Fuzzy Multi-Sets and Multi-Rules: Analysis of Hybrid Systems concerning Renewable Sources with Conventional and Flow Batteries

Alexandre Barin, Luciane Neves Canha, Alzenira da Rosa Abaide, Karine Faverzani Magnago

Federal University of Santa Maria, Brazil
CEEMA/UFSM - Avenida Roraima nº 1000, Cidade Universitária, Bairro Camobi, Santa Maria — RS – Brasil – CEP:97105-900
Phone: +55 55 32208792

E-mail: alexandrebarin@hotmail.com; lncanha@ufsm.ct.br ; alzenira@ct.ufsm.br ; kamagnago@gmail.com

Fuzzy Multi-Sets and Multi-Rules: Analysis of Hybrid Systems concerning Renewable Sources with Conventional and Flow Batteries

A. Barin, L. N. Canha, A. R. Abaide, K. F. Magnago

Abstract— The increasing market penetration of intermittent renewable resources – as a solution to green power energy production - has been resulting in the development of several types of storage technologies, such as: PHS, CAES, Flywheel, and supercapacitors. However, the constant development of different types of batteries - both conventional and by flow - turns this type of storage system one of the most useful to be applied together with renewable energy sources. This paper uses multi-rules-based decision and multi-sets considerations applied in the fuzzy logic to evaluate the main characteristics of the operation of intermittent renewable sources and batteries. The renewable sources analyzed in this work are wind generators and photovoltaic cells, while the analyzed batteries are Lead Acid, Nickel Cadmium, Lithium ion, Sodium-Sulphur, Vanadium Redox and Polysulphide bromide (flow batteries). These analyses are developed according to the desirable criteria defined to find the most appropriate renewable hybrid system, considering two different scenarios: costs and environment. The selected criteria are: environmental impacts, efficiency, costs, lifecycle, technical maturity and power application range.

***Index Terms* — batteries, fuzzy logic, renewable hybrid system, intermittent renewable sources.**

I. INTRODUCTION

In response to the energy crisis and pollution problems, it is needed to adopt new energy suppliers that use renewable energy sources (RES) and storage energy technologies (SES) in an efficient and environmentally manner. Storage energy systems have been used together with distributed generation sources (DG) in order to provide both technical and economic benefits to energy systems [1]. Besides, the increasing interest to search solutions for green power energy production has given rise to discussions about which type of renewable hybrid system would be the most appropriated choice to be used in distributed generation networks [2]. It is worth emphasizing that many renewable sources (RES), such as solar photovoltaic and wind are unavailable during long periods of time. Therefore, it is essential to use SES together with RES, improving in this way the system efficiency and reliability, as well providing the appropriate management of DG systems [3]. Although renewable hybrid systems cannot guarantee high levels of investments return comparing with systems using fossil fuels, they are capable to delivery power in an affordable scale for consumers, and also may be profitable for producers [4].

Batteries are the most common devices used to store electrical energy [5]. Traditionally, they have been used mainly for small scale applications. But due to the liberalization of electricity markets, manufacturers have been realized also some potential applications for larger scale energy storages. This paper evaluates the classical batteries lead-acid (LA) and Nickel-cadmium (NiCd), as well as it analyzes the advanced battery technologies sodium-sulphur (NaS) and lithium-ion.

Flow batteries (FB), also known as Regenerative Fuel Cells or Redox Flow Systems, are a new class of battery that has been achieving substantial progress - technically and commercially. Flow Batteries present some features that make them especially attractive for utility-scale applications. The operational principle differs from classical batteries. The latter store energy both in the electrolyte and the electrodes, while flow batteries store and release energy using a reversible reaction between two electrolyte solutions, separated by an ion permeable membrane. Both electrolytes are stored separately in bulk storage tanks, whose size defines the energy capacity of the storage system. The power rating is determined by the cell stack. Therefore, the power and energy rating are decoupled, which gives to the system designer an extra degree of freedom when structuring the system. Many different electrolyte couples have been proposed to be used in flow batteries. This paper evaluates the flow batteries namely: vanadium redox (VRB) and sodium polysulphide / sodium bromide (PSRB).

