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# Intelligent Management of Alternative Energy Sources Based on Fuzzy Logic

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**Abstract**— This paper aims to evaluate the use of *Soft-Computing* techniques, specifically *Fuzzy Logic* for the development of a management system for alternative energy sources such as wind, photovoltaic and fuel cell. The basis of a hybrid generation system checks its response availability, reliability and power supply taking into account the environmental conditions and power consumption. It realizes a comparison of several kinds of supply management in different case studies. Results show which proposed approach reaches a greater use of energy available from such generation systems. Furthermore, it shows the design of a *Fuzzy Logic*-based manager (*FLM*), able to select, according to different criteria, which one electrical source and in what proportion, is more suitable to satisfy power consumption. Alternative energy sources models are implemented. Experimental testing is performed to the consumption data base.

## Key words

Alternative Energy Sources, Electric Demand Model, Intelligent Management Energy Sources.

# 1. Introduction

Nowadays, there is a strong trend towards the appropriate use of natural resources and environment care. As a result, the popularity of alternative energy technologies has increased. The possibility to achieve higher power levels without the environmental impact that comes with conventional generation systems has motivated the use of these technologies with renewable sources [1]. Furthermore, the implementation of alternative energy systems bring some problems related to reliability, flexibility and compliance, letting them relegated as backup elements [2].

Considering the above it could reduce this inconvenient using a hybrid model that combines clean electric power generation techniques such as wind, photovoltaic and fuel cell. The integration of such technologies allows coordinating the operation of individual systems in order to provide suitable conditions of energy required by all the loads connected to the power grid.

At this time, the implementation of this technology is made according to forecasts and statistics, which change to a great degree depending on where such implementation is required. This leads in some cases designs with high requirements in order to fulfill with energy demand in the presence of peaks where it generates more energy than necessary and cannot be fully used [3].

This paper is aimed to the observation and study of the response of a power generation system capable of integrating several alternative energy sources (wind, photovoltaic and fuel cells). This seeks to supply the electricity demand in an environment of residential, commercial or industrial, through a management system based on *Fuzzy Logic*.

The rest of this paper is organized as follows. In Section II, related work is presented. In Section III, proposed approach is carried out. The fuzzy manager (FM) design is included in Section IV. Experimental results are shows in section V. A brief conclusion is shown in Section VI.

According to the revision carried out, the relevance of the management of various types of energy sources (wind, radiation, hydrogen) from the forecast energy demand is considered with the aim to minimize the system's sensitivity to possible changes in the behavior of the variables of interest. Hence this proposal presents different management types, allowing greater flexibility to the system. In addition, we propose the development of an energy management system of alternative sources, based on fuzzy logic, which will be presented in Section IV of this article.

# 2. Proposed Approach



Fig. 1. Fuzzy logic manager.

We propose the development of a fuzzy manager for alternative power station composed by three types of energy sources (wind, photovoltaic and fuel cells). The three energy sources are integrated in order to increase system reliability in terms of compliance with the electrical energy demand. Figure 1 shows the proposed system model.

Figure 1 shows the stages that constitute the intelligent management system for alternative energy sources. The arrows indicate the type of communication between systems. The meteorological variables provide information to the models used by the Fuzzy Manager (FM) to establish the amount of power that can generate by the wind generation (EGS), photovoltaic generation (PGS) and cell fuel generation systems (CGS). The supplied energy level by energy generation system is figured out by the intelligent system, which is represented for black ovals in Figure 1. The management system just has one-way communication with the load, which requests information on electricity demand. Once management is on the energy of each system is concentrated (adder) looking to fulfill electricity demand required by the load (EDR). Each of the stages involved will be analyzed separately. Subsection A. Alternative energy sources, Subsection B. Modeling of alternative power plant, Subsection C. Electricity demand. Subsection D. Management system based on fuzzy logic.

### A. Alternative Energy Sources

The selection of alternative energy sources to be used in integration to an intelligent management system is considered from the development, cost and future of this technology. According to the above, we opted for the selection of power generation from wind speed (wind), solar radiation (photovoltaic) and level of hydrogen (fuel cell). The following some relevant aspects that justify the selection of energy sources mentioned above.

1) Wind Energy: It is one of the most widely used technologies in the world, because of its simplicity, efficiency and speed payback. The previously mentioned turns this technology in one of the renewable energy sources more competitive, compared to power generation by burning fuel [4].

2) *Photovoltaic Solar Energy:* Photovoltaic solar energy is characterized by a high initial investment required [5]. Despite this, at present the scientific and economic efforts in search of improvement and positioning have increased, due to advances in predicting the behavior of solar radiation.

*3) Energy from Hydrogen*: In spite of not being a novel technology, in recent years it has had a growing, especially in the automotive sector due to its easy implementation. The possibility of controlling the generated power according to the hydrogen flow in the system, has led to increasing popularity in recent years [6] [7].

