Fuzzy Control of a Hybrid Renewable Power System based on Real-time Matlab-PLC Communication through OPC

Isaías González Pérez, A. José Calderón Godoy and Manuel Calderón Godoy
Industrial Engineering School, University of Extremadura, Avenida de Elvas, Badajoz, Spain

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Abstract: This paper presents the design of a fuzzy logic controller to operate an electrolyzer of an experimental test-bed of hybrid wind-solar system with hydrogen storage. This controller runs in Simulink and is linked through Open Process Control interface with the industrial programmable logic controller responsible of global management of the installation. Real-time data exchange and control of the process variables have been successfully achieved and obtained results under real conditions are presented.

1 INTRODUCTION

Hybrid power systems (HPS) refer to all systems that combine different energy technologies (RES, hydrogen, biomass etc.) in order to meet the required electrical and thermal loads of the consumer (Zervas, 2008). A wind-solar test-bed with hydrogen support has been developed and installed in the Industrial Engineering School of the University of Extremadura in Badajoz. It is a laboratory scale system for testing the integration and control of a stand-alone hybrid installation. Its components are two PV modules, a wind-turbine generator, a lead-acid gel battery, a PEM (Proton Exchange Membrane) electrolyzer, a PEM fuel cell, a metal-hydride system for hydrogen storage, and a supervisory control and data acquisition system. This system is based on a Siemens S7-313C-2DP Programmable Logic Controller (PLC) which integrates various modules for connecting sensors.

The electrolyzer is used for hydrogen production from deionized water and electricity provided by the PV modules. The hydrogen is stored in a set of metal hydride bottles until feeding the fuel cell to provide electricity according to the management strategy. Figure 1 shows the wind-solar generator installed on the flat roof of the School and the rest of the elements in the laboratory.

One of the main problems of the HPS is related to the control and supervision of the energy distribution. There are power fluctuations because of the variability of the renewable energy, which cause disturbances that can affect the quality of the power delivered to the load. The role of the controller is to control the interactions of the various system components and the energy flow within the system to provide a stable and reliable source of energy.

Figure 1: Wind-solar generator, electrolyzer and laboratory test-bed.

Literature review reveals that over the last decades, hybrid systems have grown rapidly and their technology has proven its competitiveness for remote area applications. It is observed that approximately 90% of studies reported are on design/economic aspects of hybrid systems (Nema, 2009). Research studies about control are, hence, scarce but there is an increasing interest on control strategies and systems for hybrid installations. Different control techniques have been studied for HPS such as control based on the battery state of charge (Ipsakis, 2009; Uzunoglu, 2009), logical

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control (El-Shatter, 2006; Khan, 2009), sliding mode control (Battista, 2006; Valenciaga, 2005), fuzzy control (Bilodeau, 2006; Erdinc, 2011; Erdinc, 2012; Hajizadeh, 2007; Jeong, 2005; Kyriakarakos, 2012; Stewart, 2009), optimal control based on genetic algorithms (Dufo, 2007), predictive control (Wu, 2009; Zervas, 2008), and Petri nets (Calderón, 2010; Figueiredo, 2008; Lu, 2010).

Lately, Fuzzy Logic Control (FLC) has received growing attention from researchers. Jeong et al. (Jeong, 2005) designed and tested a fuzzy controller for the load management of a fuel cell-battery hybrid system. El-Shatter (El-Shatter, 2007) applied fuzzy logic to control the duty cycle of two buck boost converters of the wind generator into a hybrid wind-PV-fuel cell system. In (Erdinc, 2011) Erdinc and Uzunoglu developed and simulated with real meteorological data a fuzzy controller to manage a hybrid system consisting of wind-PV generators, fuel cell, electrolyzer and battery. In (Erdinc, 2012) Erdinc et al. tested a fuzzy controller in real wind-PV-battery-fuel cell system for determining the fuel cell power reference. Hajizadeh and Aliak (Hajizadeh, 2007) simulated a fuzzy controller as second control layer for a hybrid fuel cell-battery system to decide the operating point of the fuel cell. Bilodeau and Agbossou (Bilodeau, 2006) developed and simulated a fuzzy logic controller defined using the Fuzzy Logic Toolbox of Matlab for determining the power set points of the fuel cell and the electrolyzer in a stand-alone wind-solar hybrid system. Stewart et al. (Stewart, 2009) simulated fuzzy control applied to control the switches of the battery, the fuel cell and the grid connection of a hybrid PV-battery-fuel cell system for a residential installation. Kyriakarakos et al. (Kyriakarakos, 2012) designed and simulated a fuzzy controller developed using the Fuzzy Logic Toolbox of Matlab for energy management of a wind-PV-fuel cell-electrolyzer-battery power system including a desalination unit.

