International Journal of Electrical and Power Engineering 1 (3): 279-285, 2007

Fuzzy Logic Supervisor for Power Control of an Isolated Hybrid Energy Production Unit

Ghada Boukettaya, Lotfi Krichen and Abderrazak Ouali
Department of Electrical Engineering, National School of Engineering,
University of Sfax, BP W, 3038, Sfax, Tunisia

Abstract: In this study, we present the design of a fuzzy logic supervisor for the control of the generated powers of a Hybrid Energy Production Unit (HEPU). This HEPU comprises two sources solar/diesel, a flywheel storage system and a load. The exceeded generated power than required by the load is diverted towards a pump. The diesel generator is assumed to be equipped with both voltage-control and frequency-control loops. This diesel engine is associated to a synchronous generator and only requested as a last resort. The purpose of the fuzzy logic supervisor is to guarantee the required load power under irradiation level variations. The performances of the combined production unit are analyzed for the case of a real load. The accuracy of the presented model and the effectiveness of the proposed multivariable supplementary fuzzy supervisor are confirmed by simulation results.

Key words: Fuzzy logic supervisor, photovoltaic generator, diesel generator, flywheel storage system, power control, pumping

INTRODUCTION

Due to high grid connection costs and/or high fuel and maintenance costs, hybrid energy systems (wind/PV/diesel/storage) represent an alternative to conventional diesel electrical generating power systems in many developing countries of the world. Actuality, the hybrid energy systems are expected to play a major role in power systems (Hoff *et al*., 1996). These electric generation hybrid systems are usually more reliable than the systems that use a single source of energy. When designing a hybrid system, both the sizing of the elements and the most adequate control strategy must be obtained. Relatively small changes made in the control strategy can significantly affect the performance of a PV-flywheel storage system (Muselli *et al*., 1999). However, to design a hybrid system is a complicated task. The mathematical design problem involves a significant number of variables. That is why classic design techniques are not able to obtain good results, being necessary to apply other techniques, which allow obtaining satisfactory results (Krichen, 2007).

In Dufo-Lo´peza *et al.* (2007) the power control of stand-alone hybrid renewable electrical systems with hydrogen storage is performed by genetic algorithms. According to Bansal (2003) fuzzy logic can be effectively used in power system problems to represent uncertainties by fuzzification of ambiguous variables and assigning membership functions based on preferences and/or experience.

In this study, we emphasize on a hybrid energy system comprising a PV array as primary energy source and a diesel engine. The power provided by different sources of energy can be actively controlled and the control of these power subsystems is an issue. These two resources are combined to build an integrated system for better technical and economic operations. A multivariable supplementary fuzzy logic supervisor is proposed to guarantee the required power of an isolated load. The exceeded generated power than required by the load is diverted towards a pump.

The objective of this study is to design a fuzzy power management system for a PV/diesel/flywheel storage hybrid power system so that the combination can be used as a reliable power source. In the following, the structure of the hybrid power system is first described and control strategies for power management of the hybrid power system are discussed. The proposed hybrid power system is then verified by numerical simulation.

SYSTEM DESCRIPTION

The studied Hybrid Energy Production Unit (HEPU) consists of a 4 kW (peak) PV array as primary energy source and a diesel engine of a 2 kW. The excess energy with respect to the load requirement has been stored as

Corresponding Author: Ghada Boukettaya , Department of Electrical Engineering, National School of Engineering,
University of Sfax, BP W, 3038, Sfax, Tunisia

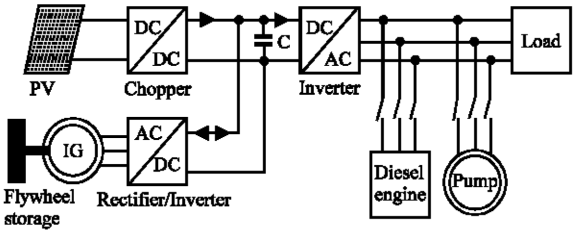

Fig. 1: Configuration of the studied hybird generation system

flywheel to generate electricity during low sunshine periods. In this study the power consumption of the isolated load is predicted around an average of 1.5 kW. The studied HEPU in this study is represented in Fig. 1.

