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Supervision of a Hybrid Renewable Energy System by an Evolutionary Fuzzy System: Modeling and Implementation

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Abstract: ***In Hybrid Renewable Energy Systems (HRES), energy flow management is necessary to ensure a continuous power supply for the load demand and a reliable HRES. However, the dynamic interaction between renewable energy sources and the load demand generates serious problems of stability. Therefore, there is a need to control and supervise systems based on renewable energy in order to overcome the transient response in energy distribution network. To carry out an HRES supervision in this work, the modeling and experimental implementation of supervisory control is presented with an intelligent systems approach inspired by the paradigm of evolutionary and fuzzy computing, on an HRES composed of two renewable energy subsystems (solar and wind) and a storage system. The methodology for the design of the supervisor is divided into several steps from the working specifications of the HRES to the experimental implementation of the supervisor in a simulation model.***

Keywords: HRES, Renewable energy, Supervision

1. Introduction

The HRES have been proposed as an option to supply energy in isolated non-electrified areas or small places that are far away from the utility grid where transporting conventional energy sources such as oil and natural gas is complicated and grid extension is not profitable. So that the energy demand can be met by using locally available renewable energy sources.

An HRES associates at least one renewable energy source, an additional source of backup and a storage device that helps manage the stochastic behavior of renewable energy sources and increases reliability of these systems. In this type of systems, energy flow management is necessary to promise continuous power supply for the load demand.

However, the dynamic interaction between renewable energy sources and the load demand and their intermittent nature, generates serious problems of stability and power quality issues. Due to this, there is a need to control and supervise these systems in order to overcome the transient response in energy distribution network.

The supervision of the HRES has been covered from different approaches and techniques, some of these are: optimal control strategy [1][2]. This strategy uses several input signals to achieve multi-objective optimization; mathematical models [3][4][5]. This method requires a detailed model and a good knowledge of power flows and the associated losses; supervision based on artificial intelligence such as multi-agent systems [6], graphical and fuzzy modeling tools [7][8] and fuzzy logic [9] [10][11]. The fuzzy logic approach has shown to be well adapted tool to manage hybrid energy sources due to the difficulty to obtain or to use a precise HRES model, and the difficulty to predict the behavior of renewable energy sources such as wind or sun and energy consumption. Under these approaches in each work, supervisory control systems have been proposed and designed, which allow to characterize the behavior of the HRES, know how to change the controllers and achieve the desired specifications to improve the performance and reliability of the HRES. Each supervisor has specific restrictions depending on the type of renewable energy source and the components involved in the HRES.

To carry out an HRES supervision in this work, the modeling and experimental implementation of supervisory control is presented with an intelligent systems approach inspired by the paradigm of evolutionary and fuzzy computing, implemented in an HRES composed of two renewable energy subsystems (solar and wind) and a storage system. The methodology for the design of the supervisor is divided into several steps from the working specifications of the HRES to the experimental implementation of supervisory control by simulations.

This work is organized as follows. The next section describes the methodology for carrying out the modeling and experimental implementation of the supervisory control proposed. Section 3 is dedicated to show the experimental work for the supervisor implementation and test their performance. The section 4 shows results obtained by simulations and finally in section 5 a conclusion of this work is given.

2. Methodology of Supervision

The supervision methodology allows to facilitate the analysis of the supervision problem, the development of supervision algorithms and an experimental implementation. For the analysis of the supervision problem, the graphics modeling

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and fuzzy logic approaches proposed in [8][7] were used. In this work for the development of supervision, the following steps are considered:

- Determination of work specifications of the hybrid system
- Supervisor design
- Determination of the HRES operating modes
- Definition of membership functions
- Extraction of fuzzy rules
- Development of evolutionary fuzzy system
- Configuration of the simulation model
- Experimental implementation of the fuzzy logic supervisor in the simulation model

2.1 Determination of work specifications of the hybrid system

In this step, the characteristics and objectives of HRES are identified. The diagram of the hybrid system of renewable energy under study is shown in Figure 1 which is composed of two subsystems of renewable energy: wind and photovoltaic, a storage system and the load. The objective of the HRES is to met the load demand all the time, depending on the atmospheric conditions. These atmospheric conditions will also define different operation modes of the HRES.

Figure 1: Components of the hybrid renewable energy system under study

2.2 Supervisor design

In this step, the inputs and outputs required by fuzzy logic supervisor are defined, which are shown in Figure 2 by a block diagram. The inputs for the supervisor are:

- The power error ($\Delta P = P_{ref} - P_{hyb}$) where P_{ref} is the reference power that is the power that must be generated to satisfy the load demand, and P_{hyb} is the power generated by the wind and photovoltaic subsystems.
- The storage level (*Lev_stor*)
- The frequency error Δf the network normal frequency f_0 (60 HZ) and the measured frequency $f_{measured}$

The outputs generated by the supervisor are:

- The reference power for the storage systems P_{ref_stor}
- The reference power for the photovoltaic system P_{ref_pv}
- The pitch angle reference β_{ref} for controlling the power generated by the wind system

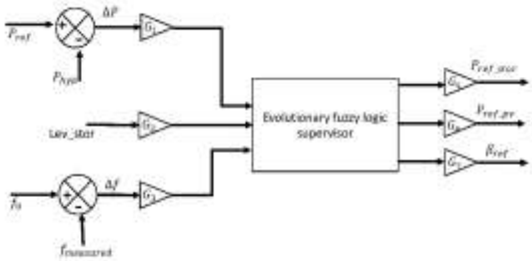

Figure 2: Block diagram of the supervisor

2.3 Determination of the HRES operating modes

The operating modes of the HRES are determined by the power balance between total generation (solar energy and wind energy) and total demand (load demand). The possible generation modes are:

- **Mode 1 (M1):** It corresponds to periods of sufficient wind power to satisfy the total demand ($P_{hyb}=P_{ref}$). Therefore, the wind subsystem must track the total demand, in this mode the storage level is medium, when the power generated by the HRES is insufficient ($P_{hyb}<P_{ref}$), the storage system compensate the difference between the reference power and the power generated by the hybrid system. If the power generated by the HRES exceeds the load demand ($P_{hyb}> P_{ref}$), the storage system accumulates excess energy.
- **Mode 2 (M2):** In this mode the storage level is high, the HRES must maintain the storage availability, therefore in this case, the storage unit must be discharged and the power of the wind subsystem must decrease or increase with the help of the pitch angle (β) to maintain frequency stability.
- **Mode 3 (M3):** In this mode the storage level is low, therefore the photovoltaic subsystem complements the wind generation to satisfy the total demand ($P_{hyb} = P_{ref}$), if the power generated by the hybrid system is greater than the load demand ($P_{hyb}>P_{ref}$) then the storage system accumulates excess energy.