On this article, vertical axis wind turbine model, single crystal cells and Silicon Oxide Fuel Cell (SOFC) are

proposed. This is because of their useful application on generation technologies distributed for medium and large installations. Section B will present the model generation systems to be implemented on fuzzy system management.

### B. Power Plant Alternative modeling

Figure 1 shows the block diagram of an alternative power plant and each of the components subsystems (wind, photovoltaic and fuel cells). The models of the selected systems are analyzed in detail.

1) Wind power generation system: It consists mainly of a wind turbine model. The equations described in this section were taken from [8]. This model includes the amount of wind turbines as length blade propellers, high cutting speeds and low power coefficient, the efficiency of the generator and the efficiency of the multiplier. The available energy of the system depends on the wind speed incident on the blades of wind turbines. The power rating of wind-turbines product is modeled considering wind characteristics shown in Table I [3].

$$P = \frac{C_P \eta_{mec} \eta_{elec} \rho A V^3}{2} \tag{3.1}$$

Where,

 $\rho$ : Wind density flowing through an area A with a velocity V.

 $C_P$ : Power coefficients

 $\eta_{mec}$ : Multiplier Mechanical performance.

 $\eta_{elec}$ : Generator performance.

Equation (3.1) defines the available power of the wind system. The power will depend of the high cutting speeds and low values. The system fails to operate when the speed is below the low cutting speed or above the high cutting speed.

For modeling of the wind incident on the wind system took winds standards provided by a meteorological station.

2) Photovoltaic generation system (PGS): This system is formed by the solar panel model, along with the battery bank. The equations described in this section were taken from [9] [10]. This model contains the number of panels and power, the battery capacity, voltage and losses inherent to this, also takes into account the loss of selfdischarge converter and others. All this determines the rating of the system. However, the available energy of the system depends on the solar radiation incident on the panels and the power accumulated in the battery bank.

For photovoltaic system modeling is a part of an overall system performance determined by the following equation.

$$R = (K_b K_C K_V) * \frac{K_a N}{P_d}$$
(3.2)

Where,

 $K_h$ : Losses in the system due to the battery bank.

 $K_C$ : System losses due to power converter DC-AC

 $K_V$ : Losses on several factors such as the Joule effect, sulfation and parasitic elements.

 $K_a$ : Losses in the battery bank because of the inherent self-discharge them.

*N*: Runtime of the battery bank.

 $P_d$ : Ratio of daily depth of discharge of the battery bank

The runtime of the photovoltaic system N is determined by the following equation.

$$N = \frac{CVP_d}{E} \tag{3.3}$$

Where,

C: Capacity in Amperes per hour (Ah) battery bank.

*V*: Rated voltage of the battery.

E: It is the electrical power produced by the panels

*3)* Fuel cell generation system (CGS): The CGS consists basically of the model fuel cell used in distributed systems. The equations described in this section were taken from [11]. This model contains the number of fuel cells with their intrinsic characteristics such as the utilization factor, activation losses, ohmic and concentration. The latter together with the hydrogen flow will determine the operation percentage of the system, which may be available as long as the system is active.

For modeling the fuel cell silicon oxide must take into the chemical reaction which develops in the cell, since not all hydrogen that enters the cell reacts with oxygen. To do this, it has to be determined by the utilization factor (Uf) through the following equation.

$$U_f = \frac{q_{H_2}^r}{q_{H_2}^{ln}}$$
(3.4)

Where,

 $q_{H2}^r$ : Reacting hydrogen flow.

 $q_{H_2}^{In}$ : Total flow of hydrogen entering the cell.

To find out how much hydrogen reacts, it is used the equation as follow

$$q_{H_2}^r = \frac{N_0}{2F}$$
(3.5)

Where,

 $N_0$ : Number of cells in series resulting in the total fuel cell. *F*: Faraday constant (96487C/mol).

To find out the power delivery by fuel cell system, it is necessary to know the DC voltage of the cell through the Nernst equation, which is described as follows.

$$E = E_{0} + \frac{R_{u}T_{k}}{2F} \left[ \ln \frac{P_{H_{2}}\sqrt{P_{O_{2}}}}{P_{H_{2}O}} \right]$$
(3.6)

Where,

*E*: FEM generated by the system of the cell.

 $E_0$ : Ideal power.

 $R_u$ : Universal gas constant (8314 J/ (kmol-°K)).

T<sub>k</sub>: Is the absolute temperature in Kelvin (1273 K).

 $P_{H_2}$ : It is the partial pressure of hydrogen.

 $P_{O_2}$ : It is the partial pressure of oxygen.

 $P_{H_2O}$ : This is the partial pressure of water vapor.

