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Energy Management of An Extended Hybrid Renewable Energy System For Isolated Sites Using A Fuzzy Logic Controller

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Abstract. This paper presents the implementation of a fuzzy logic controller to manage the flow of energy in an extended hybrid renewable energy system employed to satisfy the load for a wide isolated site at the city of Essaouira in Morocco. To achieve Efficient energy management, the system is combining two important renewable energies: solar and wind. Lithium Ion batteries were also used as storage devices to store the excess of energy provided by the renewable sources or to supply the system with the required energy when the energy delivered by the input sources is not enough to satisfy the load demand. To manage the energy in the system, a controller based on fuzzy logic was implemented. Real data taken from previous research and meteorological sites was used to test the controller.

1. Introduction

Recently, governments and industries all around the world are progressively trying to find alternatives to overcome the significant increase in the prices of conventional energy sources and to minimize the greenhouse gas emissions (GHC) and the resulting global warming. For these reasons, the implementation and diffusion of renewable energies as well as the establishment of a low-carbon economy have been subject of research in many regional and international initiatives, institutions and financial mechanisms [1]. The combination of solar and wind energy sources along with a storage unit, such as batteries, offers an excellent solution to problems caused by the stochastic nature of these sources, using the strengths of a source to overcome the weakness of the other [2] especially in developing countries where the economic development considers social and environmental issues [3].
The country of Morocco, Among the Northern African countries, is extremely depending on energy imports and fossil fuels. The electricity demand is increasing and therefore, the country will be facing in the future high energy costs if electricity prices continue to increase. To overcome these problems, the country started implementing wind farms and PV plants over big surfaces in different places in Morocco

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as mentioned in [4] [5]. However, there are only few reports on the performance of standalone hybrid systems implemented in small and large isolated sites in the country. This is due to the energy management of these systems that consists on controlling the energy between the input and output sources of energy while satisfying the load demand. Many methods were used before to control the flow of energy in PV/Wind/batteries systems as mentioned in [2], [6], [7]. However, no systems were used to manage the energy in large sites knowing a high rate of poverty and electricity problems.
This paper presents an implementation of a fuzzy logic controller to manage the flow of energy in a PV-wind-battery system for a large isolated site in the city of Essaouira in Morocco composed of 10 residential compounds and four olive oil factories providing a maximum of 850KW of energy per day. The rural electrification is also included in the load demand.
The energy management controller was implemented by an open source Java library called jFuzzyLogic that proposes a fully functional and complete implementation of a fuzzy inference system (FIS), and provides a programming interface (API) and an Eclipse plug-in in order to make it easier to design and test FCL code.
The fuzzy controller was tested on real data taken from the city of Essaouira which is known by its important solar radiation and its average annual wind speed of 8m/s. Results showed that the controller was able to manage the energy in the hybrid system while maintaining the batteries state of charge between 30% and 80%.

2. Fuzzy logic control

Although other intelligent methods such as genetic algorithms and neural networks can perform just as well as fuzzy logic in many applications, fuzzy logic has the advantage that the solution to the problem can be cast in terms that human operators can understand (using linguistic variables to represent vague concepts), so that their experience can be used in the design of the controller. It is also used when the available process model is no precise or when the analytical model is too difficult to evaluate. Thus, it can be adopted for effective energy planning. Fuzzy logic controllers (FLC) were; therefore, used in many applications to manage the energy in hybrid renewable energy systems (HRES) as in [8] and [9]. It was shown that FLCs were more efficient when applied compared to other methods.

3. PV/Wind/Battery stand-alone system for a large isolated site

The system proposed in this paper will be providing the load demand for a large isolated site that includes 10 compounds of 16 villas each and 4 factories in the city of Essaouira. The system also includes the rural lighting. To decide about the number of input and output units required to implement the HRES, the load demand should be defined.