These operating modes are represented in Figure 3 where each rectangle represents a mode and the states of the system are represented by transitions.

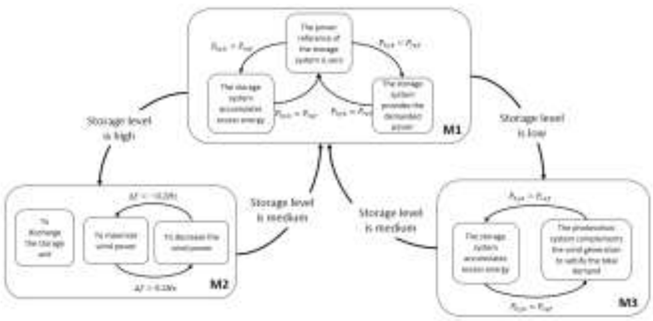

Figure 3: Chart representation of different operating modes of the HRES

2.4 Definition of membership functions

In this step the membership functions of the input and output variables of the fuzzy logic supervisor are defined. Table 1

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Table 1: Definition of linguistic terms and membership parameters of supervisor input and output variables

Input variables	*Linguistic terms*	*Output variables*	*Linguistic variables*
Level storage (Lev_stor)	Z: Zero, Trapezoidal [0,0,0.1,0.2] M: Medium, Trapezoidal [0.05,0.2,0.8,0.95] H: High, Trapezoidal [0.8,0.95,1,1]	Reference power of storage system (P_{ref_stor})	NB: Negative Big, Trapezoidal [-1,-1,-0.8,-0.4] NM: Negative Medium, Trapezoidal [-0.8,-0.4,-0.1,0] Z: Zero, Triangular [-0.1,0,0.1] PM:Positive Medium, Trapezoidal [0,0.1,0.4,0.8] PB: Positive Big, Trapezoidal [0.4,0.8,1,1]
Power error (ΔP)	NB:Negative Big, Trapezoidal [-1,-1,-0.8,-0.4] NM: Negative Medium, Triangular [-0.8,-0.4,0] Z: Zero, Triangular [-0.4,0,0.4] PM:Positive Medium, Triangular [0,0.4,0.8] PB:Positive Big, Trapezoidal [0.4,0.8,1,1]	Reference power of photovoltaic system	Z: Zero, Triangular [0,0,0.1] M: Medium, Triangular [0,0.1,0.6] H: High, Trapezoidal [0.1,0.6,1,1]
Frequency error (Δf)	N:Negative, Trapezoidal [-1,-1,-0.2,-0.1] Z: Zero, Trapezoidal [-0.2,-0.1,0.1,0.2] P:Positive, Trapezoidal [0.1,0.2,1,1]	Pitch angle reference	Z: Zero, Triangular [0,0,0.1] M: Medium, Triangular [0,0.1,0.6] B: Big, Trapezoidal [0.1,0.6,1,1]

summarizes these variables, the linguistic terms of each variable, the membership functions that represent each linguistic term and its parameters.

2.5 Extraction of fuzzy rules

In this step the fuzzy rules are determined, for this the operating modes shown in Figure 3 must be represented in fuzzy terms. Figure 4 shows the detailed operational graph in fuzzy terms according to the different operating modes of the HRES, where the transitions between the operating modes are represented by the input membership functions, and the operating modes are represented by output membership functions.

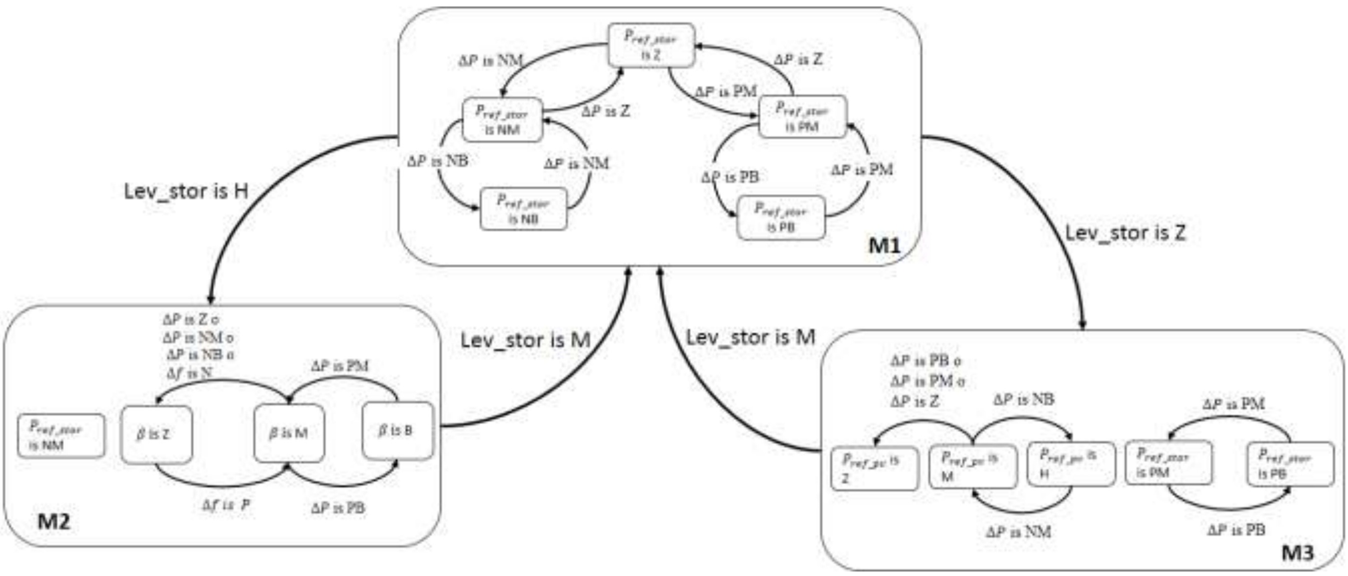

Figure 4: Detailed operational chart of HRES in fuzzy terms

The decomposition of this graph allows the extraction of the fuzzy rules of each operating mode. For example, in operating mode 1, we have the following rules:

- **If** *Lev_stor* is M **and** ΔP is NB **then** P_{ref_stor} is NB
- **If** *Lev_stor* is M **and** ΔP is PB **then** P_{ref_stor} is PB
- **If** *Lev_stor* is M **and** ΔP is NM **then** P_{ref_stor} is NM
- **If** *Lev_stor* is M **and** ΔP is PM **then** P_{ref_stor} is PM
- **If** *Lev_stor* is M **and** ΔP is Z **then** P_{ref_stor} is Z

2.6 Development of evolutionary fuzzy system

The evolutionary fuzzy system is developed in Matlab environment. For this, the fuzzy inference system of the supervisor is modeled with the help of Matlab fuzzy logic toolbox and, membership functions and rules are optimized by evolutionary computing.