Since in the fuel cell losses occur, these must be taken

into account as described as follow:

$$V_{FC} = E - V_{Ohm} - V_{Act} - V_{Conc}$$
(3.7)

 $V_{FC}$ : Is the output voltage of the fuel cell.

 $V_{Ohm}$ : Is the voltage drop due to the internal electrical resistance of the fuel cell.

 $V_{Act}$ : Is the voltage drop across the fuel cell due to its activation threshold.

 $V_{Conc}$ : It is the voltage drop across the fuel cell due to the concentration of hydrogen.

Obtaining the above is possible to know the power generated by the system of the fuel cell as follow

$$P_{FC} = 2FV_{FC}q_{H_2}^r n_{Con\nu} \tag{3.8}$$

Where,

Where,

 $P_{FC}$ : Generated power in fuel cell system

 $n_{Conv}$ : Efficiency Factor DC-AC conversion system due to generate DC power.

For this work, we consider the power available from the fuel cell solid oxide as a variable that is controlled and depends on the flow of hydrogen (constant).

#### B. Electricity Demand (EDR)

The *EDR* modeling is carried out from the expert knowledge of the behavior of electricity demand in the residential, commercial and industrial. This model (*EDR*) is made from historical records obtained in [12], where electricity demand is studied and characterize these types of users.

C. Management System Based on Fuzzy Logic

The proposed management system is described in Figure 1. In this Figure the basic components are observed for a system of this type. The structure of the fuzzy system is defined from the model Mandani. The entries in this system are: the meteorological variables (wind speed, solar radiation, amount of hydrogen available from the fuel cell system) and the required electrical demand curve (EDR). We use triangular membership functions and trapezoidal type because they fit the natural behavior of these entries. The inference engine use a set of rules like "if then", which contain information on the requirements to be met by FM. The response management system assigns a level of energy weighting each generation systems available. This in consideration of the electrical power output in each generation system and other scenarios that are described in Section IV.

## 3. Fuzzy Manager

This block provides the proper weighting of the energy available in each of the systems of power generation (wind, photovoltaic and fuel cells). The energy requirement depends mainly on the input variables related to weather conditions, electricity demand required and management criterion specified. Below is the membership functions used in fuzzy development manager.



The membership function shown in Figure 2 is oriented with the parameters described by Table I which describes the types of wind and their own velocities.



The membership function shown in Figure 3 is performed taking into account the curve of daily solar radiation [6], in this peak shows that the solar radiation in a  $1 \text{ KW/m}^2$  is standardized, which is the case cloudless noon.



Fig. 4. Input membership function to FM (level of hydrogen).

The membership function that is show on Figure 4 is determined by level of hydrogen that can be storage as fuel, which is measurement as a percentage of fuel that is on the tank.



The membership function shown in Figure 5 is normalized, so the electrical demand values become fuzzy values are delimited and can be applied to any type of demand curve.

#### E. Inference Engine

The inference engine (FM) works according to rules such as "if then" based on expert knowledge gathered from the operation of each of the proposed generation systems. With the implementation of these rules the goals are, 1) To fulfill fully with EDR, 2) To determine the power required for each subsystem of the alternative power plant based on management scenario chose and, 3) To allow the power supply grid only in cases where the hybrid alternative energy system cannot meet the EDR. Below are the rules and surface charts for each of the cases.

1) *EGS:* In Table I and Figure 6 show the surface and 16 working rules used for the development of the inference engine respectively.

Table	L	Rule	Base	for	EGS
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Inputs			
Demand	Low	Medium	High
Wind			-
Calm	Medium	Little	Null
Mild	High	Medium	Little
Slight	Very High	High	Medium
Moderate	Total	Very High	High
Regular	Total	Total	High
Strong	Total	Total	Very High

The rules shown in Table I indicate a level of satisfaction (output) or energetic level requirement between the possible fuzzy inputs to interference engine for the EGS.



Fig. 6. Workplace generated by the *FM* to the satisfaction of EGS

2) *PGS:* In Table II and Figure 7 show the 11 rules and workplace used for developing the inference engine respectively.

Inputs						
Demand	Low	Mediu	High			
Irradiation		m				
Null	Little	Null	Null			
Low	Medium	Little	Null			
Medium	High	Medium	Little			
High	Total	Very High	High			

Table II. Rule Base for PGS

The rules shown in Table II indicate the level of satisfaction (output) or energetic requirement level between the possible fuzzy inputs to interference engine for PGS.



Fig. 7. Workplace generated by the FM to PGS satisfaction

*3) CGS:* In Table III and Figure 8 show the 11 rules and workplace used for developing the inference engine.

Table III. Rule base for CGS				
Inputs				
Demand	Low	Medium	High	
Level				
Empty	Null	Null	Null	
Little	Medium	Little	Null	
Lot	Very High	High	Little	
Full	Total	Very High	High	

The rules shown in Table III indicate a level of satisfaction (output) or level of energetic requirement between the possible fuzzy inputs to interference engine for the CGS



Fig. 8. Workplace generated by the FM to the satisfaction of CGS.