The PV subsystem made up of several panels is connected to the DC bus via a filter and a DC/DC converter, which controls the operating point of the panels and therefore the generated power. The flywheel subsystem comprises a flywheel, an induction machine and an AC/DC converter (rectifier/inverter), which controls the speed of the flywheel and therefore, the exchanged power. The DC bus collects the energy generated by these two subsystems and supplies it through a converter DC/AC and a filter to a primary load or to a pump as optional load. The diesel engine is activated only as a last resort to supply the primary load.

MODELING OF THE HEPU

Modeling of the PV panel: The electric power generated by a photovoltaic panel is unstable according to the irradiation level and the temperature. The characteristic of a photovoltaic cell describing the relation between the current I_{pv} and the voltage V_{pv} is given by (Arul and Ammasai, 2004):

$$I_{pv} = I_g - I_{sat}\left[exp\left(\frac{V_{pv} + I_{pv}R_{ss}}{V_t}\right) - 1\right] - \frac{V_{pv} + I_{pv}R_{ss}}{R_{sh}} \quad (1)$$

With: I_g is the generated current under a given illumination (A), I_{sat} is the current of opposite saturation of the diode (A), V_t is the thermal potential (V), R_{ss} is the equivalent series resistance of the photovoltaic panel (Ω) and R_{sh} is the equivalent parallel resistance of the photovoltaic panel (Ω).

Modeling of the flywheel storage system: The operating point of the flywheel energy storage is based on the stored flywheel energy E_c given by Leclercq *et al.* (2003):

$$E_c = \frac{1}{2} J_f \Omega_f^2 \quad (2)$$

with J_f (kg m^{-2}) and Ω_f (rad s^{-1}) are the inertia moment and the speed of the flywheel, respectively.

The modeling of the converters is made by using the concept of instantaneous average value (Bouscayrol *et al.*, 2005).

Indeed, this type of modeling is interesting since it adapts well to a numerical integration so it is not necessary to choose a step of integration lower than the modulation period of the converters. Moreover, it makes it possible to simulate the total dynamic behaviour of the system.

Modeling of the diesel engine: The diesel generator model used in this study is proposed by Al-Alawi *et al.* (2007). The fuel consumption of the generator can be presented by a linear equation, which has an offset for the fuel consumption at the rated output power of the generator. The fuel consumption of the diesel generator is expressed by:

$$FC = \eta_{fuel}(P_{diesel} - P_{diesel,rated}) + FC_{rated} \quad (3)$$

Where FC (l/h) is the fuel consumption, P_{diesel} (W) is the actual power of the diesel generator, $P_{diesel\ rated}$ (W) is the rated power of the diesel generator, η_{fuel} is the fuel consumption efficiency and FC_{rated} is the diesel generator fuel consumption at rated power.

Modeling of the pump: Ghoneim (2006) use a detailed theoretical analysis to determine the characteristics of the motor and the centrifugal pump. The model is briefly summarized in the following. In this model, the head can be represented by using the affinity laws, which relates the head H(m) to the pump speed N (rpm) and the flow rate Q(l/s) as:

$$H = p_2N^2 + p_1NQ - p_0 Q^2$$

Where p_2, p_1, p_0 are constant coefficients at the reference condition.

To raise water at the desired head, Eskander and Zaki (1997) consider a sufficient mechanical energy to overcome the load demand. Thus, the supervisor developed in this study must assure this energy as follows:

$$E_{pump} = \int \frac{\rho g Q H}{\eta_p} dt \quad (5)$$

Where p (kg m^{-1})is the liquid density, g is the gravity acceleration and $\eta_p$is the pump efficiency.

System sizing: In the present research, the photovoltaic panels are taken as primary source of energy. This energy depends on the distribution and the availability of the solar insolation throughout the year. Referring to Prasad and Natarajan (2006) the produced energy per panel and per day $E_{T\text{-}PV}$ is given by:

$$E_{T-PV} = A\,\eta_m\,P_s\,\eta_{pc}\,H_T \tag{6}$$

With: A(m^2) is the area of each Panel, η_m is the module efficiency, η_{pc} is the conversion efficiency, P_s is the packing factor H_T (Kwh m^{-2}) and (KW) is the daily total insolation.

