FUZZY CONTROL OF AN ELECTROLYZER IN A STAND-ALONE RENEWABLE ENERGY SYSTEM

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Abstract: This paper deals with the design, configuration and experimental test of a fuzzy logic controller to manage an electrolyzer. This device is the core of a renewable energy system for stand-alone applications. The control structure integrates Simulink software and a programmable logic controller using Open Process Control technology. Real-time data exchange and control of the process variables has been successfully achieved and obtained results under real conditions are presented.

Keywords: Renewable Energy System, Energy Management System, Fuzzy Control, Programmable Logic Controller, Supervisory control.

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, *et al*., 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. Fig. 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.

Literature review reveals that over the last decades, hybrid systems have grown rapidly and their technology has proven its competitiveness for remote area applications.

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

It is observed that approximately 90% of studies reported are on design/economic aspects of hybrid systems (Nema, *et al*., 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, *et al*., 2009; Uzunoglu, *et al*., 2009), logical control (El-Shatter, *et al*., 2006; Khan and Iqbal, 2009), sliding mode control (Battista, *et al*., 2006; Valenciaga and Puleston, 2005), fuzzy

control (Bilodeau and Agbossou, 2006; Erdinc and Uzunoglu, 2011; Erdinc, *et al*., 2012; Hajizadeh, *et al*., 2007; Jeong, *et al*., 2005; Kyriakarakos, *et al*., 2012; Stewart, *et al*., 2009), optimal control based on genetic algorithms (Dufo, *et al*., 2007), predictive control (Wu, *et al*., 2009; Zervas, *et al*., 2008), and Petri nets (Calderón, *et al*., 2010; Figueiredo and Sa da Costa, 2008; Lu, *et al*., 2010).

Lately, Fuzzy Logic Control (FLC) has received growing attention from researchers. Jeong, *et al*. (2005) designed and tested a fuzzy controller for the load management of a fuel cell-battery hybrid system. El-Shatter, *et al*. (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. Erdinc and Uzunoglu (2011) 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. Erdinc, *et al.* (2012) tested a fuzzy controller in real wind-PV-battery-fuel cell system for determining the fuel cell power reference. Hajizadeh and Aliak (Hajizadeh, *et al*., 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 (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*. (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*. (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, *et al*., 2007; Linlin, *et al*., 2011; Manoj and Janaki, 2011; Mingliang, *et al*., 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 AND SUPERVISION 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 for PC based HMI and OPC communication is between 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 a process plant, such as a petrochemical refinery, an automobile assembly line, 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 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 OPC client. In this case, the OPC Toolbox of Matlab allows the communication with Simulink, that acts as OPC client. Fig. 2 shows the communication structure between the PLC, Simulink y WinCC.

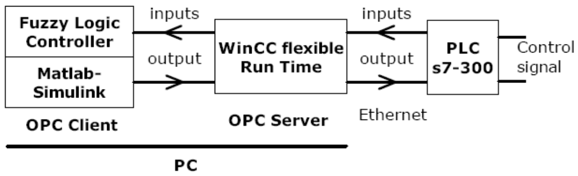


Fig. 2. Diagram of communication structure between Simulink, WinCC and the PLC.

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 (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. The signal generated by the FLC is such that voltage level.

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 plays the role of threshold to decide if the energy surplus is enough for the electrolyzer operation. It is defined as the possible surplus current that would be produced in the installation if the PV generator was providing the maximum possible current. 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, *et al*., 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.

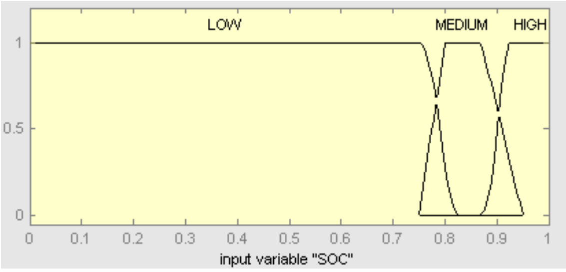
The PV panel temperature is measured with a Pt-100 probe on the backsurface. This variable is included in control process because the generation capacity and the performance of the modules depend on their temperature. The lower temperature, the higher performance.

Once the battery is enough charged and the load demand is being satisfied, the PV modules provide a surplus current that is 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, *et al*., 2010; Calderón, *et al*., 2011). Triangular, trapezoidal, S-shaped and Z-shaped membership functions have been used for input and output variables. In Fig. 3 membership functions for SOC, error signal and output variable, Vfuzzy, are presented. 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.

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 and have been enounced 8 rules. The following is an example: If the SOC is High and the irradiance is High and PV panel temperature is Low then Vfuzzy is High.

Fig. 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.



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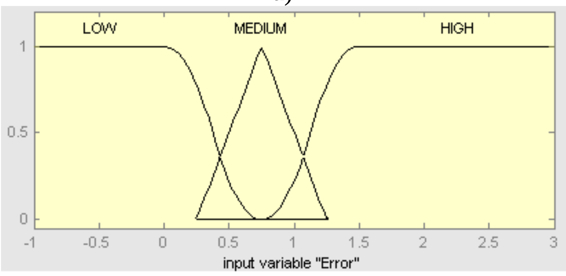

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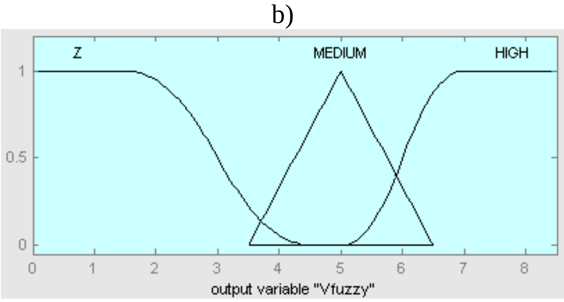


c)

