

Fuzzy Logic Operation Control for PV-Diesel-Battery Hybrid Energy System

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Abstract: In this paper an operational control technique, based on using the fuzzy logic controller (FLC), is developed and applied to a proposed Photovoltaic-Diesel-Battery (PVDB) hybrid system. The proposed scheme is modeled and simulated using MATLAB-SIMULINK and FUZZY toolbox. The FLC is designed, to work simultaneously with the commonly used ON-OFF controller, for optimizing the operation of the PVDB system under different insulations. Where, the proposed system becomes able to reliably satisfy the system's load and, also, to optimize the battery and diesel operation at all working conditions. The results indicated the high capability of the FLC in controlling the system.

Keywords: PVDB hybrid system, Fuzzy logic control, MATLAB-SIMULINK.

1. INTRODUCTION

Throughout the world, there exist a number of small isolated communities, without access to an electricity grid. Extending utility grid to these people, in many cases is not cost effective. Electrical energy is usually provided in these cases by small to medium stand-alone diesel generators. The diesel generators have a low initial capital cost, but they are very expensive to run and maintain and contribute to the environmental pollution as every liter of diesel fuel releases about 3 kg of CO₂ gas [1,2].

Combining renewable energy sources (such as photovoltaic (PV)) and conventional energy sources (such as diesel generator) with a battery bank for storage, forming a hybrid energy system, can provide an economic, environment friendly and reliable supply of electricity [1-5]. The requirement of the diesel generator in the system is to supplement the battery and the PV and to act as a back-up generator for extending periods of low renewable energy input or high load demand [1].

The operation control of such hybrid energy system is not a linear problem due to the nonlinear characteristics and the associated parameters variation of the constituent components. Therefore, the optimal operation control of such systems cannot be achieved easily using classical controllers, and hence a non classical or intelligent controller is indispensable.

Expert systems, fuzzy logic, neural networks and genetic algorithms belong to the area of artificial intelligence (AI), the AI is basically using human intelligence in a computer, so that a computer can think intelligently like a human, and these are recently finding wide applications in science and engineering problems [6].

For complex processes, it is difficult to obtain a reasonably good mathematical model. Fuzzy logic control based on operator experience is an ideal solution for applications

where a mathematical model is known or not precisely known especially for problems with varied parameters and nonlinear models [7].

Recently, fuzzy logic based control has been considered as one of the most active research area, that can control most PV applications, especially those of Photovoltaic-Diesel-Battery (PVDB) hybrid energy system. The PV arrays are characterized with highly nonlinear current-voltage curves according to the variation of solar insolation. The operation of the diesel engine and/or the battery is controlled when the output power from the PV array is not enough to satisfy the load. Since, the fuzzy logic controller (FLC) works well for complex ill-defined nonlinear systems, especially where parameter variation problem exists. Therefore, the application of the FLC for the operation of the PVDB hybrid energy system is well-suited. This paper designs the suitable FLC and ON-OFF controller for optimizing the developed operational control technique of the considered PVDB hybrid energy system, with the corresponding simulation results are indicated at the end of the paper.

2. SYSTEM MATHEMATICAL MODEL

2.1. Solar Array Generator

The terminal equation of the solar array is given by [8]:

$$V_A = AV_T \ln[(I_{ph} - I_A + I_r)/I_r] - I_A R_s \quad (1)$$

Where:

- V_A array terminal voltage
- I_A array terminal current
- I_{ph} array photo-generated current
- I_r reverse saturation current
- R_s array series resistance
- A ideality factor
- V_T thermal voltage

Thus, the array power is given as the multiplication of array voltage V_A by the array current I_A . Also, the array maximum power P_{max} can be obtained as:

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$$P_{max} = V_{mp} \cdot I_{mp} \quad (2)$$

Where: V_{mp} array maximum-power voltage

I_{mp} array maximum-power current

The maximum energy which can be extracted from the solar array throughout one-day period is given by:

$$E_{max} = \int_{t_{sr}}^{t_{ss}} P_{max}(t) dt \quad (3)$$

Where, t_{sr} is the sunrise time and t_{ss} is the sunset time.