F. Outputs

*FM* design was taken as outputs, autonomy or *EDR* satisfaction percentage by each subsystem. In Figure 9 shows the membership functions used to determine the output or response of GLD.



Figure 9 shows the output of the *FM*. The response of *FM* was defined from 0 to 100% for demand satisfaction that each subsystem can handle by itself.

#### G. Management Scenarios for the FM.

In order to provide greater flexibility on intelligent system behavior is proposed the integration of various management scenarios according to management objectives set by the user. These scenarios will be introduced as follow.

1) *Profitability:* This scenario seeks to fulfill with the demand using the most economic subsystem. Currently wind power generation systems are between cost efficiency and more cost effective than PV and these than the fuel cell.

2) *Reliability:* For this scenario the manager provides more priority to the subsystem that is generating the most power for a specific *EDR*.

*3) Priority:* In this mode the power order of each subsystem, is indicated by the operator under his own criteria.

4) *Percentage:* In this scenario the maximum percentages of operation of each subsystem are assigned by the user. The subsystems set of the plant can supply from 0 to

100% of the power required by the EDR.

# 4. Experimental Results

The problem based on residential customer energy is tested and the results are presented in this section. The energy supply system of this customer consists of distribution power grid, wind generation system (capacity of 1109 kW), photovoltaic generation system (capacity of 1100 kW) and fuel cells energy (capacity of 940 kW). The test is performed for a typical summer season, a day at the beginning of week [12] and meteorological as wind velocity data from Table I and daily solar irradiation from [13].

The test of the FM is performed and analyzed in several case studies in a day where wind velocity, solar irradiation and hydrogen level parameters change randomly producing a change in available power in each subsystem.

### 1) Evaluation and Verification FM Operation.

The results of the evaluation of FM in the three management scenarios available (cost, reliability and priority of the *CGS* and *PGS*) are carried out. The comparison is performed in a single case and one hour (20 hours), under the same environmental conditions, resulting in a level of satisfaction of the identical *EDR*.

Figure 10 presents the satisfaction percentages of active sources according to the conditions hourly weather variables.



Fig. 10. Percentage of satisfaction of the EDR for a case study.



respectively (left to right).

Figure 11 shows the results of management for a case in which the wind speed is smooth, solar irradiance is equivalent to a cloudy day (means) and the hydrogen level is full. During profitability management the *EGS* is taken as first choice. However, in reliability management the *CGS* has higher priority; this produces a behavior with similar responses for priority and reliability cases. Hence, this is represented by the same figure (Figure 11 - *right*).

### 2) Response Assessment Fuzzy Manager (FM) for Different Demand Curves

To evaluate the response of FM with several case studies we

selected three different demand curves (residential, commercial and industrial). For this experiment are randomly modified estimation parameters for the *EDR* and the nominal power of the subsystems *EGS*, *PGS* and *CGS*.



Figure 12 shows satisfaction levels for each generation system for a day.

Figure 13 shows the percentages of operation for each generation system in a management scenario based on profitability. The results show a higher level of energy from the wind, due to the low cost of operation. However, this depends on the availability and level of satisfaction in this type of generation system during each hour of the day. For this case, the first 4 hours of the day have little satisfaction from this type of energy source. This forces the system to supply the demand with energy from *PGS* because it has a better performance in terms of profitability.



Fig. 14. Operation percentages for each generation system in a reliability scenario.

Figure 14 shows the percentages of operation for each generation system in a reliability scenario. Compared with the first 4 hours of the previous case, the total demand is supplied from the energy generated by the *PGS*.

# 5. Conclusions

The proposed manager provides more flexibility during the management considering constraints and challenges of each energy sources subsystem. In this case FM guarantees the energy supply considering customer preferences. Furthermore the proposed approach allows minimizing the necessity of energy storage.

Management scenarios on profitability and reliability show similar results if is fulfilled that the most cost effective is also the most reliable.

In the reliability case *CGS* was more suitable than *EGS* and *PGS*, while in profitability case the *EGS* was more selected by fuzzy manager due to the low cost of this energy type.

Finally, since the power available from *CGS* is a function of hydrogen flow, makes it the most reliable of the three proposed in this work, as evidenced by the results discussed in section IV. In this final section shows a greater stability in the power available from *CGS*, while in the *EGS* and *PGS* vary widely around their nominal value. This is due to the characteristics that govern the stochastic behavior of energy resources from wind and radiation from the sun. The *CGS* provides the hybrid system guarantees from the point of view of reliability. However, the scenario based on profitability has a higher raw material costs in comparison with other proposed scenarios.

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