2.6.1 Fuzzy inference system modeling of supervisor

The fuzzy inference system (FIS) modeling of supervisor is done in the Matlab fuzzy logic toolbox, which provides: a FIS editor where the input and output variables of the supervisor are defined; a membership function editor that allows to view and edit the membership functions associated with the input and output variables; and a rule editor that allows to create and edit the list of rules that define the behavior of the system. Figure 5 shows the FIS editor of the supervisor, the inference system is Mamdani type, and three input variables are defined: "PowerError", "LevStorage", "FreqError", and three output variables: "RefStor", "RefPV", "RefPitch".

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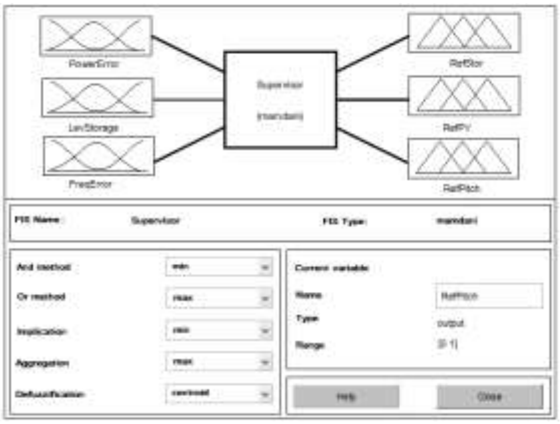

Figure 5: Identification of fuzzy supervisor inputs and outputs in fuzzy logic toolbox

2.6.2 Optimization of fuzzy rules and membership functions by evolutionary computing

Optimization of fuzzy rules and membership functions is carried out using the adaptive model proposed in [12], Figure 6 shows the schema of this model. The scheme is divided into two phases: the first phase is a genetic process optimize membership functions and the second phase is a process to learn and reduce fuzzy rules.

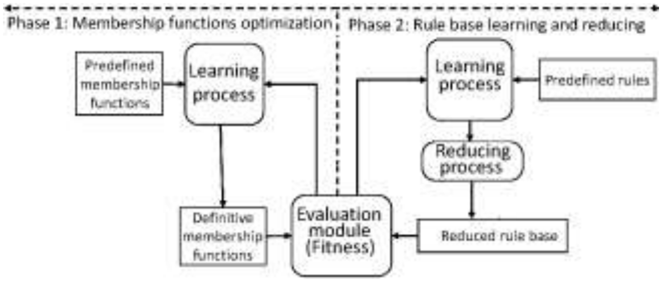

Figure 6: Scheme for optimization of fuzzy rules and tuning membership functions [12]

Optimization of membership functions is carried out by tuning parameters of the functions based on the 2-tuples linguistic representation proposed in [13], which allows the lateral displacement of the support of a label and maintains a good interpretability. The symbolic translation of a label is a number within the interval [- 0.5, 0.5), that expresses the domain of a label when it is moving between its two lateral labels. Let us consider a set of labels *S* representing a fuzzy partition. Formally, to represent the symbolic translation of a label *s*, we have the tuple:

$$(s_i, \alpha_i), s_i \in S, \alpha_i \in [-0.5, 0.5)$$

In Figure 7 an example of the symbolic translation of a label represented by the tuple (Z, 0.1) for the displacement of the corresponding membership function is shown.

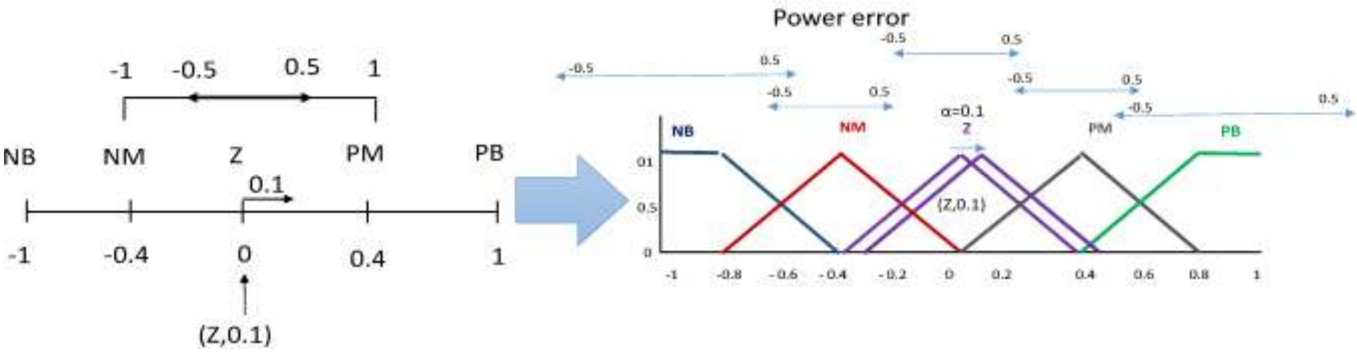

Figure 7: Symbolic translation of a label represented by the tuple (*Z, 0.1*)

For the genetic process of tuning membership functions from preliminary Database (DB), each chromosome encodes the entire DB by joining the partial coding of the different membership functions involved, Figure 8 illustrates this process. For each membership function a value $\alpha \in [-0.5, 0.5)$ is generated, if the value α is positive the membership is displaced to the right, if the value α in negative the membership function is displaced to the left.

For the process of learning and reducing fuzzy rules a genetic scheme of binary coding is applied, each chromosome is a vector of binary values, its size is the number of candidate rules by the number of the consequents of each rule. The vector contains weight factors (w_m^j) that determine the consequence of each rule. For example if we have the rules:

- R1: **If** *Lev_stor* is M **and** ΔP is NM **then** P_{ref_stor} is NM
- R2: **If** *Lev_stor* is A **then** P_{ref_stor} is NM
- R3: **If** *Lev_stor* is Z **and** ΔP is Z **then** P_{ref_pv} is (Z or M)
- …
- Rj: **If** *Lev_stor* is Z **and** ΔP is NM **then**

In figure 9 the coding scheme of the consequents and weight factors of these rules is shown.

Once the membership functions and the rules are encoded, we have a chromosome composed of two sub-chromosomes: a) the sub-chromosome that contains the membership functions parameters of antecedents and consequents and b) the sub-chromosome that contains the weight factors that determine the consequent of each rule in binary values. For the optimization process the genetic algorithm CHC (Cross-generational elitist selection, Heterogeneous recombination) [15] is applied. The global scheme of this algorithm is shown in Figure 10, CHC presents a good trade-off between exploration and exploitation, being a good choice in problems with complex search spaces. To have diversity in the population, the CHC approach makes use of an incest prevention mechanism and a restart process, instead of the mutation operator.

