Journal of Engineering and Applied Science *Volume 4, September 2012*

www.cenresinpub.org

DEVELOPMENT OF A CONTROL METHOD FOR A RENEWABLE ENERGY SYSTEM WITH FUEL CELL: A REVIEW

***Kalli, B. M., Tijjani, B. G., Baba, U. T. and Kalli, S.**
Department of Electrical and Electronics Engineering
Ramat Polytechnic Maiduguri, Borno State, Nigeria
babamaikalli@yahoo.com

ABSTRACT

The paper reviewed development of a control method for a renewable energy system with fuel cell. A novel control method developed for the renewable energy system based on hydrogen and the control system is divided in two levels: a global controller that uses fuzzy logic to manage the flow of energy in the system and a pair of local controllers that are used to control the operating power of the fuel cell and the electrolyser. The finding shows that a single module of the boost converter can output 1250 W at an efficiency higher than 91 %. It was also expected that the entire boost converter, which was composed of 4 modules, could output at least 5 kW. Two control structures were compared for the local controller: a PI controller and a fuzzy logic controller. The performances of both controllers were similar, but since the PI controller is simpler to implement, it was retained as the best option.

Keywords: *Control Method, Renewable Energy System, Fuel Cell*

INTRODUCTION

The combination of an electrolyser, a fuel cell, a stack of batteries and renewable energy sources can provide peak power control in a decentralized/distributed power system (Agbossou et. al., 2009). The electrolyser stores the off-peak energy as hydrogen and the fuel cell uses this energy to produce on-peak electricity, while the batteries are used to provide short term storage. Supplying all the energy needed by the continuously growing market has been a constant challenge for the utilities. This challenge is even more difficult since the demand slowly shifts toward greener energies. Moreover, the big sized infrastructure projects become costlier and the regulations that must be respected are getting more complex. Distributed generation systems that use renewable energies to produce electricity are an interesting solution to this problem. Agbossou et. al. (2009) reported that kind of system can be in some cases cheaper to build and it produces green energy. The Hydrogen Research Institute (HRI) developed and implemented an autonomous renewable energy system (RES) that uses wind and solar energy to power a load (Figure 1).

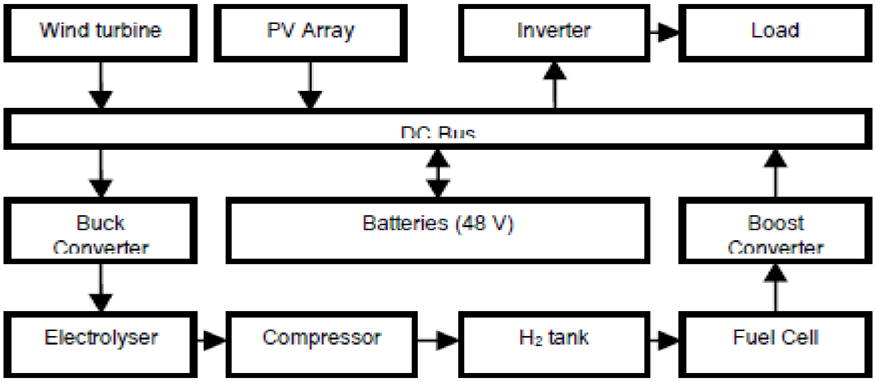

Figure 1: Renewable Energy System
Source: Agbossou et. al. (2009)

This is done by storing off-peak energy produced by the sources into hydrogen, using an electrolyser and by producing on-peak energy using a fuel cell to reconvert this hydrogen into electricity. There is also a battery stack that is used to maintain a constant DC bus voltage and to store short term energy (Agbossou et. al., 2001). One of the most important issues in these systems is the control method. Indeed, the performance of the controller is directly related to the efficiency, and thus the cost, of the system. Another important factor is the quality of the power interfaces between the components of the system. Their efficiency also has a direct impact on the global efficiency of the system. This paper presents an improved control system that was developed at the HRI. This new control method uses the fuzzy logic principle and can be added to other control methods (Kauranen et. al., 1993; Pötter et. al., 1996; Vosen and Keller , 1999). For a finer and simpler control of the electrolyser and the fuel cell. The paper also presents the design of a boost converter that is to be used between the fuel cell and the DC bus. This boost converter is one of the key power interface needed to manage efficiently the energy in the case of no sufficient energy from wind turbine or PV array. The design aimed to obtain a boost converter that offers a high efficiency and stability. The global control simulation results are also presented.