2.2. Diesel Generator Set

The relation between the diesel generator input fuel and output electrical power is assumed, here, to be linear. Another common ‘rule of thumb’ is the assumption that the fuel consumption at idling is approximately 25 to 30 per cent of the consumption at nominal rated power. The diesel plants have a clutch between the diesel engine and the generator. To be able to handle starts and stops of the diesel engine, the clutch must also be modeled.

The differential equations describing speed and fuel consumption in this model are [9]:

$$d\omega_d / dt = [K_v(K_c m_f - P_o) - D_d \omega_d - T_{dgen}] / J_d \quad (4)$$

and

$$dm_f / dt = [\omega_d - \omega_{ref} - m_f / \delta] / T_d \quad (5)$$

The Symbols are:

- ω_d Engine speed
- ω_{ref} Governor reference speed
- δ Governor gain constant
- T_d Time constant in governor
- m_f Diesel fuel consumption
- K_c Constant describing efficiency of the combustion
- P_o Motor chamber pressure when running idle
- K_v Stroke volume
- T_p Produced torque
- T_f Friction torque
- T_{dgen} Load torque from generator and clutch
- D_d Constant describing the frictional losses
- J_d Total moment of inertia of the engine, clutch and generator

2.3. Battery Model

The general equation for the used battery (24 Trojan L-16) voltage V_B and current I_B during the charge/discharge processes is [10]:

$$V_B = V_{OC} \pm I_B R_B$$

$$V_B = \left[V_o + K_B \frac{Q}{\frac{C_T}{1+aI_B^b} (1+\alpha_c \Delta T + \beta_c \Delta T^2)} \right] \pm I_B \left[\frac{P_1}{1+I_B^{P2}} + \frac{P_3}{\left[1-\frac{Q}{C_T}\right]^{P4}} + P_5 \right] (1-\alpha_r \Delta T) \quad (6)$$

Where, “+” stands for charge and “-” for discharge. In this equation:

V_{oc} battery open circuit voltage

R_B battery internal resistance

V_o initial voltage parameter

$Q = I_B t$ Ah supplied

$C = C_T (1+\alpha_c \Delta T + \beta_c \Delta T^2) / (1+aI_B^b)$ capacity equation

$P_1 / (1+I_B^{P2}) + P_3 / [1-Q/C_T]^{P4} + P_5$ internal resistance term.

Where, a, b, V_o , K_B , P_1 , P_2 , P_3 , P_4 , and P_5 are empirical parameters, α_r is the temperature coefficient of internal resistance, and $\Delta T = T - 25^\circ$.

3. THE CONTROL TECHNIQUE

The main targets of the proposed operational control technique of the PVDB hybrid energy system are to reliably satisfy the load requirements, and at the same time to optimize the battery and diesel operation at all working atmospheric conditions. The block diagram of the proposed PVDB hybrid energy system with the associated control signals, to achieve these targets, is shown in Fig. (1). In this diagram, it is clear that the solar generator satisfies the load requirements continuously as long as there is adequate illumination. Also, it works independently of the other system components until the system controller (i.e., the designed FLC and the commonly used ON-OFF controller) takes the relevant decision to compensate the change in the load profile. The actual load power is used to optimally manage the system components, to continuously cover the desired load requirements in terms of the need to charge or discharge the battery as well as the need to plug in or plug out the diesel unit.