3.1 Load demand acquisition

Given all possible appliances used in a house, the load demand was classified by priority into [6]. Since the load demand by priority varies hourly depending on the need of the electrical appliance by the user at a certain period of the day, the total load demand required was calculated for each hour.
The proposed site includes 10 compounds with an average hourly load demand equals to 26.16KW a minimum equals to 22 KW and a maximum of 36 KW. It includes also four olive oil extraction factories consuming between 80 and 352 KW hourly and with an average hourly load demand equals to 229 KW. As mentioned earlier, the public lighting will be also covered by the proposed hybrid system. The hourly load demand for it is 25KW when the lights are on and this will happen between approximately 7 pm and 6 am. During the other hours, the public lights will not consume any energy.
Taking into account all the elements of the site, the total load demand will then vary between 332.2KW and 738.8 KW with an average rate of 538KW as shown in the figure below:

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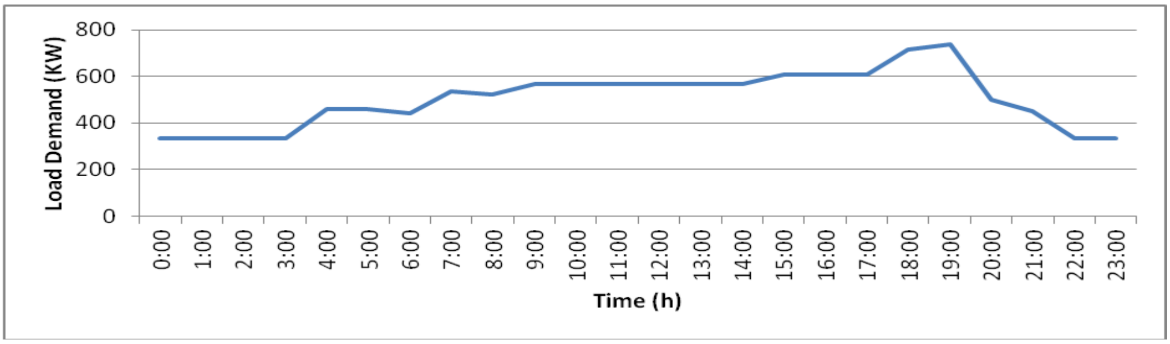

Figure 1. Variation of the load demand for the proposed site per day

3.2 Configuration of the proposed stand-alone PV/Wind/Battery system

The hybrid system proposed is composed of the following units:

- **PV panels*:*** 1600 unit implemented in series covering an area of 1km^2 to deliver a maximum power of 100 KWh per day under STC conditions and 18% efficiency.
- **Wind Turbine*:*** of type GAMEZA 52 with a maximum power of 850KWh. The performance coefficient (Cp) used in the wind equation was modified to allow the turbine to keep retrieving a maximum power even when the wind speed is too high without causing the turbine to stop [10].
- **Batteries*:*** Different storage units were compared in [11] and storage units that were found more convenient to HRES are batteries. The total number of 48V batteries required by the system is 167 Batteries with a maximum power 1600KW (200 Ah each).

4. Energy Management for the HRES proposed using fuzzy logic control

In general, load management means maintaining a balance between the energy produced by the input sources and the electrical load demand while protecting the storage units (batteries) from excessive charge or discharge [6]. The system was tested with load demand statistics (figure 1) and weather data [12] taken in the city of Essaouira in Morocco with full batteries.

4.1 PV and WT Power estimation

PV Power and Wind power were predicted using a fuzzy modeling system to overcome problems related to complex mathematical formulas and imprecise coefficients as described in [13]. Results are shown in figures 2 and 3.

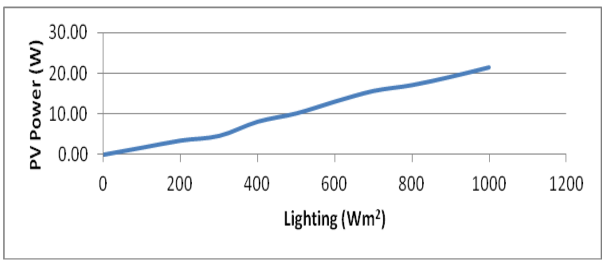

Figure 2. PV power for one panel under temperature=25°C

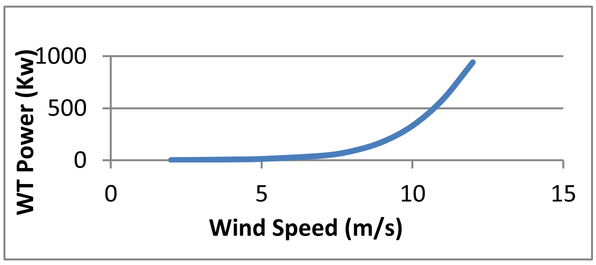

Figure 3. WT power curve

4.2 The flowchart for the fuzzy controller proposed to the HRES

To ensure the management of the power between the renewable sources and the batteries, satisfy the load demand, and protect batteries from overcharge and over discharge (battery's state of charge (SOC) between 0.3 and 0.8) a fuzzy logic controller was implemented. The flowchart is shown in figure 4.

