Fuzzy Logic Control Strategy for a Hybrid RES (PV/Lithium Battery) Feeding an off-grid Pumping Station

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Received: 03.01.2021 Accepted: 24.01.2021

Abstract- This paper presents a developed control strategy for a Hybrid Renewable Energy Source (HRES) feeding an off-grid pumping station. The HRES, composed of a PV generator and a Lithium Battery, is feeding the pumping station through a DC voltage bus. The control strategy is a centralized Energy management System (EMS) which is composed by a speed controller for the pumping system, MPPT controller for the PV generator, Charging/Discharging controller for the battery and an energy dispatching supervisor which is responsible of managing the energy flow between different parts of the system efficiently in order to realize economic profits by reducing energy production cost. This is done by exploiting the maximum possible of available PV energy. The proposed system configuration and different controllers are tested and evaluated by simulation under Matlab-Simulink environment in different weather conditions.

Keywords- Hybrid Renewable Energy Source; Pumping Station; Control Strategy; Energy Management System; Matlab-Simulink Environment.

1. Introduction

Despite the advantages presented by PV pumping systems (PVPPSs), different problems caused by the high dependence of photovoltaic (PV) power generation on solar radiation availability make it impossible to guarantee continuous water pumping [1]. Thus, researchers proposed several solutions based on hybrid configurations to surmount these problems. Among the proposed solutions, the use of Energy Storage Systems (ESS) as a second source in a traditional PVPPSs is a very efficient way allowing the storage of the PV energy whenever the available PV power exceeds the load demand in order to reuse it whenever the load demand exceeds the available PV power [2-5]. Energy storage can be realized under different forms such as electrochemical form that can be done thanks to the batteries. Many studies recommend using Lithium batteries for RESs applications thanks to their high performance and lifetime [6,7]. This type of batteries is characterized by a higher specific power and specific energy compared to traditional batteries.

In order to manage the energy flow in HRESs, the use of an Energy Management Strategy (EMS) is essential especially in standalone systems [8-11]. Many classical techniques have been used in developing EMSs, besides, new methods based on Artificial Intelligence such as (AI) techniques such as Artificial Neural Networks (ANN), Fuzzy Logic (FL) and Genetic Algorithms (GA) have been integrated in control solutions of RESs [12-15]. FL technique, the simplest method among the previously cited ones, has been proved as very reliable in energy management and optimization of such complex systems like hybrid RESs thanks to its computational efficiency and robustness in modeling uncertainties. [16, 17]

This Paper is organized as follows:

Section 2 presents the global configuration of the studied system and the models of its different parts.

Section 3 presents the developed speed controller for the pumping system and the developed MPPT controllers for the PV generator and the Lithium battery. The obtained results of the different Simulations that have been carried out to test the efficiency of each controller are also presented in this section.

Section 4 presents the working principle and the design process of the developed EMS using the Fuzzy Logic
technique. At the end of this section, the obtained results of the realized simulations under different weather conditions to test the efficiency of the developed EMS are presented.

2. System Configuration and Modeling

The studied system is composed of a PV generator, a lithium battery, and a pumping station. These different parts are connected to a DC voltage bus via 3 static converters as shown in Fig. 1.

![System configuration diagram](image)

**Fig. 1.** System configuration.

2.1. PV Generator

Figure 2 shows the configuration of the PV generator used in this study which is composed of a 2 PV strings mounted in parallel where each one is composed of 5 PV Kaneka GSA-60 modules mounted in series [18].

![PV generator diagram](image)

**Fig. 2.** Studied PV generator.

Table 1 shows the different characteristics of the PV generator and Fig.3 shows the P-V and I-V characteristic curves of its model under variable solar irradiance.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rated Power</td>
<td>600 W</td>
</tr>
<tr>
<td>$V_{OC}$</td>
<td>460 V</td>
</tr>
<tr>
<td>$I_{SC}$</td>
<td>2.38 A</td>
</tr>
<tr>
<td>$V_{MPP}$</td>
<td>335 V</td>
</tr>
<tr>
<td>$I_{MPP}$</td>
<td>1.8 A</td>
</tr>
</tbody>
</table>

**Table 1. Model parameters of the PV generator**

![P-V and I-V curves](image)

**Fig. 3.** Characteristics of the 600W PV array under variable irradiance.
2.2. Lithium Battery

Figure 4 shows the equivalent circuit (EC) model used to describe the Lithium battery behaviour and the discharge voltage of the battery is given by Eq. (1) [19].

\[ V_{\text{batt}} = V_{\text{OC}} - V_{R_0} = V_{\text{OC}} - R_0 I_{\text{batt}} \quad (1) \]

Table 2 shows the different characteristics of the battery that has been chosen for this study and Fig. 5 shows its discharging characteristics with different current values.