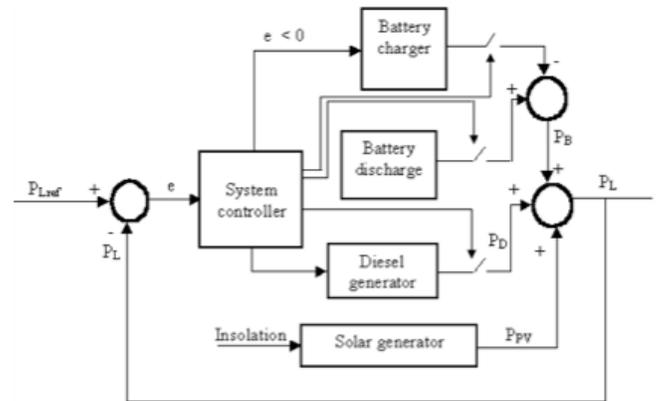


Fig. (1). Block diagram of the proposed PVDB hybrid energy system.

The interaction between the available solar insolation, the desired load profile, and the corresponding battery state of charge results in three different cases for operation control of the proposed hybrid energy system. These three cases are used, here, to make the system controller able to take the proper decision for the battery and/or the diesel generator

Table 1. Different Cases for Operation Control of the Proposed Hybrid Energy System

Case	System Error	Concluding Remark	Controller Action
1	$e > 0$	$P_{PV} < P_{Lref}$	Safely discharge the battery and switch on diesel generator if the battery power is not sufficient
2	$e = 0$	$P_{PV} + P_B + P_D = P_{Lref}$	Remain the current control settings without change
3	$e < 0$	$P_{PV} > P_{Lref}$	Safely charge the battery

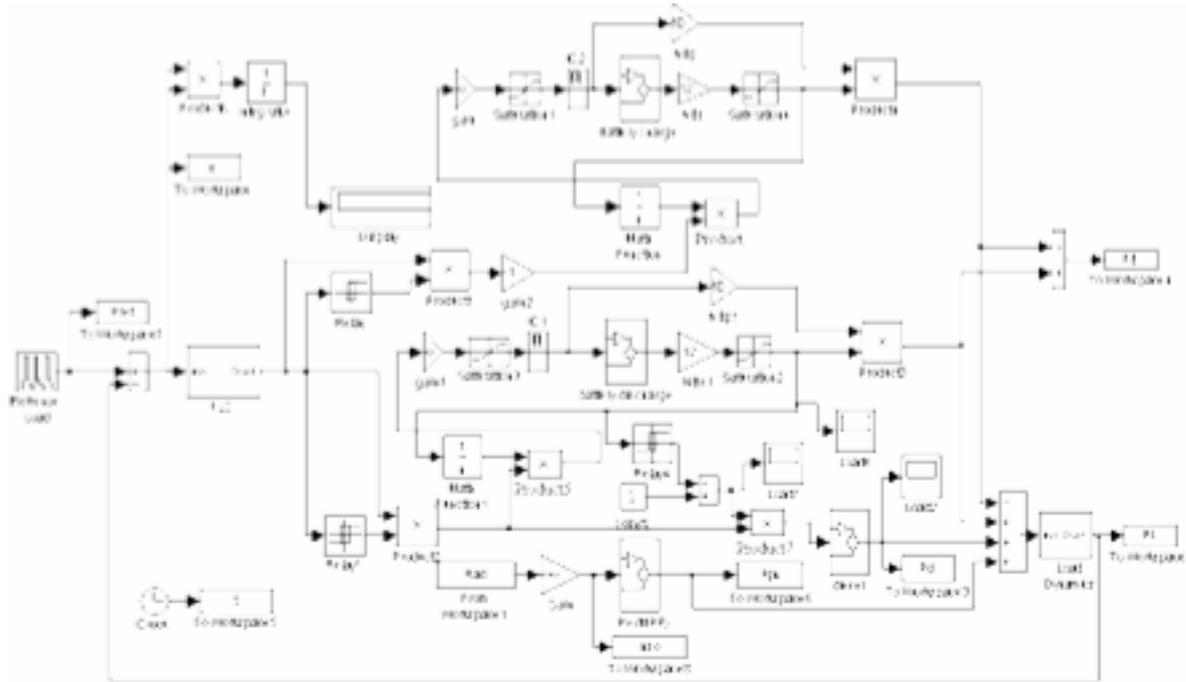


Fig. (2). SIMULINK model of the PVDB hybrid energy system with FLC.