GLOBAL CONTROL

Review of the Existing Methods

Many control methods for renewable energy systems rely only on the batteries' state of charge (SOC) to decide whether to store the available energy as hydrogen or to retrieve it to power the load. The simplest method in this family is the single hysteresis control (Agbossou et. al., 2001). With this method, the electrolyser is started when the SOC reach a high set point and the fuel cell is started when the SOC reach a low set point. The double hysteresis method is very similar except that it uses 4 set points: the electrolyser is started when the SOC is high and is stopped only when it reached a slightly lower set point. The same thing holds for the fuel cell: it is started when the SOC is low and is stopped when it reached a higher set point. Using 4 set points improves the system response since it allows for more flexibility. In both cases, it is possible to either operate the electrolyser and the fuel cell at full power all the time or to use power converters in order to control the operation power of these devices (Kauranen et. al., 1993; Kélouwani et. al., 2001). Some research teams experimented advanced control method to solve this problem. Potter and Pruschek (Pötter et. al., 1996), used dynamic programming, which is an optimization method, in order to determine the optimum SOC at all time. One major drawback of this method is that it performances depend on the quality of historical data. Power control scheme including a power control strategy power control scheme to improve the performance of a fuel cell-battery hybrid power source for residential application, is developed by some authors (Yujin Song, 2007). (Vosen and Keller, 1999) used neural network instead. They trained a neural network toward reaching an equilibrated energetic balance in the batteries while minimizing the use of the hydrogen storage. However, this method also relies heavily on historical data.

Proposed Control System

The proposed system integrates the best of both of the preview mentioned approaches. This way, one of the objectives was to avoid any form of training with historical data since it is not always readily available. On the other side, the system that was elaborated uses fuzzy logic, thus giving more flexibility to the system's designer than with hysteresis control. The proposed control system for the HRI renewable energy system uses two levels of control (Figure 2). A global controller uses fuzzy logic to manage the flow of energy in the system. The input variables are the net power flow (dP), which is the power consumed by the load subtracted from the power generated by the sources, and the batteries' state of charge (SOC). Those variables are used to determine whether to start the fuel cell or the electrolyser, and at which operating power (PEl* and PFc*). This way, it is possible to define a relatively complex behaviour using simple rules and linguistic variables. The other level of control is represented by a pair of local controllers for the fuel cell and the electrolyser. They control the output power of a buck converter that powers the electrolyser and a boost converter that interfaces the fuel cell to the DC bus. The local controllers are interesting since they give an additional degree of freedom to the global controller and they allow for a finer control of the system. Finally, this offers more possibilities for the dimensioning of the system since the fuel cell and the electrolyser can be operated at power levels other than their nominal parameters. The buck and the boost converters design was not a big challenge in itself. However, the control circuits which were designed to take into account the particularities presented by the Renewable Energy System, have some challenge.

BOOST CONVERTER

The power interfaces described in the previous section are also used to change the voltage levels between the DC bus and the hydrogen storage system (electrolyser-tank-fuel cell). In order to implement the local controller for the fuel cell, a boost converter was designed and its output power had to be controllable. The boost converter offers a port to control its output power, and it has three main characteristics. The converter uses a multiphase design

(Agbossou et. al., 2001). Indeed, this converter is made from eight smaller converters connected in parallel. This reduces the cost of the converter since smaller power components can be used. In order to reduce the interferences emitted by the power stages and to improve the quality of the output power, the control signals of each stage are shifted by 45 degrees. The converter was also divided into four modules of 1250 W, each module containing two power stages. The figure 3 shows the actual circuit for a single module while the figure 4 presents the block diagram for the entire boost.