Furthermore, several authors have reported successful applications of OPC communication between Matlab and Simulink environment and a PLC of S7 series from Siemens (Lieping, 2007; Linlin, 2011; Manuj, 2011; Mingliang, 2011).

The authors propose a control scheme based on a six input and one output fuzzy logic controller. It has been designed and tested for driving the electrolyzer of the aforementioned renewable energy system. This controller runs in Simulink and the control data exchange with the PLC responsible of global management is carried out in real time through OPC technology. The rest of the paper is organized as follows. Section 2 describes the control system, the FLC features and the integration architecture for real-time control by means of the PLC. In section 3 the results corresponding to the hybrid test-bed under real conditions are shown. Finally, conclusions and further works are outlined.

2 CONTROL SYSTEM

The test-bed monitoring and control system is implemented by the PLC S7-313C-2DP. It has electronic modules, Siemens SM331 and SM334 models, for connecting analogue sensors with voltage and current outputs. Data are displayed and stored on a TP277B touch panel (Siemens) running a SCADA (Supervisory Control and Data Acquisition) application. The touch panel logs the variables of interest at one minute intervals from the PLC's memory by a permanent MPI (Multi-Point Interface) connection.

WinCC flexible is a Human-Machine Interface (HMI) software. It can solve tasks like visualization, acquisition and data storage and control of automated processes. WinCC flexible RunTime is a HMI based on PC and OPC communication is one of its functionalities.

MATLAB is a kind of math analysis tool developed by MathWorks CO, which integrates OPC Toolbox to facilitate interoperability with other software which is used as an OPC server.

The fuzzy logic controller has been implemented with the Fuzzy Logic Toolbox of Simulink/Matlab environment, which communicates with the management PLC via OPC technology.

2.1 OPC

Open Process Control (OPC), also known as OLE for Process Control, is a series of seven specifications defined by the OPC Foundation for supporting open connectivity in industrial automation. OPC uses Microsoft® DCOM technology to provide a communication link between servers and clients. It has been designed to provide reliable communication of information in process plants, such as petrochemical refineries, automobile assembly lines, and so on.

The specification of OPC technology contains Server and Client, using the Client/Server mode. Server is the supplier of data and Client is the user of data. They establish a complete set of rules between hardware supplier and software developer. An OPC client is able to connect to one or more OPC Servers, and several OPC clients are also allowed to simultaneously connect to the same OPC Server.

A WinCC flexible RunTime software application has been developed. It runs in the computer connected to the PLC via Ethernet by using the communications processor CP-343 Advanced. This application accesses to data blocks in the PLC memory where both sensors measurements (electrolyzer current, pressure, etc.) and calculated values are stored (battery state of charge, averaged irradiance, etc.). So, these values are available for the OPC client. In this case, the OPC Toolbox of Matlab allows the communication with Simulink acting as OPC client. Figure 2 shows the communication structure between the PLC, Simulink and WinCC.

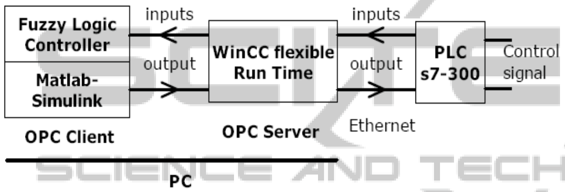


Figure 2: Diagram of communication structure between Simulink, WinCC and the PLC.