and to reliably satisfy the load requirements. The three cases, which are summarized in Table 1, can be explained as follows. In case (1), the system error (i.e., the difference between the desired load power P_{Lref} and the actual load power P_L) is greater than zero, which means that the generated solar power P_{PV} is lower than that required by the load. Thus, in this case the controller makes the battery discharge with the limiter discharger controller (in order not to exceed the maximum discharging limit) to supplement this deficit. At the same time the controller may switch on the diesel generator, if the battery power is not sufficient. In case (2), the system error equals to zero, which means that the load supplied power from the solar generator, the battery, and/or the diesel generator is just sufficient to satisfy the load requirements. Thus, in this case the controller remains the current settings without change. While, in case (3), the system error is smaller than zero, which means that the generated solar power is greater than that required by the load. Thus, in this case the controller causes the battery to be charged with the limiter charge controller (in order not to exceed the maximum charging limit). Note, here, that the operation control of such hybrid energy system is not a linear problem due to the nonlinear characteristics and the associated parameters variation of the constituent components. Therefore, the optimal operation control of such systems can not be achieved

easily using classical ON-OFF or PI controllers. Hence a non classical or intelligent controller that incorporates the action of both the FLC and the classical ON-OFF controller is proposed, to overcome the nonlinearity and parameter variation problems of the components included in the hybrid system, which greatly improves the performance of the system at transient and also ensures zero error at steady state condition.

4. MATLAB SIMULATION AND FLC DESIGN

The system mathematical models are used to construct the SIMULINK block diagram of the complete PVDB hybrid energy system, as shown in Fig. (2), by linking the individual models together. Also, the SIMULINK block diagram of the proposed FLC is shown in Fig. (3), which is a two-input single-output controller. The FLC inputs are the error e and change of error Δe , defined, respectively, by:

$$e(k) = P_{Lref}(k) - P_L(k) \tag{7}$$

and

$$\Delta e(k) = e(k) - e(k-1) \tag{8}$$

While, the FLC output is the change in control variable $\Delta u(k)$, which is added to the previous control variable $u(k-1)$ to give the current control variable $u(k)$, as

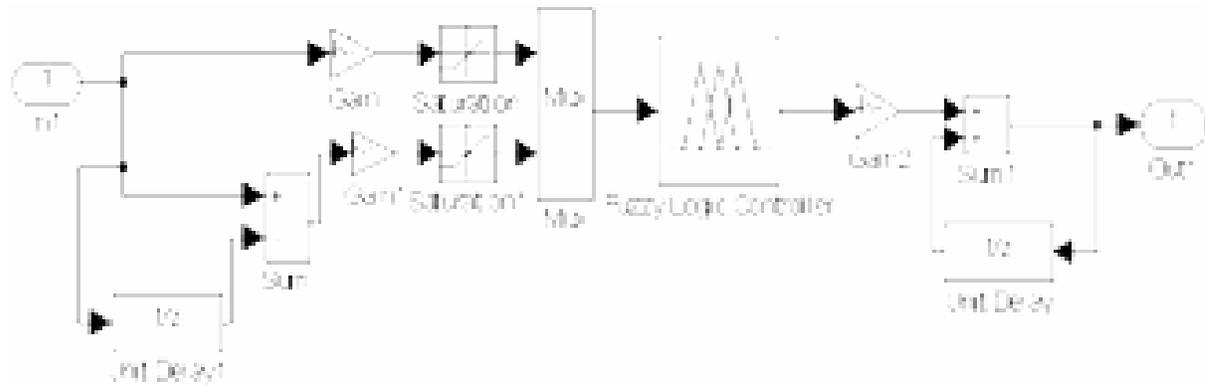


Fig. (3). SIMULINK block diagram of the FLC.