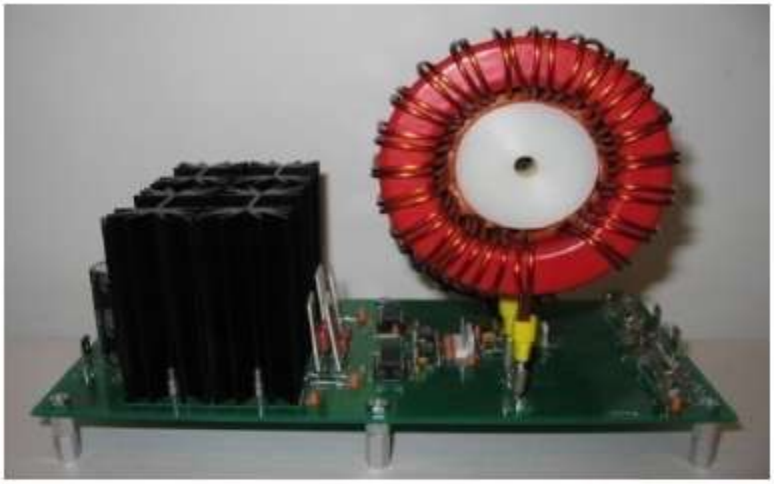

Figure 3: Boost converters 1250W module
Source: Agbossou et. al. (2009)

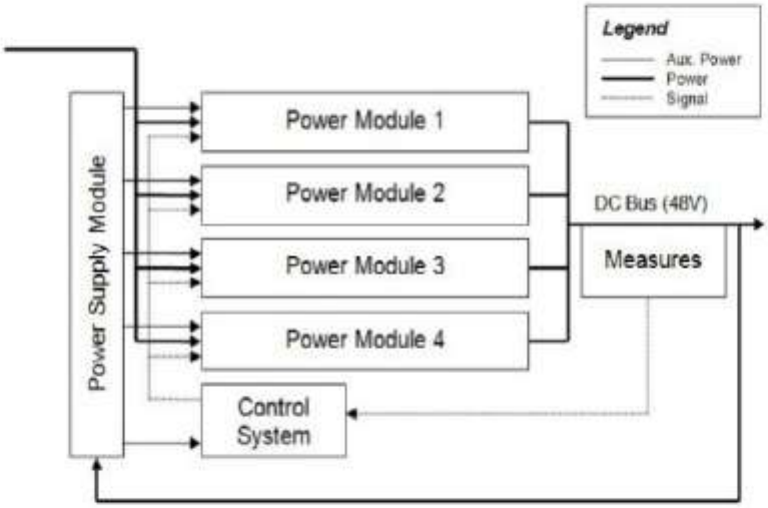

Figure 4: Boost converters Block diagram
Source: Agbossou et. al. (2009)

Separating the power stage makes the system easier to maintain since each module can be replaced individually, and it allows for the dimensioning of the boost converter according to the requirements of the application. Finally, each power stage's duty cycle can be controlled by an external controller. A closed-loop controller can thus be designed to measure the output power and adjust the duty cycles in order to reach a given set point.