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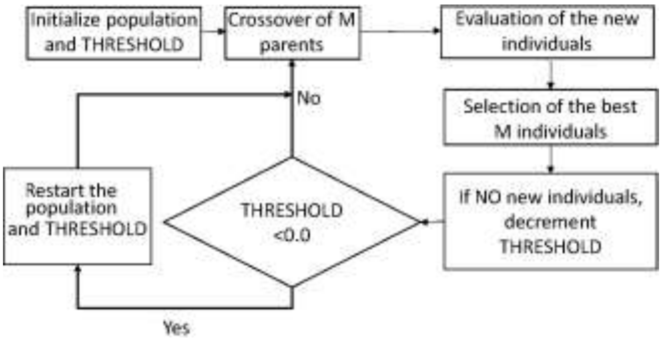

Figure 10: Scheme of CHC approach [14]

2.7 Configuration of the simulation model

In order to test the supervisor performance, the behavior of the HRES is simulated, the HRES modeled and presented in [16] in Matlab Simulink is used, which is shown in Figure 11. For the simulation of the wind and photovoltaic subsystems, we take the solar radiation and wind speed data recorded by the Centro Regional de Tecnología Eólica (CERTE) located in Juchitán, Oaxaca, each record contains date and time, wind speed, wind direction and solar radiation from January 01, 2012 00:00 hrs. to August 28, 2013 4:30 p.m. at 10 min intervals.

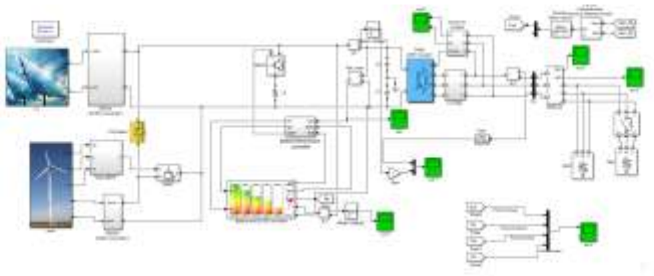

Figure 11: Simulation diagram of the hybrid wind-solar system in Simulink [16]

2.7.1 Experimental implementation of the fuzzy logic supervisor in the simulation model

In this step, the fuzzy logic supervisory control is implemented in the simulation model and the supervisor learning process is carried out. The implementation of the supervisory control in the simulation model is done through a Fuzzy Logic Controller (FLC) block in Simulink, it is shown in Figure 12 and allows to implement the supervisor Fuzzy Inference System (FIS) previously generated with the help of the fuzzy logic toolbox in Matlab.

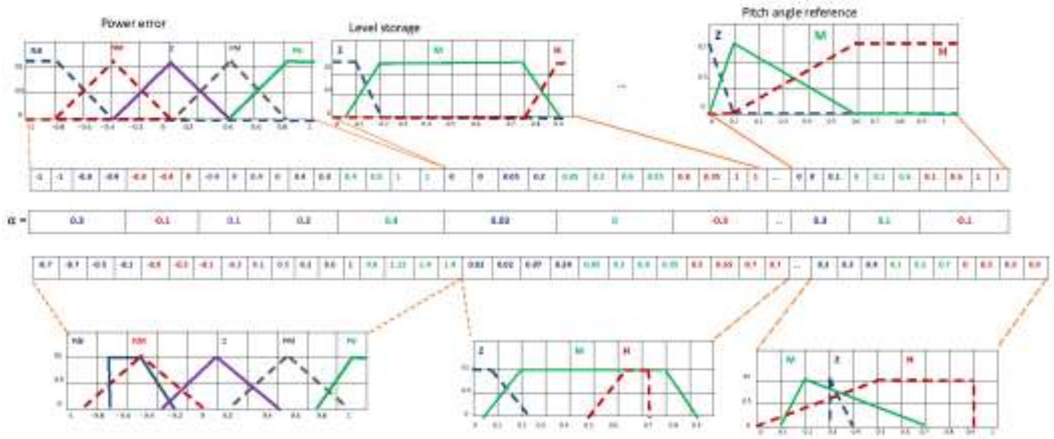

Figure 8: Scheme of encoding and symbolic translation of membership functions of some supervisor input and output variables

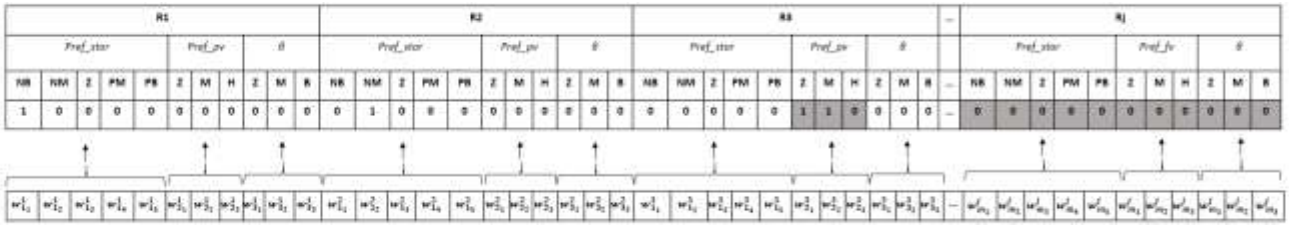

Figure 9: Coding scheme and weight factors of fuzzy rules

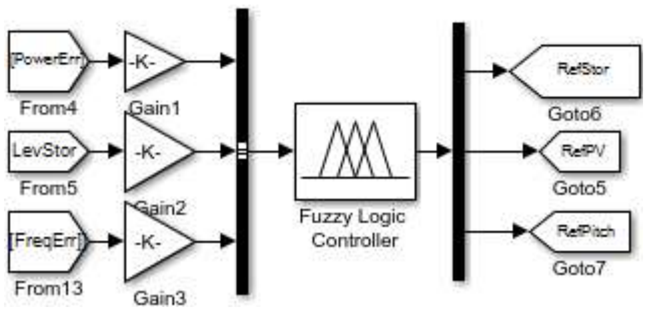

Figure 12: Fuzzy Logic Inference block of the supervisor in Simulink

The genetic process for the supervisor learning working on a FLC is described as follows:

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1. Start the initial population P(0);
   /*Evaluate P (0)*/
2. **For all** *P(0)* **do** /*Evaluate P (0)*/
   a) Take each chromosome and introduce it into the FLC;
   b) Apply the FLC to the controlled system for an adequate evaluation period;
   c) Evaluate the behavior of the controlled system by producing a performance index;
3. **End**
4. **While** *finish condition is not met* **do**
   a) Create a new generation (P(t+1)) by applying the evolution operator to the individuals;
   b) Evaluate P(t+1)
   c) Replace the current population with the new population t=t+1
5. **End**
6. Stop

3. Experimental work

In order to test the supervisor performance, experiments are designed for each operating mode of the HRES. The experiment cases and the data from the CERTE for the simulation of these cases are described below.