**Table 2.** Model parameters of the Lithium Battery

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Capacity</td>
<td>6.5 AH</td>
</tr>
<tr>
<td>Nominal Voltage</td>
<td>240 V</td>
</tr>
<tr>
<td>Max Continuous Discharge Current</td>
<td>25 A</td>
</tr>
<tr>
<td>Max Charging Voltage</td>
<td>260 V</td>
</tr>
<tr>
<td>Low Cut-off Voltage</td>
<td>165 V</td>
</tr>
<tr>
<td>Nominal Discharge Current</td>
<td>2.8261 A</td>
</tr>
<tr>
<td>Life Cycles</td>
<td>3000 – 5000</td>
</tr>
</tbody>
</table>

2.3. Pumping Station

The pumping system used in this work (Fig. 6) is composed of a 3 phased inverter used to convert DC voltage into controllable AC voltage, an induction motor, and a centrifugal pump. Different characteristics of the pumping system are presented in Table 3 and the mathematical model given by equations (2-6) is used to develop the simulation model [20].

**Fig. 4.** EC model of the Lithium battery.

**Fig. 5.** Discharge characteristic curve.

**Fig. 6.** Studied pumping system configuration

The line-to-neutral voltages at the inverter output can be expressed as in Eq. (2).

\[
\begin{align*}
V_1 &= \frac{V_{\text{dc}}}{3} (2S_{1\text{ref}} - S_{2\text{ref}} - S_{3\text{ref}}) \\
V_2 &= \frac{V_{\text{dc}}}{3} (2S_{2\text{ref}} - S_{1\text{ref}} - S_{3\text{ref}}) \\
V_3 &= \frac{V_{\text{dc}}}{3} (2S_{3\text{ref}} - S_{1\text{ref}} - S_{2\text{ref}})
\end{align*}
\]
Conversely, the DC current at the input of the inverter is expressed as a function of the line currents and the conduction states as represented in Eq. (3).

\[ I_{DC} = S_{1ref}I_a + S_{2ref}I_b + S_{3ref}I_c \quad (3) \]

Where:

- \( S_{iref} \) is the control signal corresponding to the \( K_i \) switch (With \( i=1,2,3 \))

S.t:

- \( S_{iref}=0 \) in order to open the \( K_i \) switch and close the \( K'_i \).
- \( S_{iref}=1 \) in order to close the \( K_i \) switch and open the \( K'_i \).

\[
\begin{align*}
V_{s1} &= R_sI_{s1} + \frac{d\phi_{s1}}{dt} \\
V_{s2} &= R_sI_{s2} + \frac{d\phi_{s2}}{dt} \\
V_{s3} &= R_sI_{s3} + \frac{d\phi_{s3}}{dt} \\
V_{r1} &= R_rI_{r1} + \frac{d\phi_{r1}}{dt} \\
V_{r2} &= R_rI_{r2} + \frac{d\phi_{r2}}{dt} \\
V_{r3} &= R_rI_{r3} + \frac{d\phi_{r3}}{dt}
\end{align*}
\quad (4)
\]

\[
\begin{align*}
\frac{d\omega_r}{dt} &= \frac{p}{J}C_{em} - \frac{p}{J}C_r - \frac{f}{J}\omega_r \\
\end{align*}
\quad (6)
\]

Where \( \phi \) is the total flux through the corresponding winding.

The mechanical model becomes Eq. (6):

3. Proposed Energy Management Strategy:

The developed EMS for this system is composed by several local controllers each one is used to control a specific part of the system and a supervisor used to coordinate between these parts based on the different measurements received from the system.