Therefore, this paper uses multi-rules-based decision and multi-sets considerations applied in fuzzy logic according to the main characteristics of intermittent operation of renewable sources and batteries. For the assessment of these technologies some parameters are incorporated in the fuzzy analysis. These parameters are evaluated in two different scenarios - costs and environment. The selected parameters are: environment impacts, efficiency, costs, lifecycle, technical maturity and power application range.

II. Fuzzy Methodology

Fuzzy logic is considered one of the most powerful control methods and can be used for many different applications [6], [7], [8]. In this paper, the fuzzy analysis is developed with the software MATLAB®, by multi-rules-based decisions and multi-sets considerations, regarding both quantitative and qualitative parameters.

To develop the methodology, the main operation characteristics of two types of renewable energy sources and six types of batteries are analyzed, in two different scenarios, according to six parameters. The focus of these analyses is to find the most appropriate type of renewable hybrid system to be used in each case (scenario).

By using the software MATLAB®, it is applied the Mamdani fuzzy process and the method of the Center of Gravity in the defuzzification process [9]. A basic Mamdani fuzzy system is simple characterized. It accepts numbers as input, then translate the input numbers into linguistic terms such as low, medium, high (fuzzification). Rules then map the input linguistic terms onto similar linguistic terms describing the output [10]. Lastly, the output linguistic terms are translated into an output number (defuzzification).

The main idea of the Mamdani is to describe process states by means of linguistic variables and to use them as inputs to control rules. The linguistic terms are represented in fuzzy sets with a certain shape. It is popular to use trapezoidal or triangular fuzzy sets due to computational efficiency [11].

The choice for Mamdani follows the aspects presented in sequence [12]:

- it is suitable for engineering systems because its inputs and outputs are real-valued variables;
- it provides a natural framework to incorporate fuzzy rules from human experts;
- there is much freedom in the choices of fuzzifier, fuzzy inference engine, and defuzzifier;
- it provides an effective framework to integrate numerical and linguistic information.

As regards the defuzzification process, there are several choices to be made and many different methods had been proposed [13]. In this study, it is used the method called Center of area (COA) or Center of Gravity (COG). This method chooses the control action that corresponds to the center of the area with membership greater than zero. The area is weighted with the value of the membership function. The choice for COG is justified because the use of this method is advisable not only for quantitative but also for qualitative analysis.

The number of linguistic terms in each fuzzy set determines the number of rules. In most applications certain states can be neglected either because they are impossible or because a control action would not be helpful. It is therefore sufficient to write rules that cover only parts of the state space. The definition of linguistic variables and rules are the main design steps when implementing a Mamdani controller. Besides, an appropriate classification of the parameters priority is essential to corroborate the outcome of the fuzzy methodology. Thus, the scenarios simulated in this study were evaluated by a previous classification of the parameters priority, considering different constrains. This priority was created according to different importance observed among the parameters, regarding costs and environment scenarios. The priority classification facilitates the development of simulation steps and eases the methodology understanding. The classification of the parameters priority defined for each scenario is given below:

Scenario costs: 1st costs, 2nd technical maturity, 3rd efficiency, 4th life cycle, 5th power application range and 6th environmental impacts.

Scenario Environment: 1st environmental impacts, 2nd efficiency, 3rd life cycle, 4th technical maturity, 5th power application range and 6th costs.

To develop the fuzzy analysis, it was important to share the six described parameters in two sub-groups. It follows in sequence.

A. Qualitative parameters

The qualitative parameters were expressed through weights to be applied in the fuzzy sets. These weights are defined by the decision maker in an interval from 0 to 1.0. The qualitative parameters analyzed in this paper are exposed below:

- technical maturity (TM); it also concerns self-discharge in case of batteries;
- power application range (PAR): concerning from Watts to few MW for batteries and from kW to hundreds of MW for renewable resources;
- environmental impacts: related to disposal, presence of toxic elements and energy density in case of batteries; and visual impact, presence of toxic elements and biological impacts in case of renewable resources.

B. Quantitative parameters

The quantitative parameters were expressed through rated data. The quantitative parameters evaluated in this work are presented in sequence:

- lifecycle (LC): in years, for both analyses;
- efficiency (EF): in %, for both analyses;
- costs: in US$/MWh for renewable systems; in US$/kWh for batteries.

The rated data and the weights used in the fuzzy analyses to evaluate quantitative and qualitative parameters are presented in Table I and Table II, considering intermittent RES and batteries, respectively. It is important to observe each analysis has its particular rules and fuzzy sets. Thus, each case is evaluated individually by the fuzzy methodology.