- **Experimental case of Mode 1**: The first case is an operating situation of the HRES where the wind system generates enough power to satisfy the load demand ($P_{hyb}>=P_{ref}$), so the supervisory control generates a reference of the storage system equal to zero, i.e. the battery does not provide power to the load demand. For this experiment the battery has a storage level *Medium*.
- **Experimental case of Mode 2**: In this case the battery is charged, and the storage level is *High*. The storage unit must be discharged to maintain storage availability. In this discharge process, the wind system must decrease the power generation, therefore the supervisory control generates a pitch angle reference to reduce the wind power.
- **Experimental case of Mode 3**: In this case the storage level is *Low* and the wind system is not able to generate enough power to satisfy the load, so the supervisory control generates the reference power for the photovoltaic system to help supply the power demanded by the load.

In Table 2 we have the data for the experimental case of Mode 1 and Mode 2 that correspond to periods with enough wind to satisfy the load demand, for this simulation we take the record of the day with the highest wind speed, being the date 03/01/2012, the simulated period was from 00:30 hrs. to 2:00 hrs.

Table 2: Data of solar radiation and wind speed for experimental cases of Mode 1 and Mode 2

Date and time	*Wind speed (m/s)*	*Solar radiation (W/m^2)*
03/01/2013 00:30	27.86	0.0
03/01/2012 00:40	27.19	0.0
03/01/2012 00:50	26.33	0.0
03/01/2012 01:00	25.00	0.0
03/01/2012 01:10	25.88	0.0
03/01/2012 01:20	24.77	0.0
03/01/2012 01:30	23.56	0.0
03/01/2012 01:40	24.42	0.0
03/01/2012 01:50	25.09	0.0
03/01/2012 02:00	23.70	0.0

Table 3 shows the data for the experimental case of Mode 3, where the wind system does not generate enough power and the photovoltaic system must be able to satisfy the load demand power. For this case we take the data where the wind speed is low and the solar radiation is high, being the day 08/13/2013 from 19:10 hrs. to 20:40 hrs.

Table 3: Data of solar radiation and wind speed for the experimental case of Mode 3

Date and time	*Wind speed (m/s)*	*Solar radiation (W/m^2)*
13/08/2013 19:10	13.75	1226.542
13/08/2013 19:20	12.63	1284.66
13/08/2013 19:30	11.2	1175.077
13/08/2013 19:40	11.13	1085.526
13/08/2013 19:50	12.25	1080.995
13/08/2013 20:00	11.45	1057.114
13/08/2013 20:10	11.24	1002.066
13/08/2013 20:20	10.64	1086.023
13/08/2013 20:30	10.62	717.6375
13/08/2013 20:40	9.14	528.6746

4. Results interpretation

In this section we make the interpretation of the results obtained by comparing the simulation result of the supervisor fuzzy inference system with rules and membership functions defined in the sections 2.4 and 2.5 (initial chromosome), and the simulation result of the supervisor fuzzy inference system with the optimized rules and functions once the evolutionary algorithm was applied.

- **Experimental case of Mode 1:** Figure 13 shows the simulation result for this case, where the wind system must satisfy the load. For this simulation, the initial chromosome was taken and introduced into the fuzzy logic controller (FLC) block in the simulation model. In this simulation it is observed that although the wind system (yellow line) generates enough power to satisfy the load (blue line), the power generated by the battery (red line) has several fluctuations, which means that there is a power instability in the HRES. Figure 14 shows the total power generated by the HRES (blue line) and the load demand power (red line). Due to the battery behavior, the total power of the HRES is very fluctuating, so there is no balance between generation and demand.

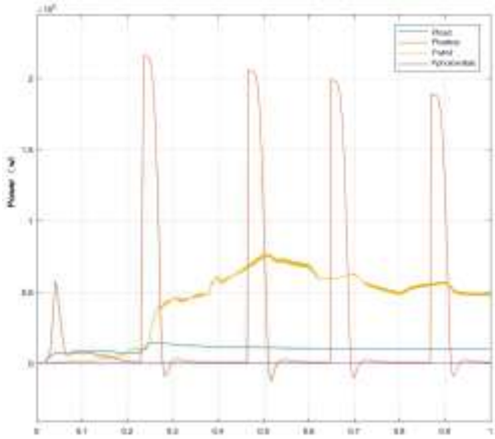

Figure 13: Power generated by the HRES subsystems in Mode 1 simulation

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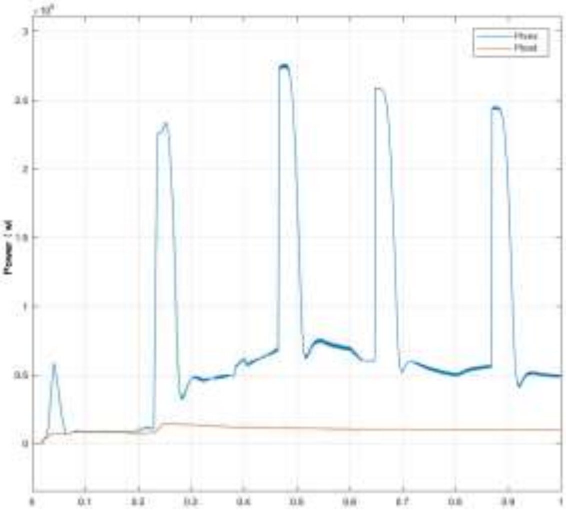


Figure 14: Total power generated by the HRES and load demand power for Mode 1 simulation

Once the evolutionary algorithm was applied under the same conditions, a new chromosome was obtained for the fuzzy inference system. To evaluate the chromosome of each individual of the population, we used the mean square error (MSE) function in Matlab. The mean square error between a signal X, and an approximation Y, is the squared norm of the difference divided by the number of elements in the signal ($\|X-Y\|^2/N$). The signals evaluated by the MSE function are the signal received from Simulink of the power error and the approximation must be a power error signal equal to zero.

Table 4 and Table 5 show the variations in the input and output functions respectively, between the initial chromosome and the chromosome of the best individual generated by the evolutionary algorithm (EA).