3.1. Working principle

Figure 7 shows the working principle of the developed EMS where the different measurements are:

- Available PV power
- Available energy on the storage device (SOC)
- Voltage measurement of the DC Bus.
- The rotational speed of the asynchronous machine

Table 3. Parameters of the pumping system

<table>
<thead>
<tr>
<th>Inverter</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum Power</td>
<td>2.2 KW</td>
</tr>
<tr>
<td>AC input</td>
<td>230 V</td>
</tr>
<tr>
<td>DC Input</td>
<td>400 V</td>
</tr>
<tr>
<td>Output Voltage</td>
<td>3 ~ 230 V</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Asynchronous Moto-Pump</th>
</tr>
</thead>
</table>

<table>
<thead>
<tr>
<th>Power</th>
<th>3 Hp = 0.37 Kw</th>
</tr>
</thead>
<tbody>
<tr>
<td>Voltage</td>
<td>3~ 240V</td>
</tr>
<tr>
<td>Nominal Current</td>
<td>1.8A</td>
</tr>
<tr>
<td>Frequency</td>
<td>50 Hz</td>
</tr>
<tr>
<td>P</td>
<td>1</td>
</tr>
<tr>
<td>Cos ( \rho )</td>
<td>0.8</td>
</tr>
<tr>
<td>Maximum Speed</td>
<td>2850 rpm = 300 rad/s</td>
</tr>
<tr>
<td>Maximum Flow rate</td>
<td>36.5 L/min</td>
</tr>
</tbody>
</table>
Using these different inputs, the controllers are developed in order to maintain an optimized working performance of the overall system.

The EMS is composed of 4 controllers which are:

- PV controller: an algorithm used to generate the control signals of the DC-DC converter connected to the PV generator.
- Battery controller: an algorithm used to generate the control signals of the Bidirectional DC-DC converter connected to the Battery.
- Speed controller: an algorithm used to generate the control signals of the voltage inverter to control the rotational speed of the moto-pump.
- Energy dispatching controller: an algorithm used to control the energy flow from and to the battery.

### 3.2. PV Control

In order to force the PVG to work at its Maximum Power Point (MPP), a Fuzzy Logic controller is used to continuously determine the D value, which is the duty cycle used to control the switch (S) state (1/0) of the DC-DC converter mounted between the PVG and the DC voltage bus. The converter used in this MPP Tracking (MPPT) system is a Boost one. The classical EC model of this type of converters is presented in Fig. 8 and the relation between the input voltage (Vi) and the output voltage (VO) is given by Eq. (7): [21]

\[
V_O = \frac{V_I}{1-D} \tag{7}
\]

Figure 9 presents the working principle of the FL controller developed for this MPPT system where two input variables, given by Eq. (8-9), are used to determine the duty cycle. [21]

\[
E(k) = \frac{P_{pv}(k) - P_{pv}(k-1)}{V_{pv}(k) - V_{pv}(k-1)} \tag{8}
\]

\[
dE = E(k) - E(k - 1) \tag{9}
\]

### 3.3. Battery Control

The Charging/Discharging process of the battery is achieved by voltage regulation at the battery level and the DC voltage bus according to the corresponding mode (Charge or Discharge). This done using a bidirectional DC-DC Buck-Boost converter mounted between the battery and the DC voltage bus. The equivalent circuit of this converter is shown in Fig. 10.
Where \( V_L \) is the low voltage side situated at the battery side and \( V_H \) is the high voltage side situated at the DC voltage bus side.

PI control technique is used to regulate the voltage flow from one side to another as follows:

- For charging process, the energy flows from the DC voltage side to the battery side and the converter works as a Buck converter. Equation (10) shows the \( D_{S1} \) and \( D_{S2} \) expressions which represents the duty cycles (generated by PI controller) of the converter’s switches S1 and S2 respectively.

\[
\begin{align*}
D_{S1} &= 0 \\
D_{S2} &= K_p[V_{\text{battery-ref}} - V_{\text{battery}}] + K_i \int [V_{\text{battery-ref}} - V_{\text{battery}}] dt
\end{align*}
\]

(10)

- For the discharging process, the energy flows from the battery side to the DC voltage side and the converter works as a Boost converter. Equation (11) shows the \( D_{S1} \) and \( D_{S2} \) expressions which represents the duty cycles (generated by PI controller) of the converter’s switches S1 and S2 respectively.