The total capacity of solar panels C_{T_PV} required to the corresponding load is expressed by:

$$C_{T-PV} = \frac{E_L - E_d}{E_{T-PV}} R_{C_{T-PV}} \tag{7}$$

With: E_L (Kwh) is the average daily demand, E_D (Kwh) is the daily total energy generated by the diesel machine and $R_{C_{T-PV}}$ is the rated capacity of the solar panel.

Thus, the available instantaneous photovoltaic energy $E_{i\text{-}PV}$, as shown in Fig. 2, is expressed by:

$$E_{i-PV} = E_{T-PV} - \int P_{i-PV}\,dt \tag{8}$$

With $P_{i\text{-}PV}$ represents the delivered instantaneous photovoltaic power.

Three different situations may arise on the considered period depending on the load demand and the total generated power (Prasad and Natarajan, 2006). If the total generated energy is less than the daily average load, then there would be a deficiency in the generated power. If the total generated energy matches with the load demand, there is neither an excess nor a deficiency in the generated power and if the generated energy is greater than the load demand, excess power is diverted towards a pump or to the flywheel storage system. It can be understood that the optimization of hybrid systems is carried out in order to minimize the deficiency as well as the excess generated power, thereby reducing the cost of the system. In the present analysis, flywheel storage energy is designed/optimized taking into account the deficiency in the generated power throughout three days, during the operation of the PV-diesel system.

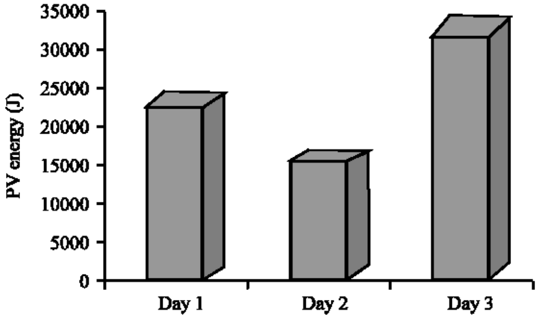

Fig. 2: Available PV energy during 3 days

If we consider a photovoltaic generator supplying between 6 h AM up to 6 h PM, the flywheel must be able to store a quantity of energy approximately equal to 12 KWh. To satisfy this condition, the rated power of the induction machine $P_{n\text{-}mas}$ driving the flywheel is equal to 3KW. As well, the flywheel inertia moment is defined by the following equation (Cimuca *et al*., 2006):

$$J_v = \frac{2\,P_{n-MAS}\,\Delta t}{\Omega_{f\,max}^2 - \Omega_{f\,min}^2} \tag{9}$$

With: $\Omega_{f\ min}$ and $\Omega_{f\ max}$ represent the minimal speed limit and the maximal speed limit of the flywheel, respectively. Δt is the storage period.

CONTROL STRATEGIES OF THE HEPU

The purpose of the proposed system is to supply an isolated load. In this case, the flywheel inverter must control the DC bus voltage (Cimuca *et al*., 2006) i.e., maintaining constant the continuous bus voltage following any change of the transited power. If we neglect the power losses, the power assessment is defined by:

$$P_{PV} + P_{diesel} + P_{flywheel} = P_{load} + P_{pump} \tag{10}$$

With: P_{PV} is the produced PV power, P_{diesel} is the produced diesel power, $P_{flywheel}$ is the storage or generate flywheel power, P_{load} is the load demand power and P_{pump} is the pump power.

The management of the flywheel power ensures the control of the DC bus voltage. This control loop is represented in Fig. 3. To determine the reference pump power $(P_{pump})_{ref}$ and the reference diesel power $(P_{diesel})_{ref}$, we considered the available instantaneous photovoltaic energy$E_{i\text{-}PV}$ and the flywheel speed Ω_f. In this study, the operating zone of the flywheel speed is fixed between two saturated limits, as shown below:

$$\Omega_{f\,min} = \Omega_{nMAS} = 1460 \text{ rpm and}$$
$$\Omega_{f\,max} = 2\Omega_{nMAS} = 290\text{rpm}$$

Where Ω_{nMAS} represents the nominal speed of the induction machine associated to the flywheel storage system.