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

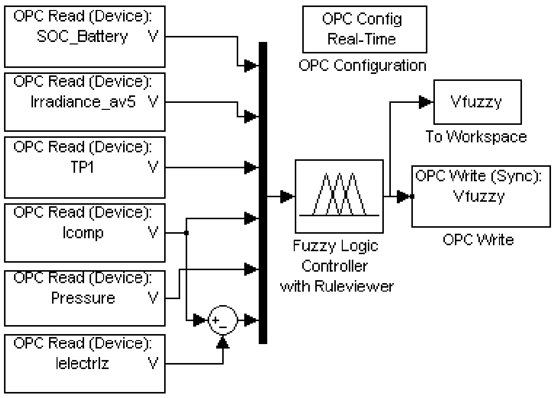


Fig. 4. Simulink block diagram of fuzzy control scheme.

2.3 WINCC, SIMULINK AND PLC INTEGRATION.

Fig. 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 for data calculated by the PLC program and accumulated in its memory. These signals constitute the inputs to the FLC, 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. The configured blocks of Simulink access real-time process variables and the FLC regulate the electrolyzer operation point.

The sampling time chosen for the OPC blocks and the 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 each 10 sec. This value is sent to the voltage analogue output of the module SM334. The software for PLC programming, STEP7, the software for supervision WinCC and Matlab software are installed in the same computer. So, the OPC Server and the OPC Client are both local machine.

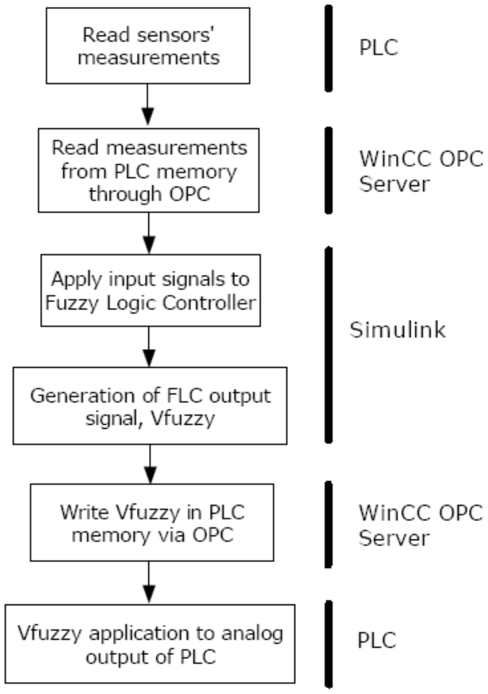
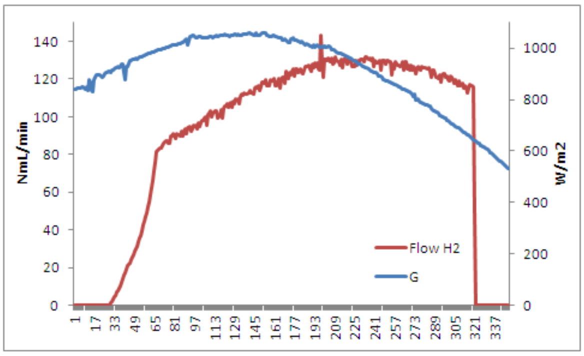


Fig. 5. Flowchart of the communication between WinCC, Simulink and PLC.

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. Fig. 6 (a, b and c) shows the most representative of involved variables for the operation of the system during the 24th February 2012 from 11 am to 17 pm. In Fig. 6 a) the irradiation and the hydrogen production are plotted. In Fig. 6 b) the evolution of the controller output, Vfuzzy, is shown with the current consumption of the electrolyzer. Finally, in Fig. 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.



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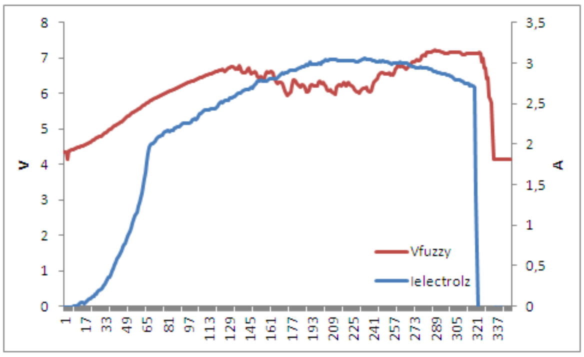

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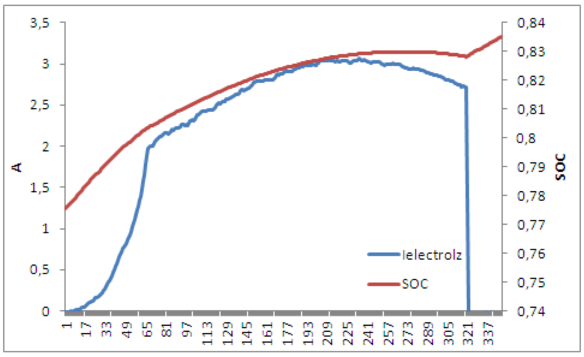

c)

Fig. 6. Evolution of: a) incident irradiance and H_2 flow, b) control signal and electrolyzer current, c) electrolyzer current and battery SOC for the 24th February 2012.

4. CONCLUSIONS AND FURTHER WORKS

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 sophisticated 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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