Table 4: Membership functions of optimized input variables

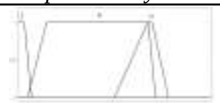
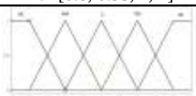
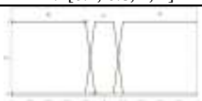
Input variables	*Initial membership functions*	*Membership functions optimized by EA*
Level storage	 Z: [0, 0, 0.05, 0.2] M: [0.05, 0.2, 0.8, 0.95] H: [0.8, 0.95, 1, 1]	 Z: [0, 0, 0.02969, 0.06697] M: [0.048, 0.14, 0.69, 0.77] H: [0.49, 0.67, 0.67, 0.71]
Power error	 NB: [-1, -1, -0.8, -0.4] NM: [-0.8, -0.4, 0] Z: [-0.4, 0, 0.4] PM: [0, 0.4, 0.8] PB: [0.4, 0.8, 1, 1]	 NB: [-0.88, -0.86, -0.72, -0.36] NM: [-0.5, -0.3, 0] Z: [-0.4, 0, 0.28] PM: [0, 0.31, 0.64] PB: [0.3, 0.75, 0.8, 0.97]
Frequency error	 N: [-1, -1, -0.2, -0.1] Z: [-0.2, -0.1, 0.1, 0.2] P: [0.1, 0.2, 1, 1]	 N: [-0.39, -0.08, -0.006, -0.0012] Z: [-0.14, -0.07, 0.108, 0.15] P: [0.06, 0.07, 0.73, 0.83]

Table 5: Membership functions of optimized output variables

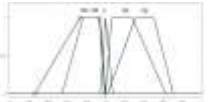
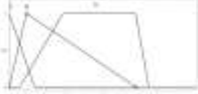
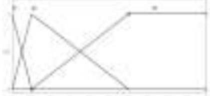
Output variables	*Initial membership functions*	*Membership functions optimized by EA*
Reference power of storage system	 NB: [-1, -1, -0.8, -0.4] NM: [-0.8, -0.4, -0.1, 0] Z: [-0.1, 0, 0.1] PM: [0, 0.1, 0.4, 0.8] PB: [0.4, 0.8, 1, 1]	 NB: [-0.73, -0.26, -0.06, -0.007] NM: [-0.44, -0.23, -0.05, 0] Z: [-0.05, 0, 0.073] PM: [0, 0.06, 0.27, 0.62] PB: [0.02, 0.31, 0.503, 0.703]
Reference power of photovoltaic system	 Z: [0, 0, 0.1] M: [0, 0.1, 0.6] H: [0.1, 0.6, 1, 1]	 Z: [0, 0, 0.1359] M: [0, 0.09, 0.67] H: [0.05, 0.28, 0.67, 0.74]
Pitch angle reference	 Z: [0, 0, 0.1] M: [0, 0.1, 0.6] B: [0.1, 0.6, 1, 1]	 Z: [0, 0, 0.02878] M: [0, 0.0786, 0.4647] B: [0.06, 0.39, 0.66, 0.664]

Figure 15 shows the result of the simulation with the chromosome of the best individual, where it is observed that even though the wind system (yellow line) tries to satisfy the load (blue line) this is not enough, therefore the battery (red line) helps to supply this power deficit by entering in a discharge mode. Figure 16 shows the total power generated by the HRES (blue line) and the load demand (red line), noting that at 0.2s the behavior between generation and demand begins to stabilize.

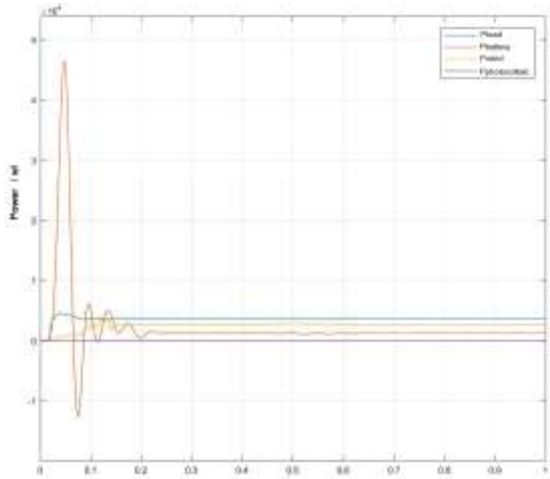


Figure 15: Powers generated by the HRES subsystems in Mode 1 simulation once the evolutionary algorithm has been applied

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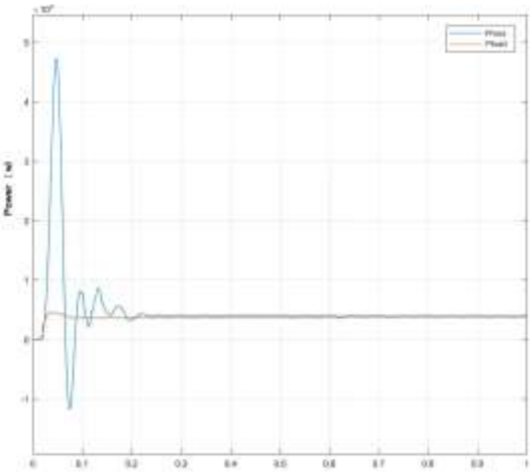

Figure 16: Total power generated by the HRES and load demand for the experimental case of Mode 1 once the evolutionary algorithm is applied

- **Experimental case of Mode 2:** In this case the battery has a *High* storage level, for this case the storage level is 90% and must be discharged to maintain storage availability. And we use the inference system of the best individual chromosome in the FLC previously generated by the EA, in order to test it under different conditions.

Figure 17 shows the powers generated by the HRES subsystems, where it is observed how the wind system generates the power (yellow line) to satisfy the load demand (blue line), given that the battery has a high storage level, it also generates power (red line) to satisfy the load entering in a discharge process. Figure 18 shows the total power generated by the HRES (blue line) and the load demand power (red line).

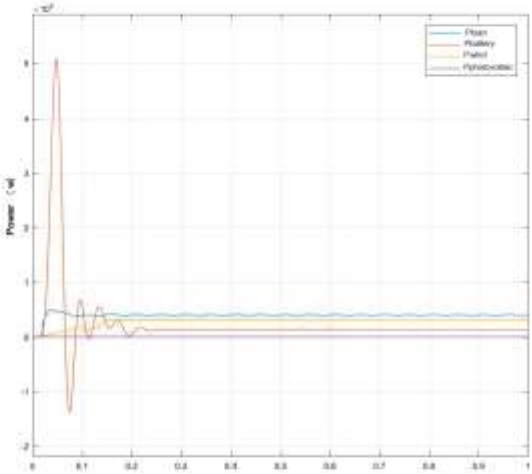

Figure 17: Powers generated by the HRES subsystems in the simulation of experimental case of Mode 2 once the evolutionary algorithm has been applied

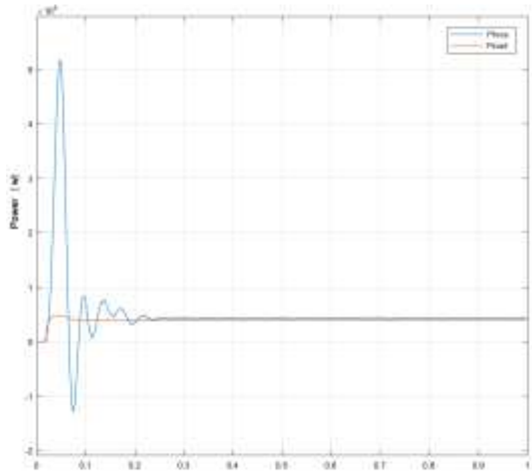

Figure 18: Total power generated by the HRES and load demand power for the experimental case of Mode 2

- **Experimental case of Mode 3:** In this case, the wind system does not generate sufficient power and the storage level is *Low*, for this simulation the storage level is at 15%, so that the photovoltaic system is in charge of satisfying the load demand.