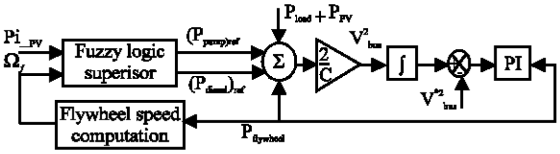

Fig. 3: Block diagram of the storage system control loop

The flywheel storage system will not be able to store any more if the speed is maximum and conversely cannot restore any more if the speed is minimal. Thus, in order to ensure the PV-diesel production control and to maintain the storage system in his correct operating zone, a supervisor should be considered. The supervisor will determine the pump consumed power and the diesel produced power according to the available instantaneous photovoltaic energy $E_{t\text{-}PV}$ and the flywheel speed Ω_f. The Control strategies of the HEPU are represented in Fig. 3.

FUZZY LOGIC SUPERVISOR

The supervision of the control algorithm with fuzzy logic make possible to improve in real time the desired performances. The computation of the fuzzy algorithm is composed in three stages: the fuzzyfication, the inference mechanism and the defuzzyfication. The inputs of the fuzzy logic supervisor are the available PV energy $E_{t\text{-}PV}$ and the flywheel speed Ω_f. Figure 4 shows the block diagram of the fuzzy logic supervisor and the outputs, which are the diesel engine power P_{diesel} pump power P_{pump}.

The advantage of the proposed algorithm is the use of the fuzzy Takagi Sugeno model and so the model provides real output values.

First, each input is classified into three fuzzy sets: Small (S), Medium (M) and Large (L). Membership functions of fuzzy subsystems: S, M and L for the available PV energy variable and S, M and L for the flywheel speed variable are depicted in Fig. 5 and 6, respectively. The inference mechanisms are performed by 9 mathematical rules which are based on the Takagi-Sugeno (TS) technique (Dash and Mishra, 2003):

Rule (ij): if ($E_{i\text{-}PV}$ is A_i) and (Ω_f is B_j) then:

$$P_{diesel\ ij}\ a_{ij} \text{ and } P_{pump\ ij} = b_{ij}$$

With: i = 1, A_i = S, M and L for the wind speed variable and B_j= S, M and L for the stator voltage variable.

The output of the fuzzy supervisor can be written as ($y = P_{diesel}$ or P_{pump}):

$$y = \frac{\sum\limits_{\substack{i=1:3\\ j=1:3}} \mu_i(E_{i-PV})\mu_j(O_f)y_{ij}}{\sum\limits_{\substack{i=1:3\\ j=1:3}} \mu_i(E_{i-PV})\mu_j(O_f)}(y_{ij} = P_{diesel\ ij} \text{ or } P_{pump\ ij})$$