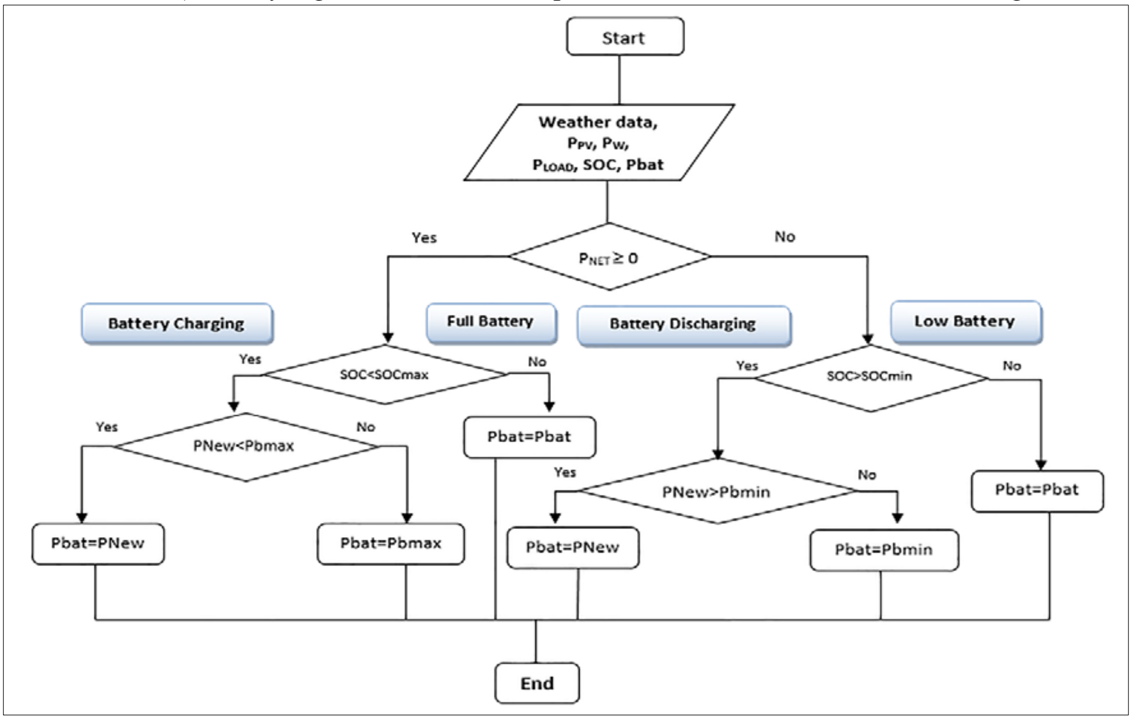

Figure 4. Flowchart representing the energy management system based on type-1 fuzzy control

P_{sys} is the system power calculated from the power generated by the PV panels (P_{pv}) and the power generated by the Wind turbine (Pw) at each period of time (t):

$$P_{sys}(t)=P_{pv}(t)+P_w(t) \quad (1)$$

$$P_{Net}(t)= P_{sys}(t)-P_{load}(t) \quad (2)$$

P_{load} represents the load power demand and it will be obtained from the data in figure 1.

The Net power (N_{et}) can be either positive: the power generated by the renewable sources is fully satisfying the load demand and the excess of energy is stored in the batteries (charging), or negative: the power generated by the renewable sources cannot fully satisfy the load demand and therefore, the batteries should provide the remaining energy demanded by the load (discharging).

SOC should remain between 30% and 80%. The SOC is calculated at each period of time t (1 hour) by the following formula:

$$SOC(t) = \frac{P_{bat}(t)}{BC} \quad (3)$$

Where BC is the battery capacity and P_{bat} is the battery power calculated, SOC_{min}=30% (the battery cannot be discharged if it is at its minimum level), SOC_{max}=80% (the battery cannot be charged if it is at its maximum level). The maximum and minimum level of the batteries are then calculated as follows:

$$Pb_{min}=SOC_{min}*BC \quad (4)$$

$$Pb_{max}=SOC_{max}*BC \quad (5)$$

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P_{new} shows the battery level that it is supposed to reach after adding the P_{Net} and is calculated at each period of time (t) by the following formula:

$$P_{new}(t)=P_{Net}(t)+P_{bat}(t-1) \quad (6)$$

- **Case of battery charging:**

When $P_{Net}>0$, batteries will be charged if $SOC<SOC_{max}$. SOC_{new} is calculated from P_{new} .
If $SOC_{new}<SOC_{max}$ then P_{Net} will be charged totally and therefore $P_{bat}(t)=P_{new}(t)$.
If $SOC_{new}>SOC_{max}$ then P_{Net} will be charged partially therefore $P_{bat}(t)=Pbmax$