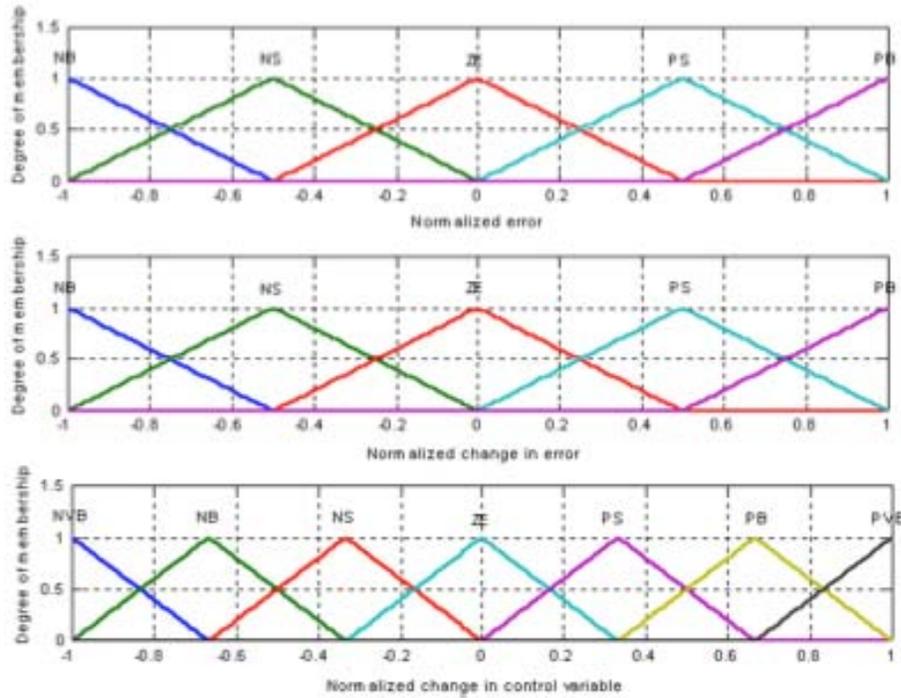


Fig. (4). Membership functions of the fuzzy variables.

$$u(k) = \Delta u(k) + u(k-1) \tag{9}$$

Where, k is sampling time. The design of the considered FLC is primary based on trial and error procedure. The triangular membership function (with 50 % overlapping for the neighboring fuzzy subsets) is considered because of its simplicity of implementation and because less computational intensity is required. Since the sensitivity of a variable determines the number of fuzzy subsets associated to its membership function. Thus, due to the high sensitivity of the output variable Δu over that of the input variables, a finer partitioning for its fuzzy subsets is necessary [11,12]. Fig. (4) indicates the membership functions of the input and output variables. In this case five subsets are used for both the input variables (e and Δe), while seven subsets are used for the output control variable (Δu). It is to be noted that the number of subsets of the output variable doesn't have an influence on the number of fuzzy control rules, but changes

the response of the whole system significantly. The designed fuzzy control rules, expressed in a matrix form, are shown in Table 2. This table indicates that the considered number of rules is 25. Where, the linguistic values of the used fuzzy subsets are defined as:

- N negative
- ZE zero
- P positive
- S small
- B big
- V very

The parameters of the FLC (i.e., its scaling factors) are tuned using the trial and error iterative approach, until the optimal response of the PVDB hybrid system is obtained. The controller tuning is carried out at insulation level of

Table 2. Rule Base of the FLC

$e \backslash \Delta e$	NVB	NVB	ZE	PS	PB
NB	NVB	NB	NB	NS	ZE
NS	NB	NB	NS	ZE	PS
ZE	NB	NS	ZE	PS	PB
PS	NS	ZE	PS	PB	PVB
PB	ZE	PS	PB	PVB	PVB

