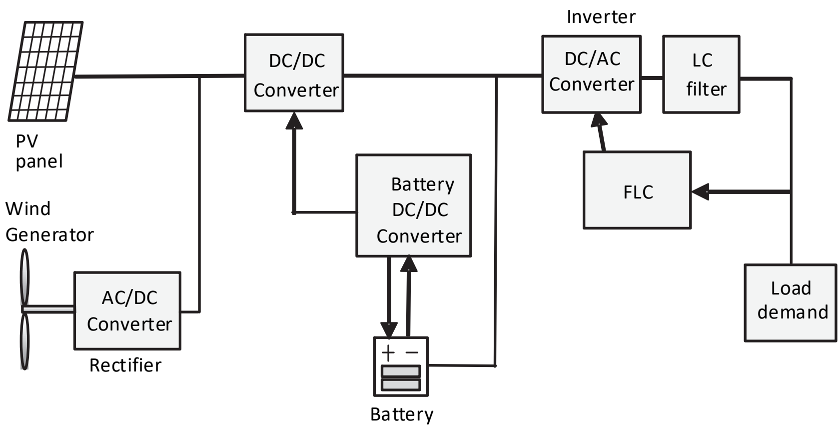


**Fig. 2** – *The system configuration of PV/wind hybrid power system.*

## 3 Modeling of the system

### 3.1 Modeling the wind system generator

Fig. 3 illustrates the configuration of the wind energy system. The wind generator consists of a wind turbine; coupled with a permanent magnet synchronous generator (PMSG). PMSG presents several advantages compared to other types of electric generators (e.g., good dynamic performance and high factor) [23].

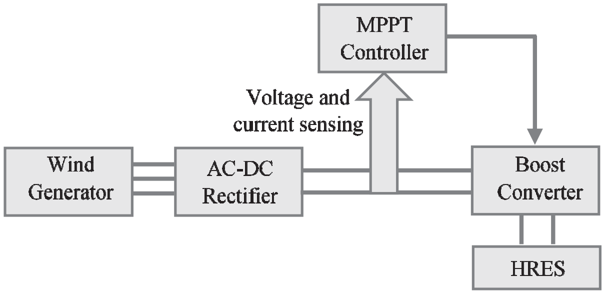


**Fig. 3** – *The configuration of wind energy system.*

To find the dynamical model for PMSG that would be useful to design the control scheme, the equations of PMSG are transformed to synchronous reference.

The stator flux could be stated as follows

$$\psi_d = L_d i_d + \psi_m, \quad \psi_q = L_q i_q, \tag{1}$$

where $\psi_m$ is the constant power corresponding to the excitation flux in the *d*-*q* reference.

The PMSG voltage equations are given by the following equations [24]:

$$v_d = R_S i_d + L_d \frac{\mathrm{d}i_d}{\mathrm{d}t} - \omega_r L_q i_q, \quad v_q = R_S i_q + L_q \frac{\mathrm{d}i_q}{\mathrm{d}t} + \omega_r L_d i_d + \omega\psi_m, \tag{2}$$

where $V_d$ and $V_q$ are respectively *d* axis and *q* axis voltages, $I_d$ and $I_q$ are respectively *d* axis and *q* axis currents, $L_d$, $L_q$, $R_s$ are respectively *d* axis and *q* axis inductance and resistance, and ω is generator speed.

The electromagnetic torque is given by:

$$C_{em} = \frac{3p}{2}\left(\psi_v i_q + \left(L_d - L_q\right) i_d i_q\right), \tag{3}$$

and the mechanical dynamic equation is:

$$T_{em} - T_l = J\frac{\mathrm{d}\Omega}{\mathrm{d}t} + f_v \Omega, \tag{4}$$

where $J$ is rotor inertia, $f_v$ is friction constant, and $T_l$ is the torque produced by wind turbine.

Concerning the wind turbine, in this paper we use a one with horizontal axis drove directly the PMSG, the wind turbine converts the wind power into mechanical power using producing torque shown in Fig. 4.

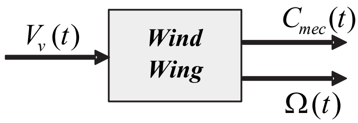


**Fig. 4** – *Model of the wing.*

The wind power developed by the turbine is given in [25, 26].

$$P_{wt} = \frac{\rho S V^3 C_p}{2}, \tag{5}$$

where $C_p$ is a performance coefficient of WT, $V$ is wind speed, ρ and $S$ are the air density in kg/m$^3$, and the WT swept the area in m$^2$, respectively.