- **Case of battery discharging:**

In case $P_{Net}<0$, batteries will be discharged if $SOC>SOC_{min}$,
If $SOC_{new}>SOC_{min}$ then P_{Net} will be taken totally from batteries, $P_{bat}(t)=P_{new}(t)$.
If $SOC_{new}<SOC_{min}$ then P_{Net} will be taken partially, $P_{bat}(t)=Pbmin$

4.3 Application of the Fuzzy controller

Fuzzy control language (FCL) was incorporated in the Jfuzzylogic package (IEC 61131 part 7) to implement the phases of the FLC (Fuzzification, Inference rules, and deffuzification).

4.3.1. *Fuzzification phase*

- *Input linguistic variable:* **P_{Net}**, (P (Positive), N (Negative)), **SOC**(Low, Medium, High)**,** **P_{New}** (VeryLow, Low, Medium, High, VeryHigh)
- *Output linguistic variable:* **Bat_status** (VeryLow, Low, Medium, High, VeryHigh)

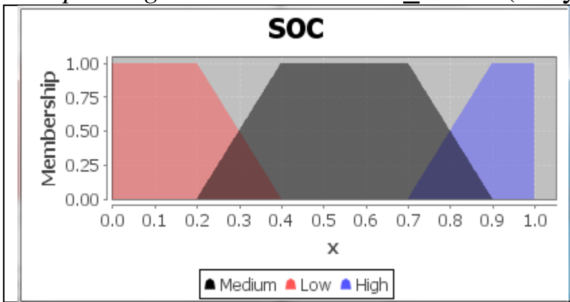

Figure 5. Membership function for the input variable SOC

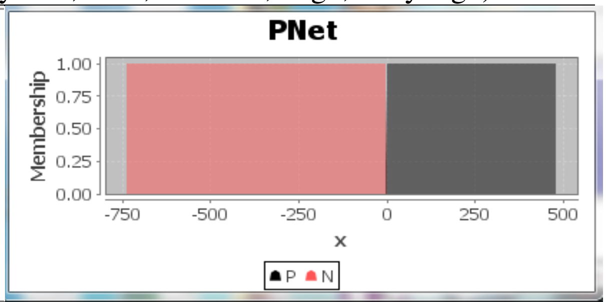

Figure 6. Membership function for the input variable P_{Net}

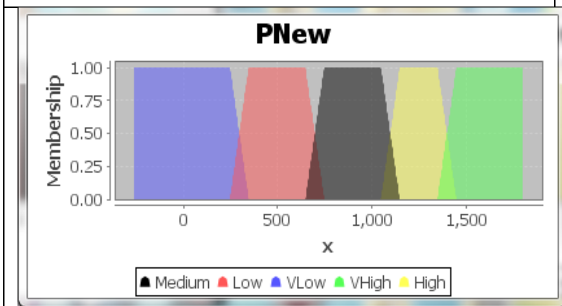

Figure 7. Membership function for the input variable P_{New}

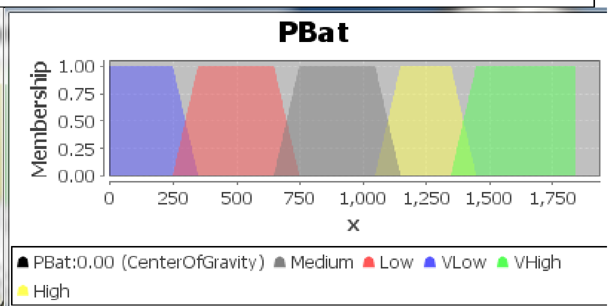

Figure 8. Membership function for the output variable Battery Status

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Figures 5,6,7 and 8 show the membership functions of the input variables SOC, P_{Net}, and P_{New} and the output variable P_{bat}.