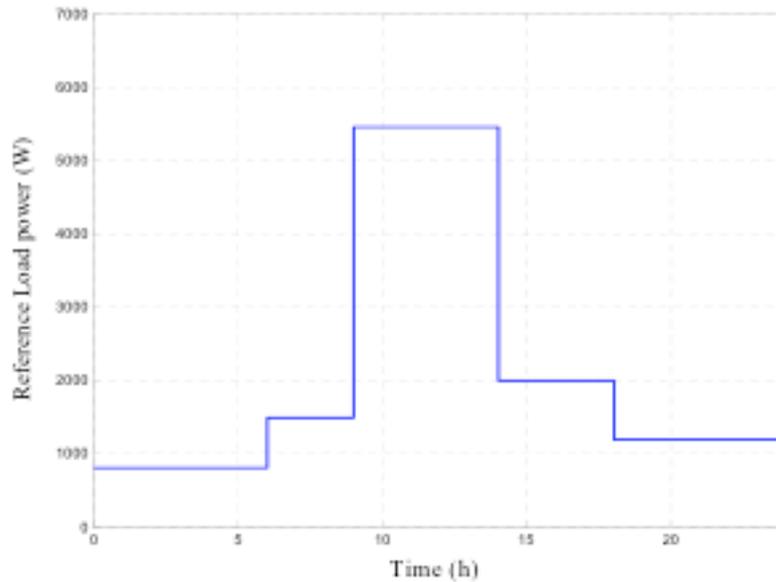


Fig. (5). Load profile.

Table 3. Modified Rule Base of the FLC

$e \backslash \Delta e$	NVB	NVB	ZE	PS	PB
NB	NVB	NB	NB	NS	ZE
NS	NB	NB	NS	ZE	PS
ZE		NS	ZE	PS	PB
PS			PS	PB	PVB
PB					

1000 W/m² and at the maximum daily load of the load profile, illustrated in Fig. (5). Afterwards, the weight of each individual fuzzy control rule is evaluated successively, until the number of the actual used rules decreases to 17. The useful fuzzy rules and the corresponding control surface of the designed FLC are indicated in Table 3 and Fig. (6), respectively.

5. RESULTS AND DISCUSSIONS

Initially, to indicate the high capability of the designed FLC (with the ON-OFF controller) in controlling the proposed PVDB hybrid energy system, the response of the load power using the ON-Off controller alone is indicated in Fig.

(7), which is carried out at the daily peak load of 5500 W and at insolation level of 1000 W/m². Thus, Fig. (7) indicates that using the classical ON-OFF controller alone yields a poor dynamic response for the load power that have not zero error at steady state. The transient response of the load power can be improved and at the same time the steady state error of the response can be eliminated from the system by using another controller that works simultaneously with the ON-Off one, as shown in Fig. (8). This figure illustrates comparison between the relative responses of the load power using the classical PI controller and the designed FLC. This comparison is carried out, also, at the daily peak load of 5500 W and at insolation level of 1000 W/m². Thus, Fig. (8) indicates