The simulation result with the inference system of the initial chromosome is shown in Figure 19. We notice that the photovoltaic system is generating enough power (purple line) to satisfy the load (blue line), however it has several fluctuations, at 0.4s the wind speed increases and the wind system begins to generate power (line yellow), so the load demand is satisfied between the photovoltaic and wind systems. Figure 20 shows the total power generated by the HRES (blue line) and the load demand (red line). We can notice that even though the HRES satisfies the load, there are variations between generation and demand, which means that there is not stability in the system.

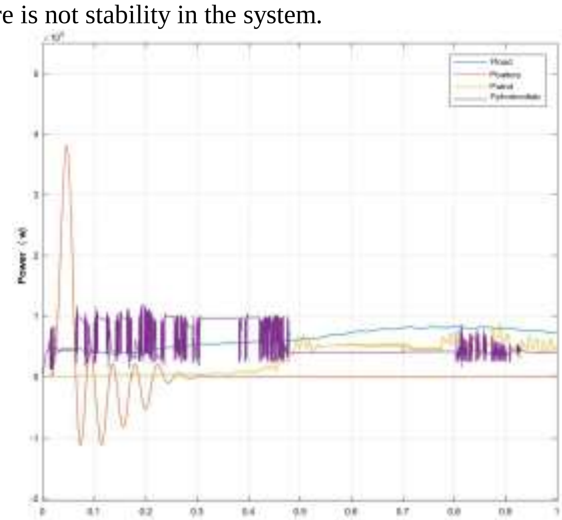

Figure 19: Power generated by each subsystem of the HRES in the simulation of experimental case of Mode 3

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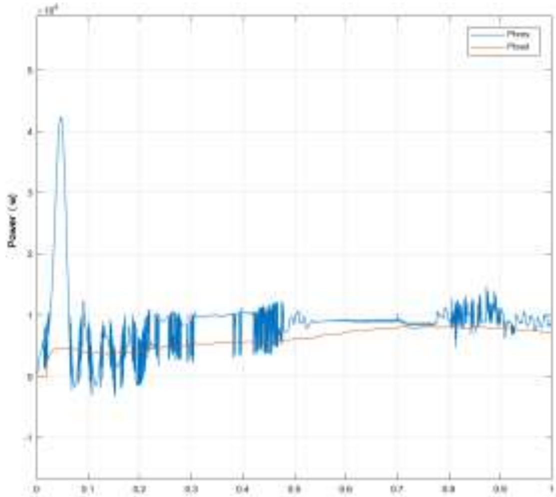


Figure 20: Total power generated by the HRES and load demand power of the experimental case of Mode 3

Once the evolutionary algorithm was applied under the same conditions, a new chromosome was obtained for the inference system. Table 6 and Table 7 show the variations in the input and output functions respectively, between the initial chromosome and the chromosome of the best individual generated by the evolutionary algorithm. Figure 21 shows the simulation result with the best individual chromosome, where we can see that the photovoltaic system generates the power (purple line) to satisfy the load, approximately at 0.4 s the wind system begins to generate power (yellow line) and between both subsystems try to satisfy the load demand power (blue line). Figure 22 shows the total power generated by the HRES (blue line) and power demanded by the load (red line), where there is less variation between generation and demand than in the case of results obtained with the inference system of the initial chromosome.

Table 6: Membership functions of the optimized input variables

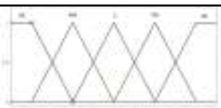
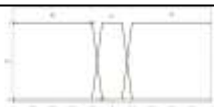
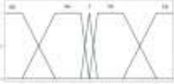
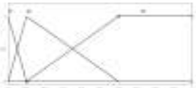
Input variables	*Initial membership functions*	*Membership functions optimized by EA*
Level storage	 Z: [0, 0, 0.05, 0.2] M: [0.05, 0.2, 0.8, 0.95] H: [0.8, 0.95, 1, 1]	 Z: [0, 0, 0.03378, 0.1351] M: [0.06, 0.26, 1.07, 1.27] H: [0.66, 0.78, 0.82, 0.82]
Power error	 NB: [-1, -1, -0.8, -0.4] NM: [-0.8, -0.4, 0] Z: [-0.4, 0, 0.4] PM: [0, 0.4, 0.8] PB: [0.4, 0.8, 1, 1]	 NB: [-0.8, -0.8, -0.64, -0.32] NM: [-1.096, -0.548, 0] Z: [-0.456, 0, 0.3509] PM: [0, 0.3636, 0.7273] PB: [0.556, 1.112, 1.39, 1.39]
Frequency error	 N: [-1, -1, -0.2, -0.1] Z: [-0.2, -0.1, 0.1, 0.2] P: [0.1, 0.2, 1, 1]	 N: [-1.25, -1.25, -0.25, -0.125] Z: [-0.202, -0.101, 0.099, 0.198] P: [0.123, 0.246, 1.23, 1.23]

Table 7: Membership functions optimized output variables

Output variables	*Initial membership functions*	*Membership functions optimized by EA*
Reference power of storage system	 NB: [-1, -1, -0.8, -0.4] NM: [-0.8, -0.4, -0.1, 0] Z: [-0.1, 0, 0.1] PM: [0, 0.1, 0.4, 0.8] PB: [0.4, 0.8, 1, 1]	 NB: [-1.3, -1.3, -1.04, -0.52] NM: [-1.024, -0.512, -0.128, 0] Z: [-0.06757, 0, 0.148] PM: [0 0.109, 0.436, 0.872] PB: [0.33, 0.66, 0.83, 0.83]
Reference power of photovoltaic system	 Z: [0, 0, 0.1] M: [0, 0.1, 0.6] H: [0.1, 0.6, 1, 1]	 Z: [0, 0, 0.147] M: [0, 0.14, 0.84] H: [0.076, 0.458, 0.763, 0.763]
Pitch angle reference	 Z: [0, 0, 0.1] M: [0, 0.1, 0.6] B: [0.1, 0.6, 1, 1]	 Z: [0, 0, 0.06667] M: [0, 0.121, 0.726] B: [0.137, 0.822, 1.37, 1.37]