4.3.2. *Inference Rules.* The inference rules were interpreted by the De Morgan's Law (min-max for the activation and accumulation methods) to determine the Battery status as shown in Table 1.

Table1. Inference rules of the fuzzy controller

P_{Net}	SOC	P_{New}	P_{bat}	P_{Net}	SOC	P_{New}	P_{bat}
N	Medium	VeryLow	Low	**P**	Low	Low	Low
N	Medium	Low	Low	**P**	Low	Medium	Medium
N	Medium	Medium	Medium	**P**	Low	High	High
N	Medium	High	High	**P**	Low	VeryHigh	High
N	Medium	VeryHigh	High	**P**	Medium	Low	Low
N	High	VeryLow	Low	**P**	Medium	Medium	Medium
N	High	Low	Low	**P**	Medium	High	High
N	High	Medium	Medium	**P**	Medium	VeryHigh	High

4.3.3. *Deffuzification phase.* The Center of gravity (COG) method was applied for this phase, the battery level was determined by a crisp value for each period of time t (1h).

5. Results and discussions

In case of P_{Net} is P (Positive) the following rules were derived:

- SOC is High (80% full or more): Battery kept at its maximum level of charge.
- SOC is low or medium, excess power can be stored totally in case P_{New} is very low, low, medium, or high. If P_{New} is very high then the battery cannot absorb all the excess of energy. The battery can absorb until its maximum is reached ($SOC=SOC_{max}=80\%$).

In case of P_{Net} is N (Negative), the following rules were derived:

- SOC Low: battery level at its maximum depth of discharge.
- SOC medium or high, battery able to provide the power demanded by the load totally in case P_{New} is very low. In case P_{New} is low, medium, or high, the battery will be able to provide part of the energy demanded until its minimum is reached ($SOC=SOC_{min}=30\%$).

Given all the rules above, the battery's level fuzzy value can be determined by the fuzzy controller for each case depending on its state of Charge and the energy provided by the renewable sources.
The controller was tested with full batteries of a total capacity of 1600kw. The batteries minimum and maximum levels (Pb_{min} and Pb_{max}) were calculated with equation (4) and (5): Pb_{min}=480KW and P_{max}=1280KW. The battery's level variation estimated ($P_{bat\_estimated}$) by the fuzzy controller was compared to the one calculated by a mathematical formula ($P_{bat\_theoretical}$) and represented by figure 9. The chart is showing a convergence which means that the proposed fuzzy controller gave good estimation to the batteries level for each period of time.

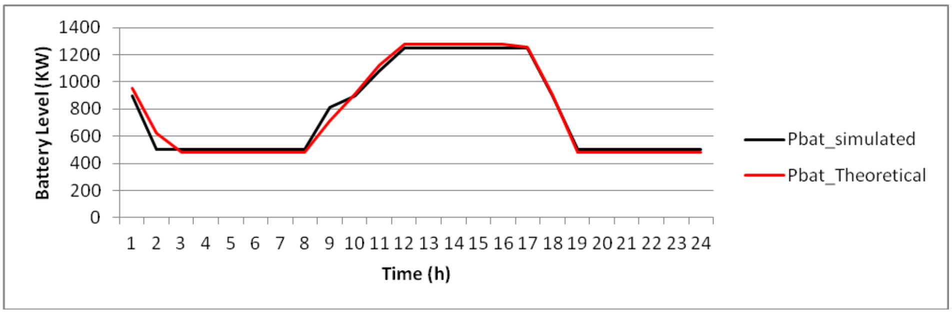

Figure 9. Battery status comparison between the theoretical calculation and the fuzzy estimation

6. Conclusion

This paper presented a stand-alone (off-grid) hybrid system combining solar and wind sources of energy with batteries in one system to satisfy the electrical load demand for a large isolated site in the city of Essaouira in Morocco. A controller based on fuzzy logic was proposed in this paper to manage the flow of energy in the system and determine the status of the battery at each period of time while maintaining the battery's SOC level between 30% and 80%. The algorithm was tested using real data for the region captured for one day in the month of April. Results showed that the fuzzy controller presented an efficient way to control the flow of energy between input sources and storage units while ensuring a continuous power supply for the load demand. The variation of values shown is due to the choice of the fuzzy sets.
Since complicated systems may require several iterations to find a set of rules resulting in a stable system, other models and techniques can help in finding an optimal action-selection policy for any given Markov decision process (MDP). These models can be functions such as parametric functions or algorithms such as Q-learning [14].

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