\[
\begin{align*}
D_{S1} &= K_p[V_{\text{bus-ref}} - V_{\text{bus}}] + K_i \int [V_{\text{bus-ref}} - V_{\text{bus}}] dt \\
D_{S2} &= 0
\end{align*}
\]

(11)

3.4. Speed control of the AMP

In order to achieve an efficient speed control of the AMP, a hybrid FL-IFOC control system is developed. This control system is composed of three main controllers working in a cascaded way as follows:

- First Controller: is a Fuzzy Logic (FL) speed controller and its working principle is given by Fig. 11 where the two inputs speed error (E) and its variation \( dE \) given by Eq.(12) and Eq.(13) respectively, are used to calculate the Torque reference.

\[
\begin{align*}
E(k) &= \Omega^* - \Omega \\
dE &= E(k) - E(k - 1)
\end{align*}
\]

(12)

(13)

- Second Controller: is an Indirect Field Oriented Controller (IFOC) and its working principle is given by Fig. 12 where the current measurements and the torque reference generated by the previous controller are used to determine the 3 current references that will be used by the last controller.

\[
S_i = \begin{cases} 
1 & \text{if } I_i^* - I_i > \Delta i \\
0 & \text{if } I_i^* - I_i < \Delta i \\
K_{i-1} & \text{if } I_i^* - I_i = \Delta i 
\end{cases}
\]

(14)

With:

- \( I_i \) (i = a, b, c) are the measured currents of the stator phases.
- \( I_i^* \) (i = a, b, c) are the reference currents generated by the controller.
- \( \Delta i \) is the hysteresis band.

3.5. Energy Dispatching

The energy dispatching controller is developed in a way that ensures to control the energy flow from and to the battery in order to guarantee a maximum utilization of the available PV energy.

This controller works on two steps, the first step consists in calculating the difference between the total power demand and the available PV power as shown in Fig.13.
Where:
- $P^*$ is the electrical power needed of the AMP which is determined according to speed reference using Eq. (15):

$$P^* = \frac{1.38 \times 10^{-5} (\Omega^*)^3}{0.8} \times 1.5 \quad (15)$$

- $P_{\text{needed}}$ is the difference between the available PV power and the AMP power reference given by Eq. (15) and it is calculated using Eq. (16):

$$P_{\text{needed}} = P^* - P_{\text{PV}} \quad (16)$$

The second step consists in calculating the power reference for the battery system using two input variables which are the $P_{\text{needed}}$ previously calculated at the previous step and the State Of Charge (SOC) of the battery. This is done by a FL controller as shown in Fig. 14.

Figure 15 shows the membership functions used to present the different input and output variables of the developed fuzzy logic controller and Fig. 16 shows the rules surface of the inference engine.
4. Simulation Results

4.1. Speed Controller

The developed controller is tested under different variations in speed reference (given in Table 4) in order to prove its robustness against sudden variations of load nature. The obtained results are given in Fig. 17.

### Table 4. Speed reference variations

<table>
<thead>
<tr>
<th>Time Range</th>
<th>Speed reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>[0s, 1s]</td>
<td>80 rad/s</td>
</tr>
<tr>
<td>1s</td>
<td>80 rad/s → 120 rad/s</td>
</tr>
<tr>
<td>[1s, 2s]</td>
<td>120 rad/s</td>
</tr>
<tr>
<td>2s</td>
<td>120 rad/s → 100 rad/s</td>
</tr>
<tr>
<td>[2s, 3s]</td>
<td>100 rad/s</td>
</tr>
<tr>
<td>2s</td>
<td>100 rad/s → 150 rad/s</td>
</tr>
<tr>
<td>[2s, 3s]</td>
<td>150 rad/s</td>
</tr>
</tbody>
</table>

**Fig. 17.** Measurements with variable speed reference.

Obtained results show that the controller makes the measured speed pursue perfectly the different imposed references with an almost 0% overshooting during each variation.

4.2. FL-MPPT Controller

The developed controller is tested with a variable solar irradiance and ambient temperature (given in Table 5) with constant load parameters (speed reference=100 rad/s and load torque=0N.m). The obtained results are given in Fig. 18.