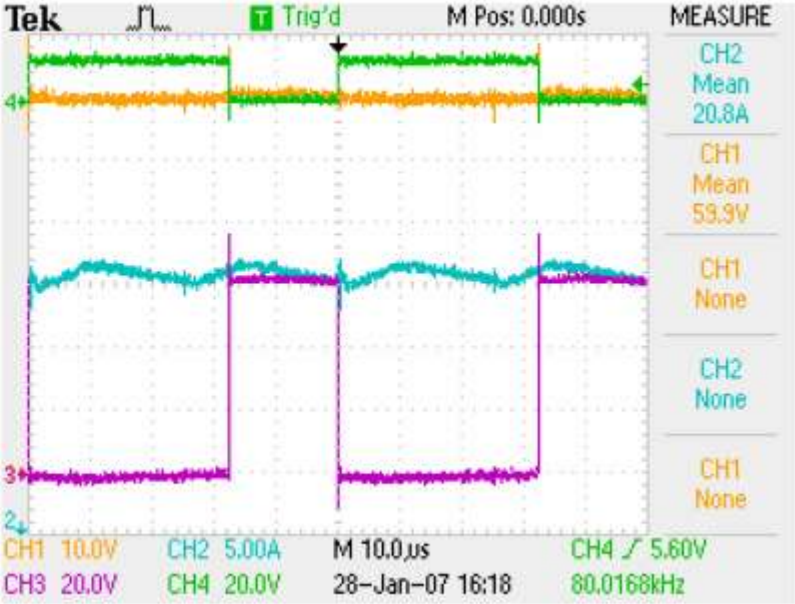

Figure 5: Boost Converter Waveforms
Source: Agbossou et. al. (2009)

Figure 5 shows the output waveforms of one module of the boost converter. The first waveform from the top (CH4) shows the duty cycle applied to one of the power stages, for reference purpose. The second waveform (CH1) shows the output voltage, which has a mean value of 59.9 V. The third waveform indicates a mean output current of 20.8 A (CH2). Finally, the fourth waveform (CH3) shows the MOSFET's drain voltage. The module operated at 1 246 W when this figure was taken, and its efficiency was over 91 %. It is then possible to see that the module is able to work at its nominal power with a very high efficiency. It is of interest to note that the module operates at half load with an efficiency of 97 %. It is also possible to extrapolate that the complete boost converter will be able to output the full 5 kW. Finally, the voltage spikes on the drain's voltage waveform are very low and it thus generates less interferences. In addition, the local controller that regulates the boost converter's output power had to be designed. Two different control strategies were evaluated: a PI controller defined by the equation 1 and a fuzzy logic controller defined by the equation 2. Both controllers include an integral action, so the steady-state error is eliminated. In order to determine which controller offers the best performance, a model of the system was developed in Matlab/Simulink environment. This model represents the fuel cell, the boost converter and the batteries connected to the DC bus (See Figure 6).

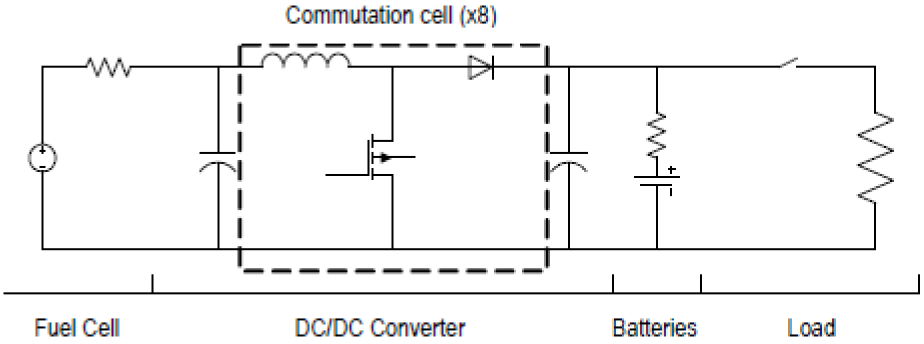

Figure 6: System Model Block Diagram
Source: Agbossou et. al. (2009)

The models of the boost converter and the batteries were implemented using elements from the SimPowerSystems toolbox in Simulink. However, the fuel cell model was developed using the equation 3 (Fournier et. al., 2002).

$u = K_p\, e + K_1 \int e\, dt$ (1)

$$u = \int \left[f\left(e, \frac{de}{dt} \right) \right] dt \qquad (2)$$

u : control signal of the converter (duty cycle); KP : proportional gain; KI : integral gain; e : output power error. The gains were initially selected and improved during the simulation until the dynamic response of the system becomes the stable one. This means that the gains are not optimal, but the system response was improved when the next variations of the gains did not more improve the system's dynamic response from one iteration to another.