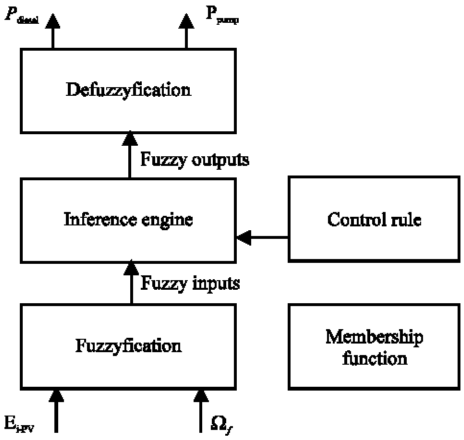

Fig. 4: Block diagram of the fuzzy logic supervisor

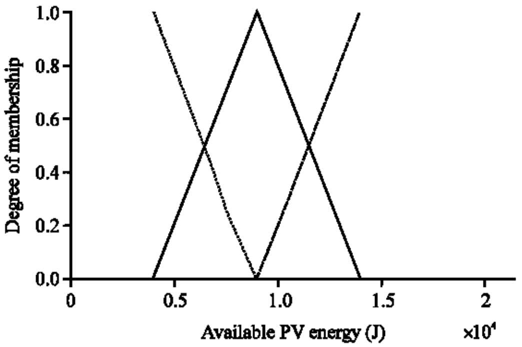

Fig. 5: Membership functions of the available PV energy

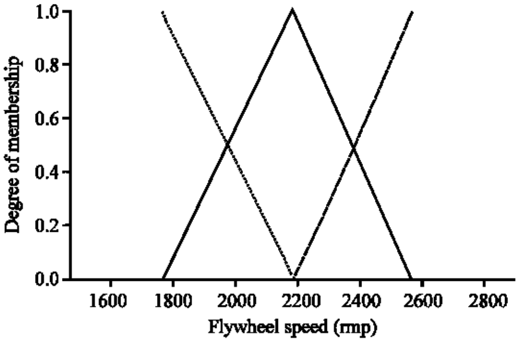

Fig. 6: Membership functions of the flywheel speed

Figure 7 and 8 represent the fuzzy distribution of the reference diesel power and the fuzzy distribution of the reference pump power, respectively according to the available PV energy $E_{it\text{-}PV}$ and the flywheel speed Ω_f.

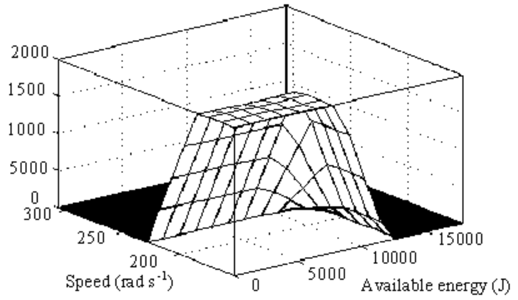

Fig. 7: Fuzzy distribution of the reference diesel power

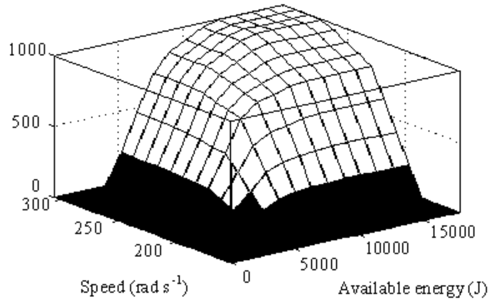

Fig. 8: Fuzzy distribution of the reference pump power

RESULTS

Figure 9 shows the irradiation level during 72 h. The corresponding PV power is represented in Fig. 10. We note that, PV power generation presents three different situations. In the first day (0-24 h) the production is typical, in the second day (24-48 h) the PV production is low and in the third day (48-72 h) the production is high, comparing to the average consumed power by the isolated load which is represented in Fig. 11.

Initially, the speed of the flywheel is 2500 rpm, his evolution during the 72 h is represented in Fig. 12. Fig. 13 depicts the active power stored (negative) or generated (positive) by the flywheel system. As shown in Fig. 14, the diesel machine is solicited only when the last available PV energy is insufficient (Fig. 2) and the flywheel speed is minimal, according to Fig. 12. The centrifugal pump is working only during two periods when the available PV energy is greater than the load demand. Figure 15 represents the excess power consumed by the pump. The performances of the HEPU control strategies are confirmed by the evolution of the DC bus voltage shown in Fig. 16. This voltage is kept satisfactorily to the reference value equal to 600 V during the test.