The tip speed ratio is defined as the ratio of turbine blade linear speed and the wind speed, is written as follows:

$$\lambda = \frac{\Omega R}{V}, \tag{6}$$

where $R$ is the radius of the wind turbine rotor.

Substituting (6) in (5), we have:

$$P_w = \frac{1}{2} C_p(\lambda) \rho S \left(\frac{V}{\lambda}\right)^3 \Omega^3. \tag{7}$$

The torque of the wind turbine is calculated by:

$$P_w = \frac{1}{2} C_p \rho S \left(\frac{V}{\lambda}\right). \tag{8}$$

The power coefficient $C_p$ has a maximum of 0.59, this theoretical limit called Betz limit which determines the maximum extractable power for a given wind speed.

### 3.2 Modeling the PV generator

A solar cell is a PN junction diode operated in reverse biased condition. The electromagnetic radiation of solar energy breaks the covalent bond and produce free electrons that produce photovoltaic current $I_{pv}$, when external voltage $V_{pv}$, is applied [27].

The general mathematical model for the solar cell studied over the past three decades. Sun irradiances, solar cellule temperature, and the zone of implementation are the factors, which affect the production of electric energy extracted from PV panels. In our study, we consider a single diode model [28].

The characteristic (*V-I*) of a photovoltaic module is a nonlinear and depends on solar radiation and cell temperature. The output voltage-current relationship is nonlinear relationship governed by the next equation [29]:

$$I_{pv} = I_{ph} - I_0 \left\{ \exp\left( \frac{q(V_{pv} + R_s I)}{aV_t} \right) - 1 \right\} - \frac{V_{pv} + R_s I}{R_p} \ , \tag{9}$$

where $R_S$ and $R_p$ are equivalent series/ parallel resistance of PV panel, $I_{ph}$ and $I_d$ are respectively the photocurrent and the junction diode current, $I_0$ is the reverse saturation current, $V_t = N_s kT/q$ is the thermal voltage of the array with $N_S$ cells connected in series, *a* is the diode constant, *k* is the Boltzmann's constant, *T* is temperature of the p-n junction, and *q* is electron charge.

### 3.3 Battery storage and controller of DC/DC converter

The mathematical modeling of the Li-Ion battery bank used in the simulation program is been introduced in this partition. The open voltage source is calculated with a non- linear equation based on the actual SOC of the battery as follows [30]:

$$V_{batt} = E_{batt} - RI. \tag{10}$$

The controlled voltage source is described by (11)

$$E_{batt} = E_0 - K\frac{Q}{Q - it} + A\exp(-bit)\ , \tag{11}$$

where $E$ is no-load voltage, $E_0$ is Battery constant voltage, $K$ is polarisation voltage, $V_{batt}$ is battery voltage, $Q$ is battery capacity, $I$ is actual battery charge, $A$ is exponential zone amplitude, $B$ is exponential zone time constant inverse and $R$ is internal resistance.

The charging and discharging efficiency are nonlinear functions of current and state of charge (SOC). The SOC defined as the percentage of the remaining capacity of a battery. SOC can be expressed by the equation below [31].

$$SOC = \frac{Q}{Q_{rated}} \times 100\%\ , \tag{12}$$

where, $Q$ and $Q_{rated}$ are remaining capacity and the rated capacity of the battery respectively, both in ampere-hour (Ah). In order to optimize the battery charge and discharge state during the energy conversion and increase its lifetime.

In this proposed control strategy, Battery controller plays the main role in regulating DC bus voltage through a DC/DC bidirectional converter works in a buck mode to charge the battery when the power is in excess mode and in a boost mode to discharge it to fill up the gap of power deficiency.

This indirectly manages the energy exchange between the power generation and battery storage. The control of the bidirectional converter and the battery storage system is achieved by using a PI controller [31].

### 3.4 PEM electrolyzer unit

A typical PEM electrolyzer is modeled according to experimental test results concerning the efficiency at specific power levels [32]. The efficiency curve of the electrolyzer unit considered linear. This was decided for the simplicity of the model since this is very close to real-world electrolyzer performance according to their manufacturers.

$$P_{el} = OP_{el} P_{elN}, \tag{13}$$

$$EFF_{el} = \left( A_{el} OP_{el} \right) + B_{el}, \tag{14}$$

$$H_{prod} = \left( \frac{P_{el} EFF_{el}}{LHV_{h2}} \right) PTS, \tag{15}$$

where $P_{el}$ is power consumed by the electrolyzer unit, $OP_{el}$ is fractional operation point of the electrolyzer unit, $P_{elN}$ is nominal power of the electrolyzer unit, $EFF_{el}$ is efficiency of the electrolyzer unit for the given time step, $A_{el}$ is slope of the linear equation of the efficiency (this determined by linear curve fitting to the performance data supplied by the manufacturer of the electrolyzer unit), $B_{el}$ is the $y$-axis intercept of the linear equation of the efficiency (this determined by linear curve fitting to the performance data supplied by the manufacturer of the electrolyzer unit), $H_{prod}$ is Hydrogen produced by the electrolyzer unit, $LHV_{h2}$ is lower heating value of Hydrogen, and $PTS$ is the parameter for calculating energy from power for a given time step. For a simulation time step equal to 1 h this parameter equals to 1.