U= u : control signal of the converter (duty cycle); e : output power error; f() : non-linear function defined by the rules and the membership functions of the fuzzy logic controller.

Cell Nerst act ohm conc $V = E + \sigma + \sigma + \sigma$ (3) ENerst : cell's theoretical voltage; σact : activation over voltage; σohm : ohmic over voltage; σconc : concentration over voltage (Agbossou et. al., 2009). Both controllers were tuned by using an iterative process. The gains were modified until there was no significant improvement in the response. This process demonstrated that the PID is much simpler to tune since the response to each gain change is easier to predict. The fuzzy logic controller, on the other hand, is more flexible as it can easily be designed to provide a non-linear behaviour that is sometimes desirable. In this case, the PID controller offers better performances, as can be seen on figure 7: the response does not present overshoot but is still faster than that of the fuzzy logic controller. Moreover, the PID controller can be implemented in the low-cost microcontroller that controls the boost converter. The simulations showed that the results are comparable for both controllers. However, the PID controller is simpler to design and implement in a microcontroller. Then the PID controller was chosen to control the output power of the boost converter.

FUZZY LOGIC CONTROLLER

The next step in the design of the control system was the global controller. This controller had been designed using fuzzy logic. In order to design and validate the fuzzy logic controller, a model of the entire system was developed in Matlab/Simulink (Agbossou et. al., 2009). The model represents the batteries, the fuel cell, the electrolyser, the energy sources and the load. The model was simulated using real historical data for the sources and the load. So the results are nearer from the real operating conditions. The structure of the fuzzy logic controller was made as simple as possible. Indeed, it uses only triangular and trapezoidal membership functions (Figure 8). This figure also shows that only three symmetrical functions were used for each variable, thus again keeping the complexity as low as possible. It is of interest to note that the SOC membership functions are the only ones that are not symmetrical (Agbossou et. al., 2009). The low SOC was effectively made larger on purpose in order to avoid as much as possible operating in this area. Keeping the state of charge higher is a good way to improve batteries' life. Finally, a set of five rules was enough to properly define the system's behaviour.

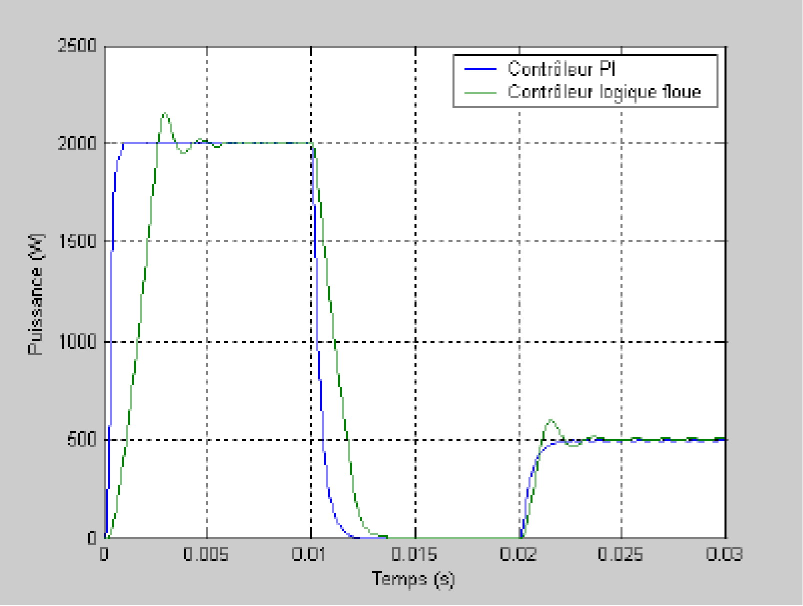

Figure 7: Step response for the fuzzy logic controller and the PID controller
Source: Agbossou et. al. (2009)