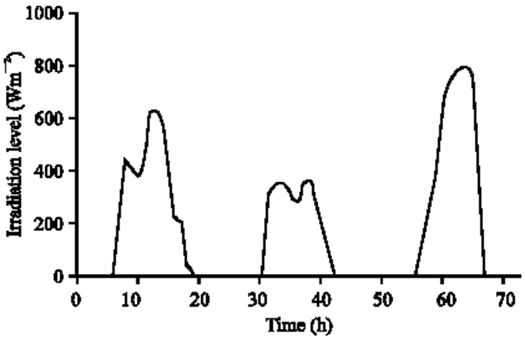

Fig. 9: Irradiation level

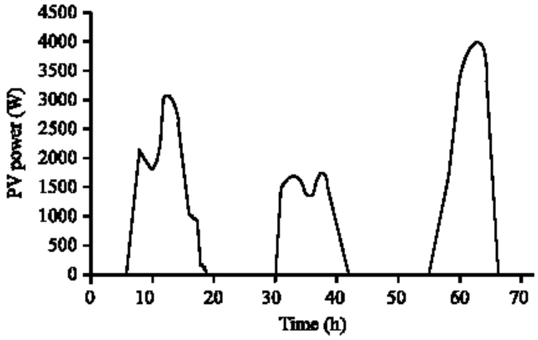

Fig. 10: PV power

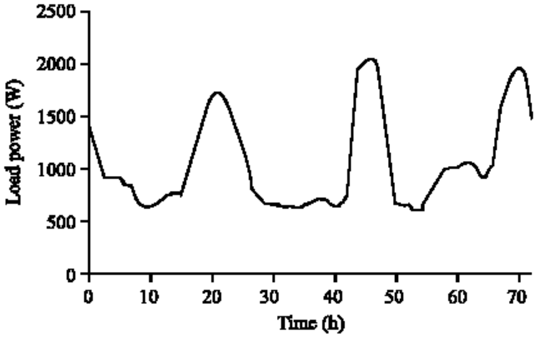

Fig. 11: Load power

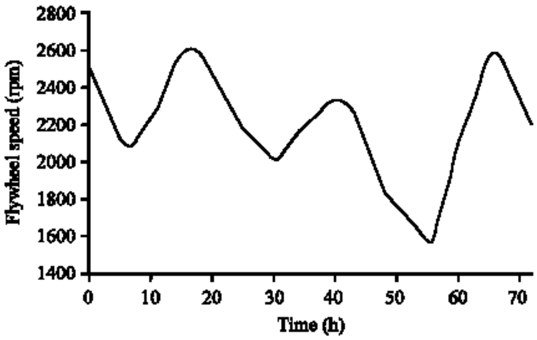

Fig. 12: Flywheel speed

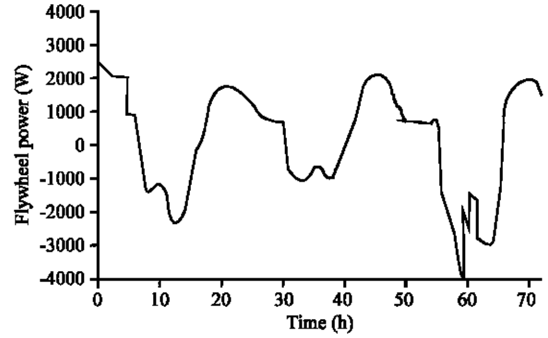

Fig. 13: Flywheel power

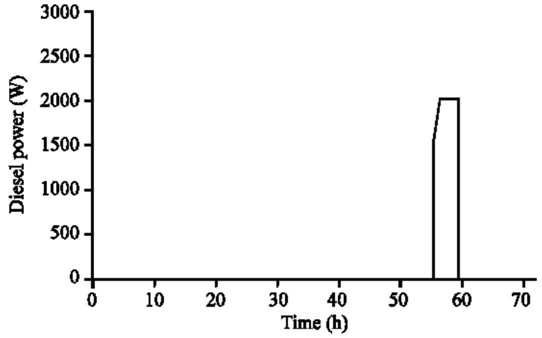

Fig. 14: Diesel power

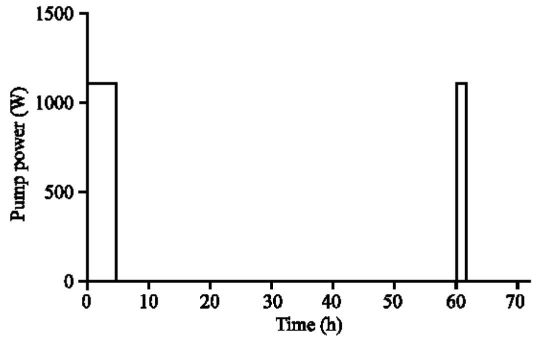

Fig. 15: Pump power

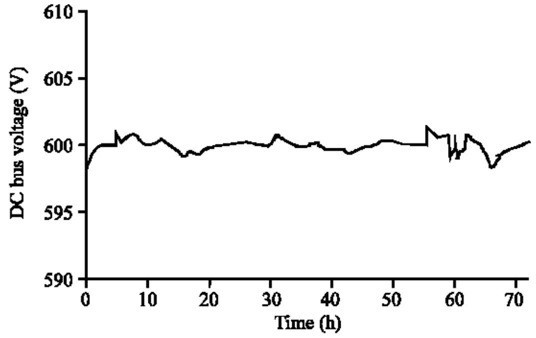

Fig. 16: DC bus voltage

These simulation results emphasize that, owing to the fuzzy logic supervisor associated to this structure, the generated and transited powers are controlled and are less depending on the solar fluctuations.

CONCLUSION

In this study, a model and a control strategy of a Hybrid Energy Production Unit (HEPU) comprising two sources solar/diesel, a flywheel storage system and a load has been proposed. The control of the power exchanged between the flywheel energy storage system and the load is achieved with the help of a fuzzy logic based supervisor, with the aim to minimize variations of the power generated by the diesel generator and to supply a centrifugal pump as much as possible. The interesting performance of the proposed supervisor has been shown with the help of simulations.

REFERENCES

Al-Alawi, A., S.M. Al-Alawi, S.M. Islam, 2007. Predictive control of an integreted PV-diesel water and power supply system using an artificial neural network. ELSIVIER, Renewable Energy, 32: 1426-1439.

Arul Daniel, S. and N. Ammasai Gounden, 2004. A Novel Hybrid Isolated Generating System Based on PV Fed Inverter-Assisted Wind-Driven Induction Generators. IEEE Trans. Energy Conversion, 19: 416-422.

Bouscayrol, A., P.H. Delarue, X. Guillaud, 2005. Power strategies for maximum control structure of a wind energy conversion system with a synchronous machine. Renewable Energy, 30: 2273-2288.