## 4 Controller for the DC/AC VSI

The architecture of the fuzzy logic controller (FLC) applied in this study is shown in Fig. 5. The two blocks are used to define the FLC controller.

### 4.1 Fuzzification block

The fuzzification process is mapping the crisp value of input to linguistic variables using membership functions. Here inputs to fuzzification block are: The error $e(k)$ between the measured phase voltage and reference voltage ($V_{ref}$) and change of error $de(k)$ at sampling instant $k$. The output is the switching sequence of the VSI on PWM technique based on FLC mode to ensure voltage amplitude in sine waveform (Fig. 5).

$$e(k) = V_{ref} - V_m(k)\,, \tag{16}$$

$$de(k) = e(k) - e(k-1)\,. \tag{17}$$

The output membership functions of error and change error are identical. The load voltage may be positive or negative, then seven levels are considered: NL (Negative Large), NM (Negative Medium), NS (Negative small), Z (Zero), PS (Positive Small), PM (Positive Medium), PL (Positive Large), have been chosen for inputs variables ($e(k)$, $de(k)$) and the output variable $V$ for PWM of VSI.

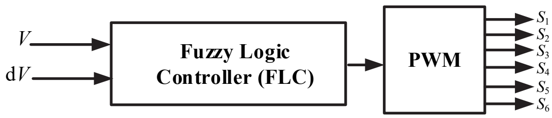


**Fig. 5** – *Input and output for the FLC.*

### 4.2 Fuzzy inference system and defuzzification

Fuzzy rules are formulated using Mamdani-type fuzzy rule which comprises “IF/THEN” conditional statements. In this paper, 49 (7_7 D 49) rules are formulated using “IF/THEN” statements with the membership functions of two input variables and one output variable which are tabulated in **Table 1**. The range for input and output variable is set between [–1 1]. In this paper, the impact of parameter $de(k)$ in the function of FLC formulation is studied on a variation of energy production from different generators in the MG. the FLC technique compared to the classical PI controller in which the results and discussion showed in Section 5. Control surface of the FLC is given in Fig. 6, the range for input and output variable is set between [–1 1]. The FLC rules for error and change of error referred to in **Table 1**.

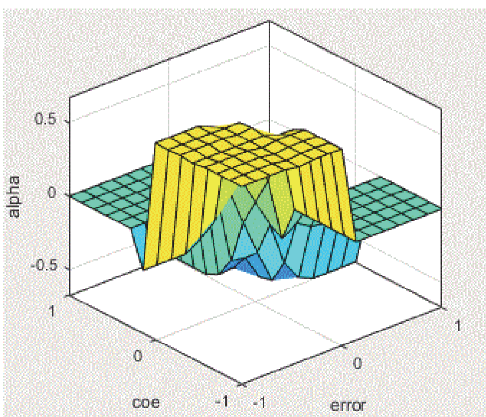


**Fig. 6** – *Control surface for the FLC.*

**Table 1**
*Rules for FLC.*

| Inputs | NL | NM | NS | Z | PS | PM | PL |
|---|---|---|---|---|---|---|---|
| NL | PL | PL | PL | PL | Z | Z | Z |
| NM | PL | PL | PM | PM | Z | Z | Z |
| NS | PL | PL | PS | PS | NM | NS | NM |
| Z | PL | PM | PS | Z | NS | NM | NL |
| PS | NM | PS | PS | NS | NS | NL | NL |
| PM | Z | Z | Z | NM | NM | NL | NL |
| PL | Z | Z | Z | NL | NL | NL | NL |

## 5 Simulation and Results

Results (showed in next figures) of the proposed HRES model was effected using Simulink environment by MATLAB software. They used to demonstrate the effectiveness of the proposed to FLC in order to maintain stability in voltage and frequency output compared to a classic PI controller.