### Table 5. Imposed weather variations

<table>
<thead>
<tr>
<th>Time Range</th>
<th>Irradiance</th>
<th>Temperature</th>
</tr>
</thead>
<tbody>
<tr>
<td>[0s,3s]</td>
<td>1000 W/m²</td>
<td>25°C</td>
</tr>
<tr>
<td>3s</td>
<td>1000 W/m² → 400 W/m²</td>
<td>25°C</td>
</tr>
<tr>
<td>[3s,6s]</td>
<td>400 W/m²</td>
<td>25°C</td>
</tr>
<tr>
<td>6s</td>
<td>400 W/m² → 1000 W/m²</td>
<td>25°C</td>
</tr>
<tr>
<td>[6s,8s]</td>
<td>1000 W/m²</td>
<td>25°C</td>
</tr>
<tr>
<td>8s</td>
<td>1000 W/m²</td>
<td>25°C → 0°C</td>
</tr>
<tr>
<td>[8s,10s]</td>
<td>1000 W/m²</td>
<td>0°C</td>
</tr>
<tr>
<td>10s</td>
<td>1000 W/m²</td>
<td>0°C → 50°C</td>
</tr>
<tr>
<td>[10s,15s]</td>
<td>1000 W/m²</td>
<td>50°C</td>
</tr>
</tbody>
</table>

**Fig. 18.** PV generator measurements with variable weather conditions.
4.3. Charging/Discharging Controller

In order to test the efficiency of the developed controller, several voltage reference changes (Table 6) in both charging and discharging modes were imposed on the system. Figure 19 shows the simulation results proving the efficiency of the developed controller.

**Table 6.** Mode and voltage reference variations

<table>
<thead>
<tr>
<th>Time range</th>
<th>Mode</th>
<th>Charging voltage reference</th>
<th>Discharging voltage reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>[0s,1s]</td>
<td>Charging</td>
<td>270V</td>
<td>-</td>
</tr>
<tr>
<td>1s</td>
<td>Charging</td>
<td>270V (\rightarrow) 250V</td>
<td>-</td>
</tr>
<tr>
<td>[1s,2s]</td>
<td>Charging</td>
<td>250V</td>
<td>-</td>
</tr>
<tr>
<td>2s</td>
<td>Charging (\rightarrow) Discharging</td>
<td>-</td>
<td>350V</td>
</tr>
<tr>
<td>[2s,3s]</td>
<td>Discharging</td>
<td>-</td>
<td>350V</td>
</tr>
<tr>
<td>3s</td>
<td>Discharging</td>
<td>-</td>
<td>350V (\rightarrow) 400V</td>
</tr>
<tr>
<td>[3s,4s]</td>
<td>Discharging</td>
<td>-</td>
<td>400V</td>
</tr>
</tbody>
</table>

![Fig. 19. Battery measurements.](image1)

![Fig. 20. Available PV power.](image2)

![Fig. 21. Battery measurements.](image3)

(a) Generated battery power reference (b) SOC evolution

Obtained results show that battery is properly controlled in order to achieve an efficient energy flow. It gets charging power references only when the available PV power exceeds the power demand (between 11AM and 4 PM) and it gets discharging references when the power demand exceeds the available PV power (before 11AM and after 4PM).

4.4. Energy Dispatching Controller

In order to test the efficiency of the developed energy dispatching controller, values of available PV power taken at the LAPER laboratory on October 10th, 2016 are injected in the simulation model. Figure 20 shows the used measurements between 10AM and 6PM, generated battery power reference and the evolution of its SOC (initialized at 50%) are shown in Fig. 21.a and 21.b respectively. The power need is maintained at 400W all along the simulation.

![Fig. 20. Available PV power.](image4)

![Fig. 21. Battery measurements.](image5)

(a) Generated battery power reference (b) SOC evolution

Obtained results show that battery is properly controlled in order to achieve an efficient energy flow. It gets charging power references only when the available PV power exceeds the power demand (between 11AM and 4 PM) and it gets discharging references when the power demand exceeds the available PV power (before 11AM and after 4PM).

5. Conclusion

The different techniques used in this work showed that energy demand can be continuously satisfied thanks to the hybridization of sources and different control techniques used to develop an efficient novel centralized Energy Management...
References


INTERNATIONAL JOURNAL of RENEWABLE ENERGY RESEARCH
W. Ben SALEM et al., Vol.11, No.1, March, 2021