Bansal, R.C., 2003. Bibliography on the Fuzzy Set Theory applications in Power Systems (1994-2001)'', IEEE Trans. Energy Conversion, 18: 1291-1299.

Cimuca, G.O., C. Saudemont, B. Robyns and M.M. Radulescu, 2006. Control and Performance Evaluation of a Flywheel Energy-Storage System Associated to a Variable-Speed Wind Generator. IEEE. Tran. Ind. Elect., 53: 1074-1085.

Dash, P.K. and S. Mishra, 2003. Damping of multimodal power system oscillations by FACTS devices using non-linear Takagi-Sugeno fuzzy controller. Elec. Power and Energy Sys., 25: 481-490.

Dufo-Lo´peza, R., J.L. Bernal-Agustin and J. Contreras, 2007. Optimization of control strategies for stand-alone renewable energy systems with hydrogen storage. Renewable Energy, 32: 1102-1126.

Eskander, M.N. and A.M. Zaki, 1997. A Maximum efficiency photovoltaic induction motor pump system. ELSEVIER, Renewable Energy, 10: 53-60.

Ghoneim, A.A., 2006. Design optimisation of photovoltaic powered water pumping systems. ELSIVIER,Energy Covertion and Manage., 47: 1449-1463.

Hoff, T.E., H.J. Wenger and B.K. Farmer, 1996. Distributed generation: An alternative to electric utility investments in system capacity. Energy Policy, 24: 137-147.

Krichen, L., 2007. Modelling and Neural Control of a Hybrid Production Unit Using Wind and Photovoltaic Energy. Fourth International Multi-Conference on Systems, Signals and Devices, PES, Hammamet, Tunisia. Vol. II.

Muselli, M., G. Notton and A. Louche, 1999. Design of hybrid-photovoltaic power generator, with optimization of energy management. Sol Energy, 65: 143-57.

Leclercq, L., B. Robyns and J. M.Grave, 2003. Control based on fuzzy logic of a flywheel energy storage system associeted with wind and diesel generators. Math. Comput. Sim., 63: 271-280.

Prasad, A.R. and E. Natarajan, 2006. Optimisation of integrated photovoltaic-wind power generation systems with battery storage. ELSEVIER, Energy, 31: 1943-1954.