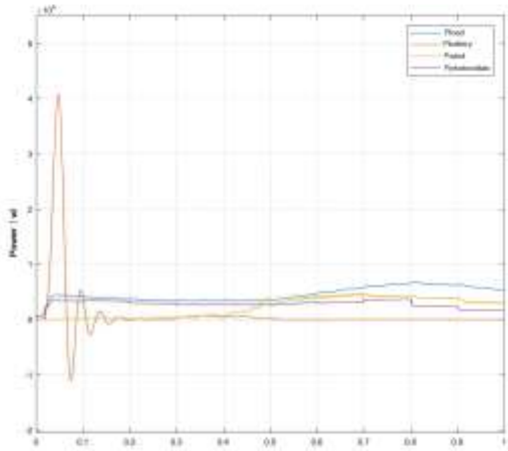


Figure 21: Powers generated by the HRES subsystems in simulation of Mode 3 once the evolutionary algorithm is applied

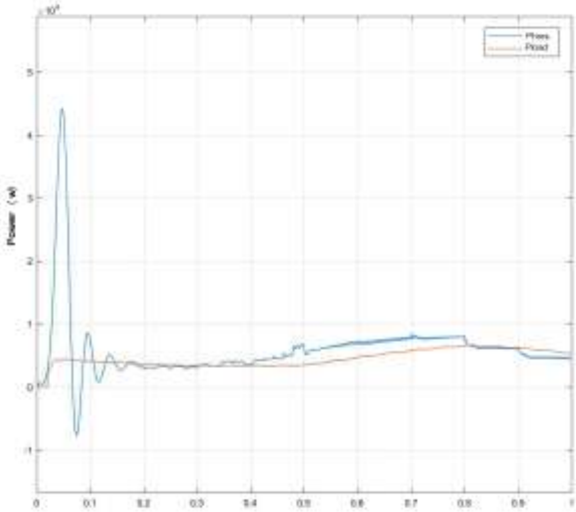


Figure 22: Total power generated by the HRES and load demand power for the experimental case of Mode 3 once the evolutionary algorithm is applied

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5. Conclusions

In this paper, the modeling and experimental implementation of supervisory control with an evolutionary and fuzzy approach was presented in an HRES composed of two renewable energy subsystems (solar and wind) and a storage system. The fuzzy approach allows the management of renewable energy sources while the evolutionary approach had the purpose of optimizing membership functions and fuzzy rules in order to improve the performance of supervisory control. The experimental results showed that the evolutionary approach allows to suggest new rules and parameters of the membership functions for a better performance of the supervisor that allows to manage the renewable energy sources in the HRES.

References

[1] M. Fadaee and M. A. M. Radzi, "Multi-objective optimization of a stand-alone hybrid renewable energy system by using evolutionary algorithms: A review," *Renew. Sustain. Energy Rev.*, vol. 16, no. 5, pp. 3364–3369, 2012.

[2] A. Anvari, A. Sei, T. Niknam, M. Reza, and A. Pahlavani, "Multi-objective operation management of a renewable MG (micro-grid) with back-up micro-turbine / fuel cell / battery hybrid power source," vol. 36, pp. 6490–6507, 2011.

[3] T. Alnejaili, D. Mehdi, S. Drid, and L. Chrifi-Alaoui, "Advanced supervisor control for a stand-alone photovoltaic super capacitor battery hybrid energy system for remote building," *2015 4th Int. Conf. Syst. Control. ICSC 2015*, pp. 278–283, 2015.

[4] F. Valenciaga and P. F. Puleston, "Supervisor control for a stand-alone hybrid generation system using wind and photovoltaic energy," *IEEE Trans. Energy Convers.*, vol. 20, no. 2, pp. 398–405, 2005.

[5] M. Kalantar and S. M. G. Mousavi, "Dynamic behavior of a stand-alone hybrid power generation system of wind turbine , microturbine , solar array and battery storage," *Appl. Energy*, vol. 87, no. 10, pp. 3051–3064, 2010.

[6] J. Lagorse, M. G. Simoes, and A. Miraoui, "A Multiagent Fuzzy-Logic-Based Energy Management of Hybrid Systems," *Ind. Appl. IEEE Trans.*, vol. 45, no. 6, pp. 2123–2129, 2009.

[7] M. Nasser, A. Vergnol, J. Sprooten, and B. Robyns, "A global supervision for wind / hydro power plant and storage system connected to AC grid Keywords I . Introduction II . Modelling of the system under study," *Power*, pp. 1–10, 2009.

[8] V. Courtecuisse, J. Sprooten, B. Robyns, M. Petit, B. Francois, and J. Deuse, "A methodology to design a fuzzy logic based supervision of Hybrid Renewable Energy Systems," *Math. Comput. Simul.*, vol. 81, no. 2, pp. 208–224, 2010.

[9] S. Berrazouane, K. Mohammedi, L. Energétique, and I. Lemi, "Hybrid System Energy Management and Supervision based on Fuzzy Logic Approach for Electricity Production in Remote Areas," *Technology*, vol. 0, no. 1, pp. 324–329, 2012.

[10] G. Boukettaya, L. Krichen, and A. Ouali, "Fuzzy logic supervisor for power control of an isolated hybrid energy production unit," *International Journal of Electrical and Power Engineering*, vol. 1, no. 3. pp. 279–285, 2007.

[11] I. Abadlia, T. Bahi, and H. Bouzeria, "Energy management strategy based on fuzzy logic for compound RES/ESS used in stand-alone application," *Int. J. Hydrogen Energy*, vol. 41, no. 38, pp. 16705–16717, 2016.

[12] P. C. Shill, M. A. H. Akhand, M. Asaduzzaman, and K. Murase, "Optimization of Fuzzy Logic Controllers with Rule Base Size Reduction using Genetic Algorithms," *Int. J. Inf. Technol. Decis. Mak.*, vol. 14, no. 5, 2015.

[13] R. Alcalá, J. Alcalá-Fdez, and F. Herrera, "A proposal for the genetic lateral tuning of linguistic fuzzy systems and its interaction with rule selection," *IEEE Trans. Fuzzy Syst.*, vol. 15, no. 4, pp. 616–635, 2007.

[14] R. Alcala and F. Herrera, "Genetic learning of accurate and compact fuzzy rule based systems based on the 2-tuples," vol. 44, pp. 45–64, 2007.

[15] L. J. Eshelman, "The CHC Adaptive Search Algorithm: How to Have Safe Search When Engaging in Nontraditional Genetic Recombination," *Elsevier*, vol. 1, pp. 265–283, 1991.

[16] K. P. Reddy and M. V. G. Rao, "Modelling and Simulation of Hybrid Wind Solar Energy System using MPPT," *Indian J. Sci. Technol.*, vol. 8(23), no. September, pp. 4–8, 2015.

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