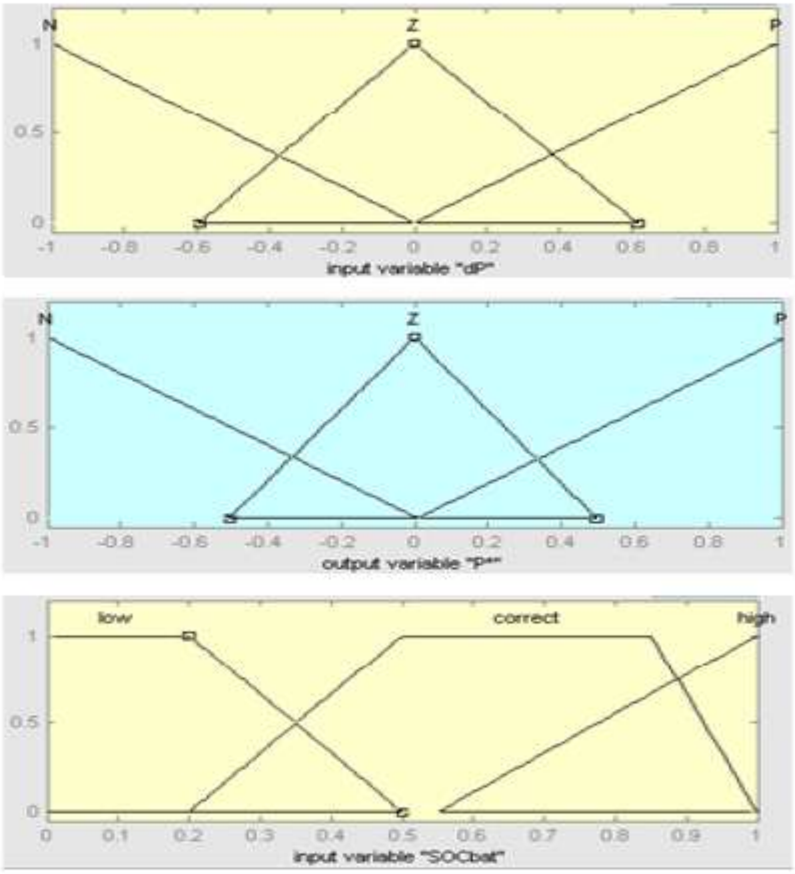

Figure 8: fuzzy logic controllers membership function
Source: Agbossou et. al. (2009)

Rules:
If the net power flow is Negative then the power set point is Positive;
If the net power flow is Zero then the power set point is Zero;

If the net power flow is Positive and the SOC is higher than the power set point is Negative; If the SOC is low, then the power set point is Positive; If the SOC is high, then the power set point is Negative. Figure 9 shows the net power flow, the fuel cell and electrolyser set points and the energy storage state for a week of operation. It is possible to see that the electrolyser is started whenever the net power flow is more positive and the batteries are sufficiently charged. On the other side, when the net power flow tends to be negative, the fuel cell is started and the hydrogen storage decrease. The controller keeps the batteries' SOC between 40 % and 60 % and thus avoids deep discharges (Agbossou et. al., 2009). These results show that the energy balance is negative for that particular week since there is less hydrogen in the tank at the end and the SOC is almost the same. It could be that the power provided by the sources was lower than usual for that week. However, should this situation occur for another week, the system sources would have to be increased in order to avoid power outages.