2.2 Fuzzy Logic Controller

The main advantages of fuzzy logic are the fast decision capability and that there is no need of historical data neither mathematical models. Erdinc and Uzunoglu (Erdinc, 2011) indicate the usefulness of these features and the suitable structure of fuzzy logic for the control of power systems.

The control objective of the proposed strategy is to regulate the operation point of the PEM electrolyzer depending on the conditions of the system such as energy availability from PV generator, from the battery, and others. A dc-dc converter carries out the conditioning of voltage and current provided by the PV modules to the electrolyzer levels. The PLC applies a signal control to this converter by means of an analogue output of voltage. This voltage level is generated from the FLC output.

FLC input variables are: State Of Charge (SOC) of the battery, solar irradiance, temperature of PV panel, compromise current, pressure of metal hydride system, difference between compromise and electrolyzer currents. This latter is considered as error signal because it represents the deviation between the surplus available current and the one delivered to electrolyzer. This error signal is calculated in Simulink before entering the FLC block.

Compromise current is defined by the authors as the possible surplus current that would be produced in the installation if the PV generator was providing the maximum possible current. It plays the role of threshold to decide if the energy surplus is enough for the electrolyzer operation. It is calculated as the difference between the maximum current from modules, Ipmax, and the load current. Ipmax depends on the panels voltage, Vpan, and the irradiance, G, according to equation 1 that has been obtained from experimental data:

$$Ipmax = 2 * G * (0.0049 - 0.0002 * Vpan) \quad (1)$$

The battery SOC is estimated in the PLC with the Ampere-counting method (Piller, 2001) from values of current and capacity of the battery.

Incident irradiance in the PV modules plane is used. It is averaged each 5 minutes in order to reduce the transitory fluctuations due to clouds.

The PV panel temperature is measured with a Pt-100 probe on the backsurface. This variable is included in control process because the generation capacity and the performance of the modules depend on their temperature. The lower temperature is, the higher performance will be.

Once the battery is charged enough and the load demand is being satisfied, the PV modules provide a surplus current used for hydrogen generation. These conditions are evaluated by means of the incident irradiance, the compromise current and the battery SOC. Furthermore, technological factors must be taken into account such as the no operation of the fuel cell and the available capacity for storing in the metal hydride bottles, i.e., their pressure has to be under the maximum level.

When such conditions are fulfilled, the voltage control signal generated by the FLC is applied to the dc-dc converter that feeds the electrolyzer from PV modules. This voltage varies with meteorological and technological changes according to the rules defined for the controller, so that the current drawn by the electrolyzer and, hence, the flow of hydrogen produced are adapted to the availability of energy.

The structure of the FLC has been made as simple as possible. The fuzzy controller is of Mamdani type, the And method is Min, the implication operator is Min, the Aggregation is Max and the defuzzification strategy is the Centroid of area. The membership functions have been defined based on the experience acquired by the research team through the operation of the test-bed (Calderón, 2010; Calderón, 2011). Triangular, trapezoidal, S-shaped and Z-shaped membership functions have been used for input and output variables. These ones conform to the desired design among those available in the Fuzzy Logic toolbox of Matlab Membership functions for SOC, error signal and output variable, Vfuzzy, are presented in Figure 3. Irradiance, compromise current and pressure input variables have been defined by means of 2 fuzzy subsets; while SOC, PV module temperature and error signal use 3 fuzzy subsets. In the case of SOC, the Low subset has been made larger to avoid operating on such low values to enlarge the battery life span.