TABLE I
RENEWABLE SYSTEMS DATA AND WEIGHTS

Parameters	RES	
	PV	WIND
T.Maturity	0.5	0.8
LC (years)	25	20
EF (%)	15	30
COSTS (U$/MWh)	900	150
PAR	0.75	1.0
Impacts	0.75	0.85

TABLE II
BATTERIES DATA AND WEIGHTS

Parameters	Batteries					
	LA	NiCd	Lithium	NaS	VRB	PSRB
T.Maturity	0.85	0.6	0.7	0.6	0.5	0.45
LC (years)	8	10	10	13	25	25
EF (%)	80	65	90	80	90	65
COSTS U$/kWh	150	600	500	500	600	450
PAR	0.75	0.7	0.3	0.5	0.55	0.55
Impacts	0.65	0.5	0.7	0.55	0.55	0.55

Figures 1 to 9 show the fuzzy sets for each parameter, according to RES and battery analyses. The number of membership functions of the fuzzy set used in each parameter, and the multi-rules, are determined according to the previous classification of the parameters priority. Besides, both shape and position of the fuzzy set are chosen subjectively, but satisfying the requirements of each parameter analysis.

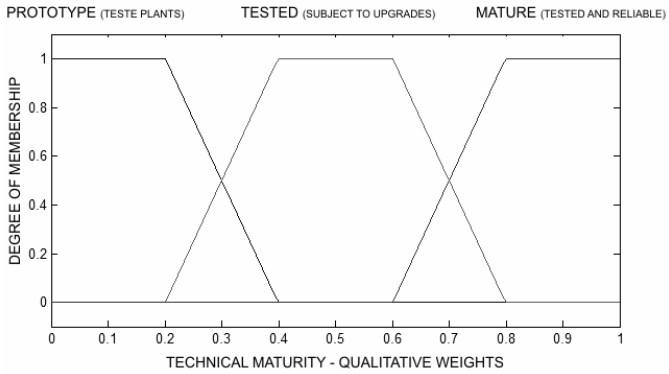

Figure 1 – Criterion: Technical maturity (TM) – RES and Battery Analyses.

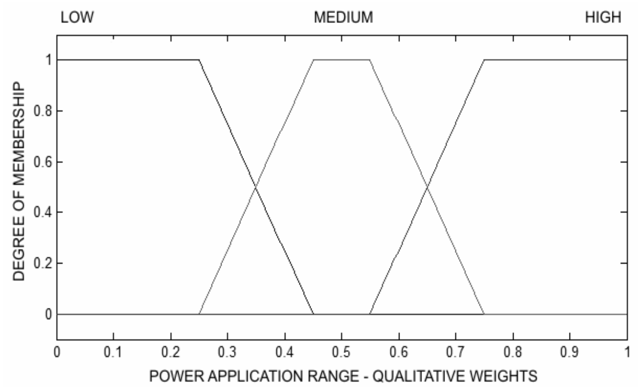

Figure 2 – Criterion: Power Application Range (PAR) – RES and Battery Analyses.

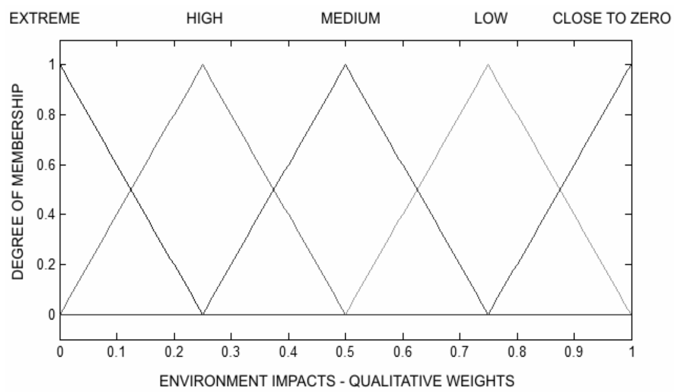

Figure 3 – Criterion: Environmental Impacts (EI) – RES and Battery Analyses.