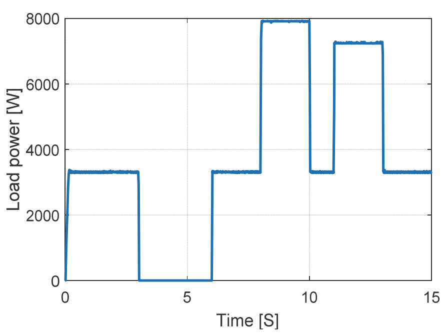


**Fig. 7** – *Load demand.*

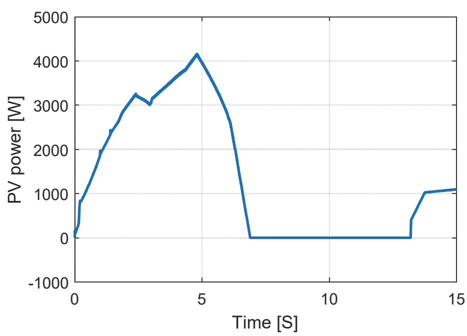


**Fig. 8** – *Solar power.*

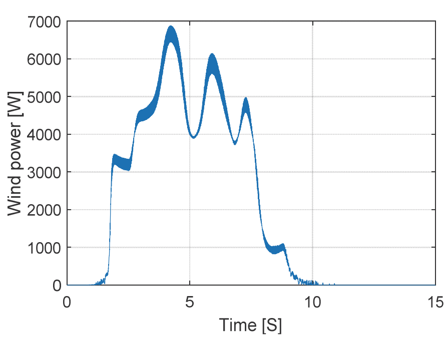


**Fig. 9** – *Wind power.*

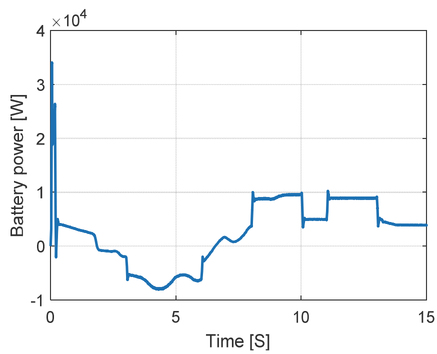


**Fig. 10** – *Battery power.*

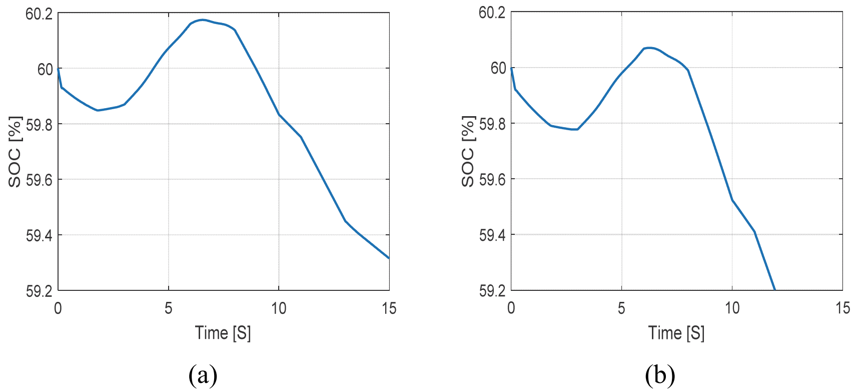


**Fig. 11 –** *SOC of battery:* (a) *FLC;* (b) *PI controller.*

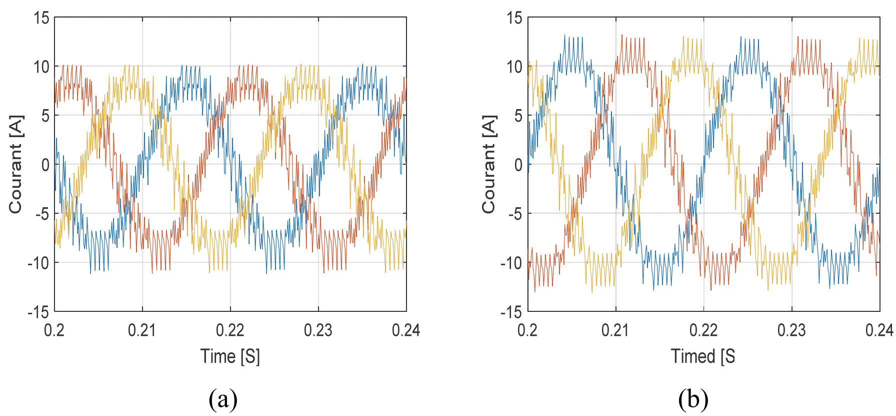


**Fig. 12 –** *Load currents:* (a) *FLC;* (b) *PI controller.*

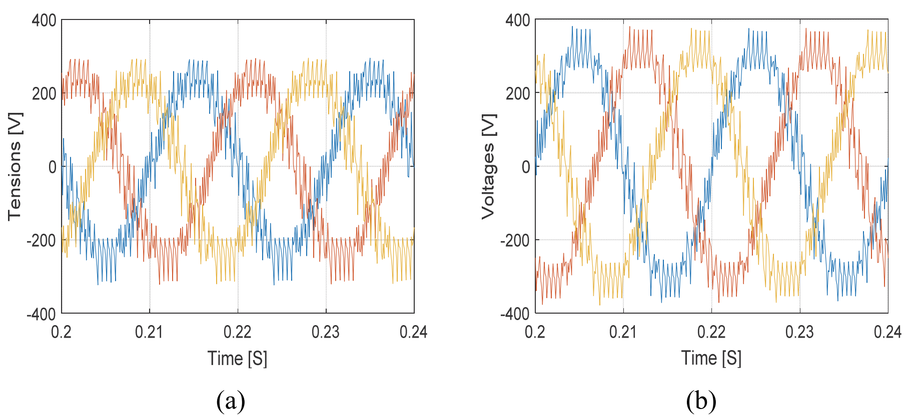


**Fig. 13 –** *Load voltages:* a) *FLC;* b) *PI controller.*

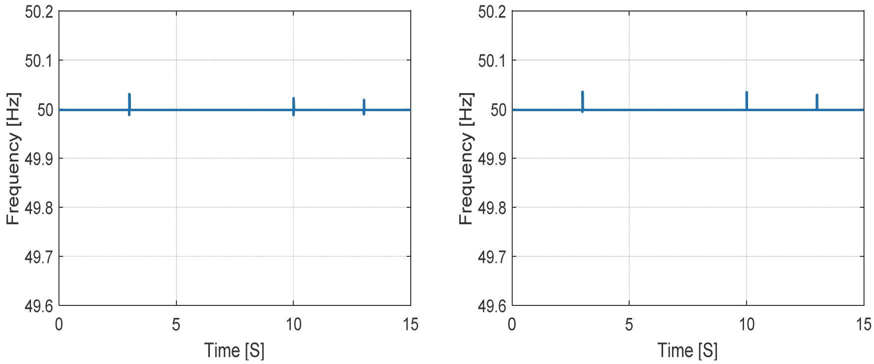


**Fig. 14** – *Load frequency.*

The powers of HRES is given by:

$$P_l = P_w + P_{pv} + P_{bat} \ , \tag{17}$$

where $P_{pv}$ is solar power, $P_w$ is wind power, $P_{bat}$ is battery power and $P_L$ represent power of load demand.

- Between 0 and 3s, power demand by the load is about 3.3 kW (Fig. 7), the response to this demand is assured by the sufficient production of power from PV panel (Fig. 8) and the wind generator (Fig. 9).
- Between 3 and 6s, we notice that there is no load demand for power in this period. However, the production of renewable energy is directly going to be a part of the charging operation mode for the battery, adding power to that already recorded in the previous period with the excess of energy production (Fig. 10).
- Between 6 and 15s, with the increase in power demand reaching 8 kW (Fig. 7) in the tenth second. The battery enters the discharge operation mode to meet the demand of power, with completely been the only source of energy in the system, in the case where the renewable sources are absent totally from generating power from 10 to 13 seconds (Figs. 8 and 9).
- From Fig. 12 (SOC of the battery), in the same scenario and conditions, the charge of the battery is more meaningful for the FLC compared to the PI controller with a rapid discharge operation.
- The voltages and currents of the load are in sinusoidal forms are shown in Figs. 12a – 13b. In can be seen that the FLC maintain the waves more in shape compared to the classic PI controller do, with a lot of harmonics and passages on margin in values as illustrated in the Figs. 12b and 13b.

The two controllers maintain the frequency of the system stable in a presence of wind and PV power fluctuations (Fig. 14), with a little advantage for the FLC with less sensitivity to variations.

From these simulation results, we remark a good tracking performance for proposed FLC and good management of power compared to the classic PI controller.

## 6 Conclusion

Electrical energy generation systems based on renewable energies known for their fluctuation as regards the production of electrical energy. The addition of an electrical energy backup system is essential to remedy this problem. For such hybrid generation systems, control strategies need to develop to dispatch power. Therefore, control of Wind/PV/Battery system using FLC proposed in this paper compared to a PI classic controller. Simulation for different scenarios under variable weather conditions presented, the designed FLC controller tracks better the reference generated.

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