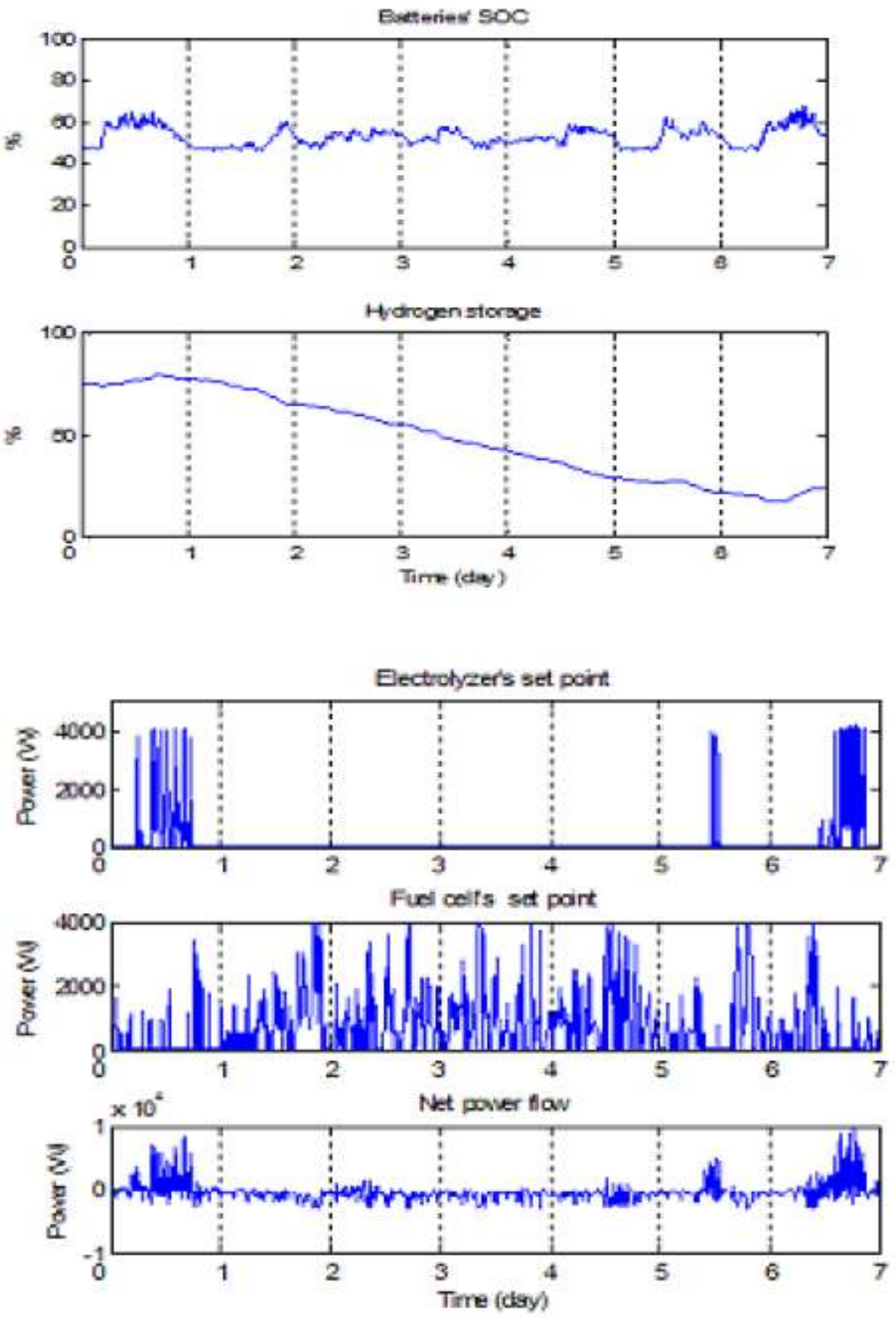

Figure 9: Complete system simulation Result
Source: Agbossou et. al. (2009)

The fuzzy logic was implemented in Labview using the Control System Toolkit. This toolkit includes fuzzy logic functions that ease the process of defining the controller. The software reads the actual power data from sensors that are installed at the HRI, processes it through the fuzzy logic controller module and communicates the electrolyser and the fuel cell set points to their respective controllers (Agbossou et. al., 2009).