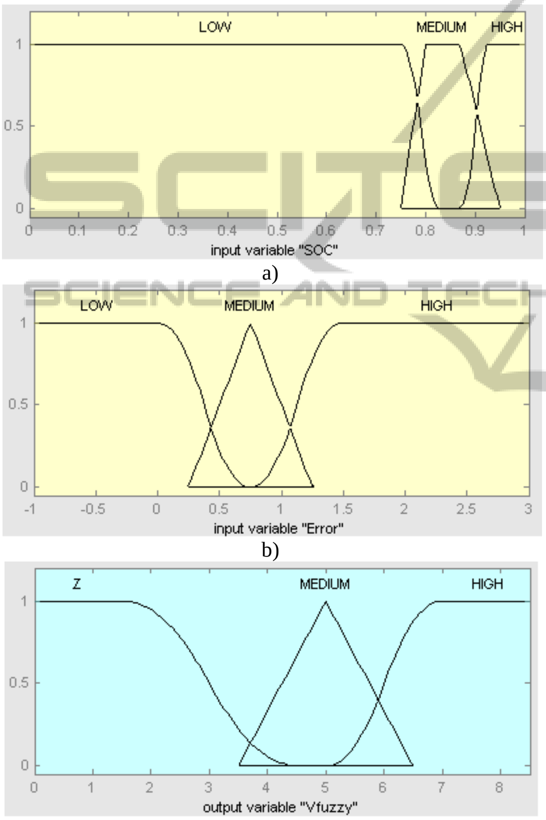


Figure 3: Membership functions for: a) SOC, b) Error signal, c) Output signal.

The linguistic variables are Low, Medium and High for input variables and Z, Medium and High for output signal. Input ranges depend on the variable. The narrowest range goes from 0 to 1 for SOC and the widest one goes from 0 to 1000 W/m^2 for solar irradiance. The range of output signal is 0 to 8’5 V, interval where the electrolyzer behaviour is lineal. The fuzzy rules define the FLC behaviour. Table 1 contains the 9 rules that have been enounced.

Table 1: Rules of the FLC.

If the SOC is High and the irradiance is High and PV panel temperature is Low then Vfuzzy is High
If the SOC is High and the irradiance is High and PV panel temperature is Medium then Vfuzzy is High
If the SOC is High and the irradiance is High and PV panel temperature is High then Vfuzzy is Medium
If the SOC is Medium and the irradiance is High and PV panel temperature is Low then Vfuzzy is High
If the SOC is Medium and the irradiance is High and PV panel temperature is Medium then Vfuzzy is High
If the SOC is Medium and the irradiance is High and PV panel temperature is High then Vfuzzy is Medium
If the SOC is Low or the irradiance is Low or the compromise current is Low or the pressure is High then Vfuzzy is Zero
If the error signal is Medium then Vfuzzy is Medium
If the error signal is High then Vfuzzy is High

Figure 4 contains the block diagram of the real-time control system implemented in Simulink. It consists of three subsystems: OPC Read blocks for acquisition of input signals, fuzzy controller block for control signal generation and OPC Write block for real-time writing on PLC memory. The communications parameters are defined with the OPC Configuration block, so Simulink acts as OPC client.

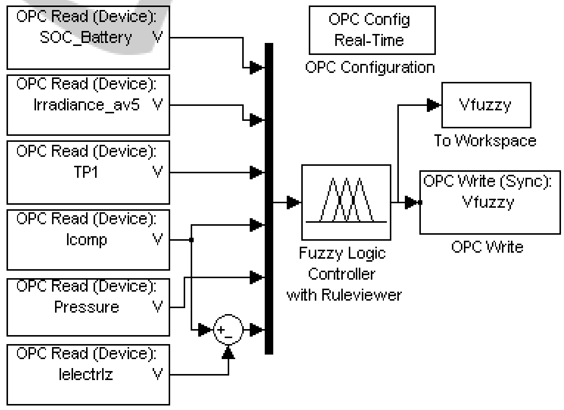


Figure 4: Simulink block diagram of fuzzy control scheme.

2.3 WinCC, Simulink and PLC Integration

Figure 5 shows the sequence of operations from the reading of sensors connected to PLC. Those values are stored in data blocks in the PLC memory. The OPC server of WinCC flexible RT allows the access to these memory positions from Simulink by means of the OPC Read blocks. The same happens to data calculated by the PLC program and accumulated in its memory. These signals constitute the FLC inputs, which applies the defined control rules to the fuzzyfied inputs in order to generate a signal output, that is defuzzyfied. This control signal is written in the PLC memory by the OPC server of WinCC using the OPC Write block of Simulink. PLC carries out the conditioning of the signal Vfuzzy and transfers it to the analog output connected to the dc-dc converter of the electrolyzer.

Configured blocks of Simulink access to real-time process variables and the FLC regulates the electrolyzer operation point.