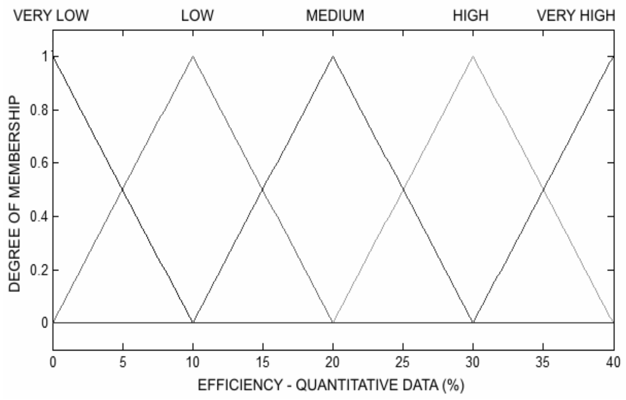

Figure 4 – Criterion: Efficiency – RES Analysis.

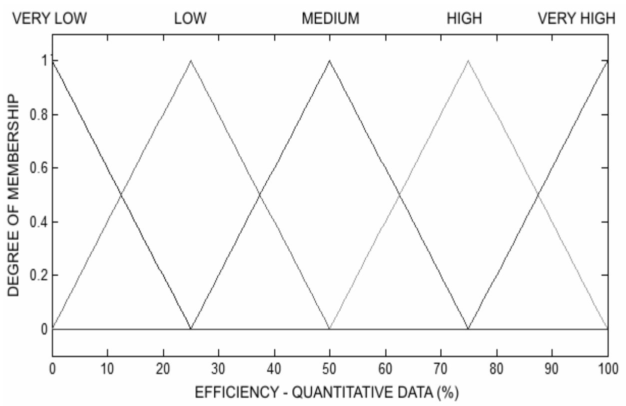

Figure 5 – Criterion: Efficiency – Battery Analysis.

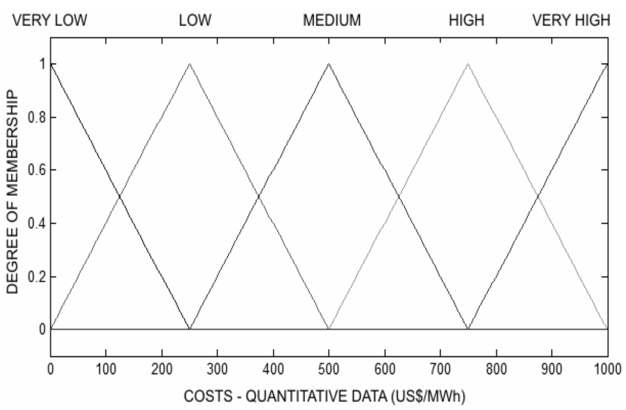

Figure 6 – Criterion: Costs – RES Analysis.

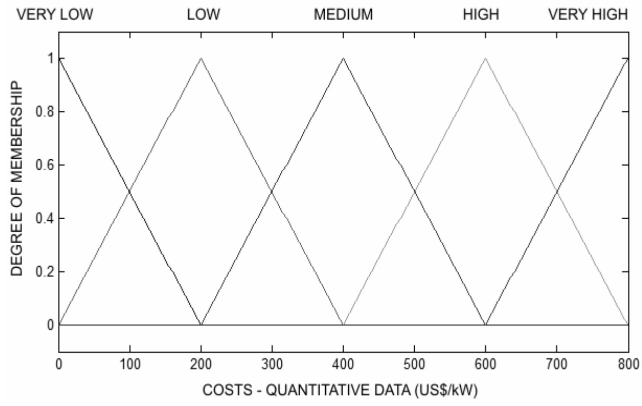

Figure 7 – Criterion: Costs – Battery Analysis.

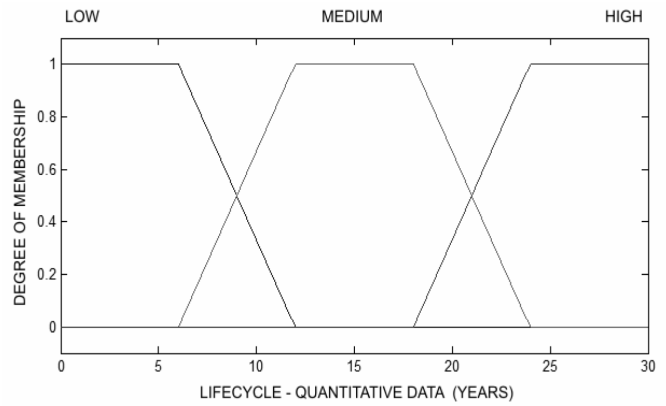

Figure 8 – Criterion: Life Cycle (LC) – RES Analysis.