SUMMARY AND CONCLUSION

The HRI developed a renewable energy system that can be used as a distributed generation system. This system is an interesting alternative to provide power in remote areas or as backup for the grid. However, there are still a few challenges to address with this system, the main one being its control. This paper presented a novel control method that was developed for the renewable energy system based on hydrogen. The control system is divided in two levels: a global controller that uses fuzzy logic to manage the flow of energy in the system and a pair of local controllers that are used to control the operating power of the fuel cell and the electrolyser. The design of a boost converter that is used as a power interface between the fuel cell and the DC bus is also presented. The experimental results gathered to date shown that a single module of the boost converter can output 1 250 W at an efficiency higher than 91 %. Then it is expected that the entire boost converter, which is composed of 4 modules, could output at least 5 kW. Two control structures were compared for the local controller: a PI controller and a fuzzy logic controller. The performances of both controllers were similar, but since the PI controller is simpler to implement, it was retained as the best option. Finally, the description of the fuzzy logic global controller along with the model that was used to validate its performance was presented in the last section. The simulation results show that the controller behaved as expected. Indeed, it managed to keep the batteries sufficiently charged to avoid reducing their lifetime. It also stored hydrogen when there was more power entering the system than exiting the system. When the load needed more power, the controller used the stored hydrogen to provide on-peak energy. The control system that was developed helped to make the renewable energy system more flexible. However, an interesting feature that could be added in the future would be to implement a load dumping subsystem that could insure that the critical loads are always powered even when the energy provided by the renewable energy sources is lower.

REFERENCES

Agbossou, K., Bilodeau, A. and Doumbia, M.L. (2009). Development of a Control Method for a Renewable Energy system with Fuel Cell, IEEE AFRICON, Nairobi, Kenya, September, Pp. 23 - 25,

Dunsky, P.U. (2004). VertigO – La revue en sciences de l'environnement, 5 (2004) 1-13.

Agbossou, K., Chahine, R., Hamelin, J., Laurencelle, F., Anouar, A., St-Arnaud, J.M., Bose, T.K. (2001). "Renewable Energy Systems Based on Hydrogen for Remote Applications", J. Power Sources 96: 168–172.

Kauranen, P.S., Lund, P.D. Vanhanen, J.P. (1993). "Control of Battery Backed Photovoltaic Hydrogen Production", Int. J. Hydrog. Energy 18:383–390.

Pötter, R., Pruschek, R., Brocke, W.A., Barthels, H. (1996). "Examination of the design of the energy management for the PV plant PHOEBUS Jülich by dynamic programming", in: Proceedings of the 11th World Hydrogen Energy Conference Hydrogen '96, Stuttgart, Germany, June, 1996.

Vosen, S.R. and Keller, J.O. (1999). "Hybrid energy storage for stand-alone electric power systems: optimisation of system performance and cost through control strategies", Int. J. Hydrog. Energy 24:1139– 1156.

Kélouwani, S., Bergeron, P., Agbossou, K., Hamelin, J., Chahine, R. and Bose, T.K. (2001)." State of charge modeling of stand-alone systems based on hydrogen ", 11th Canadian Hydrogen Conference, Victoria (British Columbia), Canada, June 17-20,

Yujin Song; Han, S.B.; Li, X.; Park, S.I.; Jeong, H.G.; Jung, (2007). "A Power control scheme to improve the performance of a fuel cell hybrid power", Power Electronics Specialists Conference, PESC – IEEE, p. 1261 -1266,.

Agbossou, K., Simard, R., Kelouwani, S., Bose, T.K. (2001). " Commande multiphasée d'un survolteur pour un système d'énergies renouvelables", in: Proceedings of the IEEE Canadian Conference on Electrical and Computer Engineering, Toronto, Canada, May.

Fournier, M., Hamelin, J., Agbossou, K. and Bose, T.K. (2002)." Fuel cell operation with oxygen enrichment", Journal: Fuel Cells – From Fundamentals to Systems 2, no 2, p. 117-122.