The sampling time chosen for OPC blocks and configuration parameters of Simulink is 10 seconds. The conditioning and un-scaling of the value Vfuzzy is carried out by the PLC cyclic interruption block OB35 every 10 sec. This value is sent to the voltage analogue output of the module SM334. The PLC programming software STEP7, the supervision WinCC software and Matlab software are installed in the same computer. So, the OPC Server and the OPC Client are both local machines.

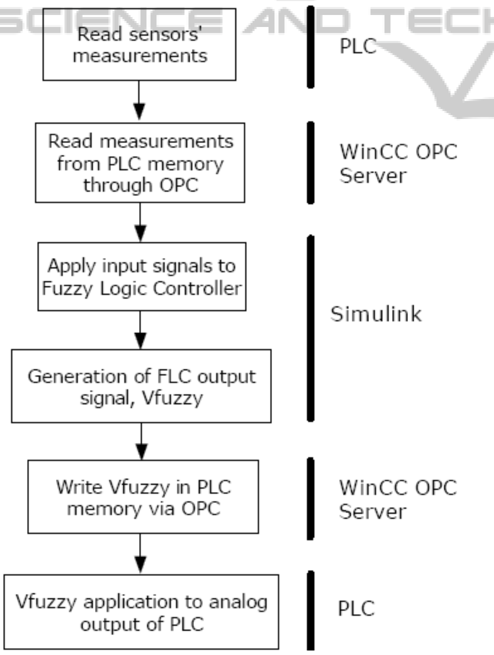
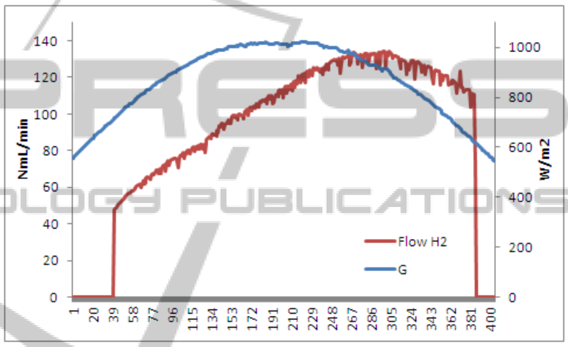


Figure 5: Flowchart of the communication between WinCC, Simulink and PLC.

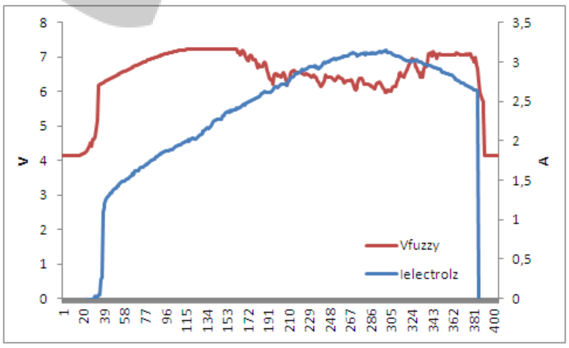
3 EXPERIMENTAL RESULTS

The FLC has been tested under real conditions in the test-bed for several days. The membership functions and rules were adjusted during trials with different climatic conditions in order to avoid fluctuations of the output signal and deviations from the expected behaviour of the electrolyzer. Figure 6 (a, b and c) shows the most representative of involved variables for the system operation during 20th February 2012 from 10:00 to 17:00. In Figure 6 a) the irradiation and the hydrogen production are plotted. In Figure 6 b) the evolution of the controller output, Vfuzzy, is shown with the current consumption of the electrolyzer.