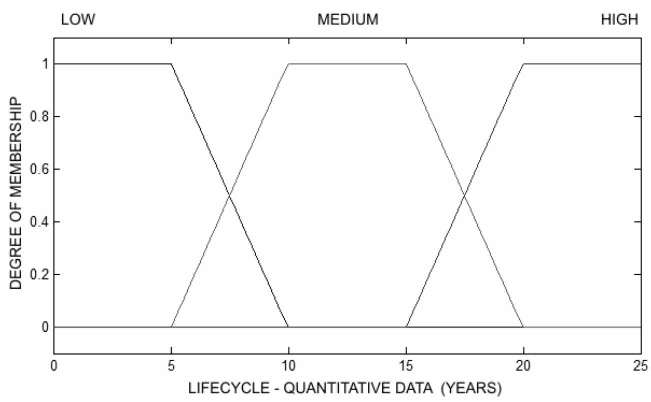

Figure 9 – Criterion: Life Cycle (LC) – Battery Analysis.

III. Main Results

The final classifications (CL) obtained with the Fuzzy logic, concerning both the renewable resources and batteries, are presented in Table III and IV.

TABLE III
INTERMITTENT SOURCES CLASSIFICATION

Sources	Costs	CL	vironEn	CL
PV	0.061	**2nd**	0.648	**2nd**
WIND	0.805	**1st**	0.740	**1st**

TABLE IV
BATTERIES CLASSIFICATION

Batteries	Costs	CL	Environ	CL
LA	0.825	**1st**	0.598	**3rd**
NiCd	0.140	**6th**	0.490	**4th**
Lithium	0.580	**2nd**	0.740	**1st**
NaS	0.502	**3rd**	0.608	**2nd**
VRB	0.264	**5th**	0.740	**1st**
PSRB	0.490	**4th**	0.490	**4th**

Based on the data presented above, the most appropriate hybrid system is a wind generator with a lead acid battery for the costs scenario, and a wind generator with a VRB flow battery or a lithium battery for the environment scenario. It is important to emphasize this study may consider several parameters and scenarios by just evaluating and changing the fuzzy multi-rules and multi-sets for each case in the analysis.

IV. Conclusion

This paper presented an effective study to find the most appropriate type of hybrid system to be used as distributed generation, by evaluating the main operation characteristics of two types of renewable energy sources and six types of batteries, via costs and environment scenarios.

Fuzzy multi-rules and fuzzy multi-sets related with significant quantitative and qualitative parameters were used. Besides, a previous classification of the criteria priority was defined with relation to each scenario. This arrangement had the purpose to facilitate the development of the simulation steps and ease the methodology understanding. The final results corroborate the use of Fuzzy logic by developing multi-rules and multi-sets for the analysis of the main characteristics of hybrid systems.

To summarize, this paper highlighted the importance of storage energy sources together with intermittent renewable systems. In this way, an improvement of distributed generation management can be achieved, taking into account social, economic and environmental aspects.

Acknowledgment

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Biographies

Alexandre Barin was born in Santa Maria, Brazil. He received the Bachelor's degree from the Federal University of Santa Maria in 2005 and the Master’s (2007). Currently he is a doctorate student in Electrical Engineering of the Federal University of Santa Maria. He is a Student Member of IEEE since 2006.

Luciane Neves Canha was born in Santa Maria, Brazil. She received the Bachelor's degree from the University of Santa Maria in 1994, the Master’s (1995) and the Post-Graduated as Doctor in Electric Engineer (2004). She has been professor and researcher of the UFSM since 1997.

Karine Faverzani Magnago was born in Santa Maria, Brazil. She received the Bachelor's degree from the Federal University of Rio Grande do Sul in 1995 and Master (1998). She received Post-Graduated's degree as Doctor in Applied Mathematics from the State University of Campinas (2005). She has been professor and researcher of the UFSM since 2006.

Alzenira da Rosa Abaide was born in Santa Maria, Brazil. She received the Bachelor's degree from the University of Santa Maria in 1980, the Master’s (2000) and the Post-Graduated as Doctor in Electric Engineer (2005).She has been professor and researcher of the Federal University of Santa Maria since 1989.