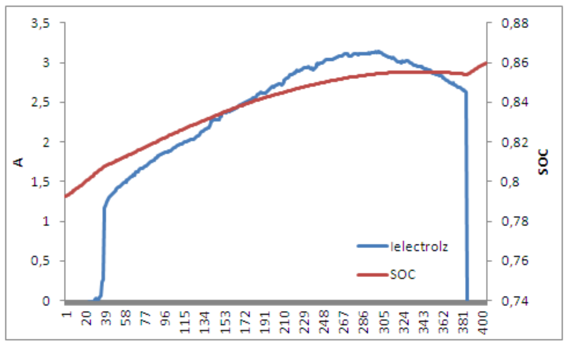
Finally, in Figure 6 c) the battery SOC variation and the electrolyzer current are shown. As can be seen, whereas the electrolyzer is producing hydrogen, the battery SOC is still growing because the PV modules provide current for both demands. Low subset has been made larger to avoid operating on such low values to enlarge the battery life span.



a)



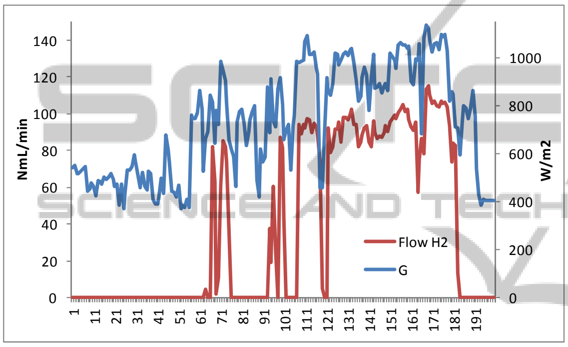
b)



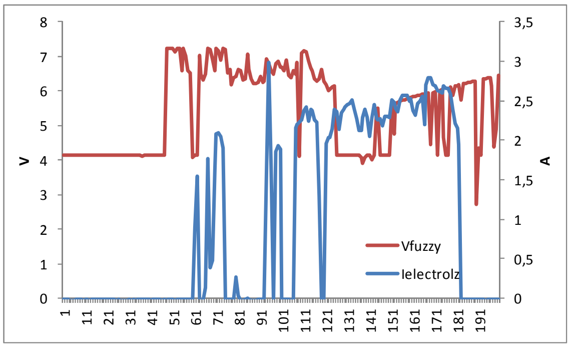
c)

Figure 6: Evolution of: a) incident irradiance and H_2 flow, b) control signal and electrolyzer current, c) electrolyzer current and battery SOC for the 20th February 2012.

Figure 7 (a, b and c) shows data corresponding to 23rd March 2012 from 10:00 to 13:30, illustrating the operation of the system during a cloudy day. As can be seen in Figure 7 a), the hydrogen production follows the variations of the incident irradiance, so such production adapts to the power availability. In Figure 7 b) the effects of the clouds on the output signal of the FLC, Vfuzzy, and the corresponding change in the electrolyzer current are showed. Figure 7 c) shows a similar situation to that of 20th February 2012, the battery SOC is incrementing at the same time that hydrogen is being generated due to the current delivered by the PV modules. These results demonstrate the ability of the developed controller to adjust the control signal to the power availability.



a)



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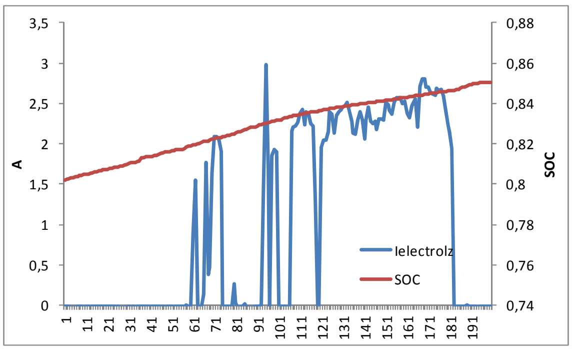

c)

Figure 7: Evolution of: a) incident irradiance and H_2 flow, b) control signal and electrolyzer current, c) electrolyzer current and battery SOC for the 23rd March 2012.

4 CONCLUSIONS

A fuzzy controller for real-time regulation of the operation point of a PEM electrolyzer has been presented. The hydrogen generator constitutes the core of a hybrid wind-solar test-bed with hydrogen storage. The fuzzy controller has been designed and implemented in Simulink and communicated with the PLC that plays the role of mastermind of the automation system by means of OPC technology.

The versatility and ability of the proposed control scheme for being used as a platform for testing different and advanced control strategies have been demonstrated and serve as basis for future works in that sense.

The results under real operating conditions constitute a proof-of-concept of the validity of the proposed control structure.

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