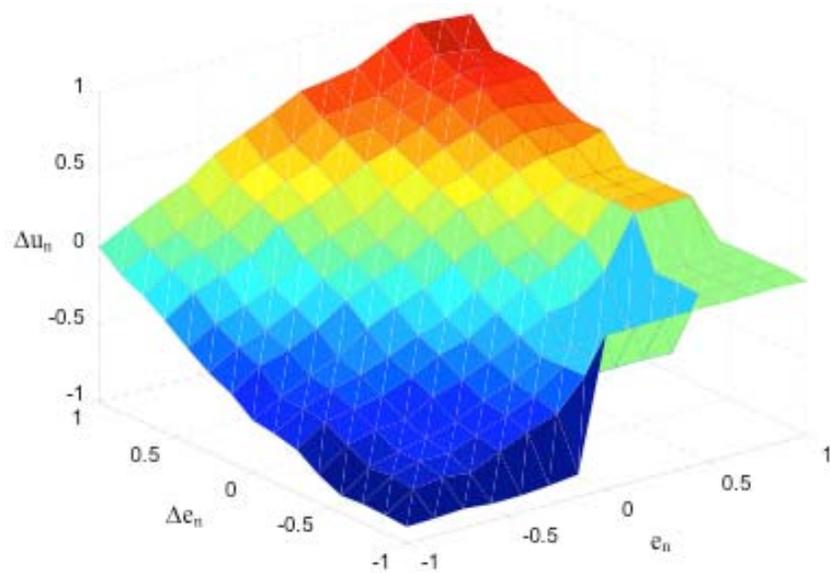


Fig. (6). Control surface of the designed FLC.

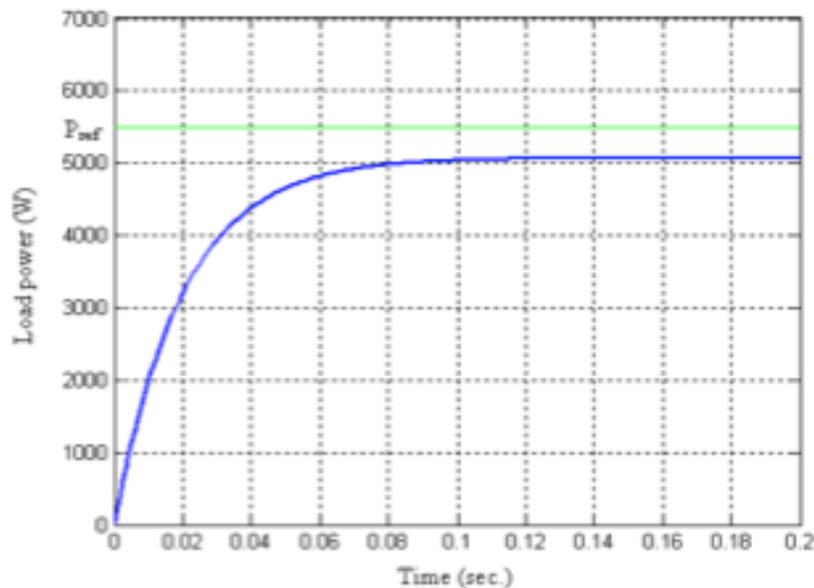


Fig. (7). Responses of the load power using the NO-OFF controller.

that the response obtained using the FLC is better than that obtained when the PI controller is used. This fact can be confirmed by illustrating the time domain specifications of the two responses, as shown in Table 4.

Also, to evaluate the relative robustness of both controllers in controlling the proposed PVDB hybrid energy system at different atmospheric conditions, the PVDB system is subjected to sudden variations in insolation level of 1000 W/m², 200 W/m², and 800 W/m², respectively. The corresponding responses of the load power, using the two controllers, are depicted in Fig. (9). Thus, Fig. (9) indicates that when there is a sudden variations in the atmospheric conditions the response of the load power using the FLC is good and faster and having a lower integral of squared error (ISE) value compared to the case of using the PI controller. Therefore, this indicates the high suitability of the FLC over the

classical controllers in controlling the PVDB hybrid energy systems.

As, the main objectives of the designed FLC and the ON-OFF one are to reliably cover the load demand continuously at all days and at the same time to optimize the battery and diesel operation at all working atmospheric conditions. Then, the performance of the PVDB hybrid energy system is evaluated and compared, here, for two different days (one is cloudy and the other is sunny). Fig. (10) illustrates this comparison. Thus, it is clear that whatever the day is cloudy or sunny the load is completely covered, and this is achieved by optimally adjusting the battery and/or the diesel to supply the complementary power when the PV generation, which is shown to be variable according to the incident solar insolation levels for the cloudy and sunny days, is not enough. Also, it is cleared that the excess PV power is used to charge

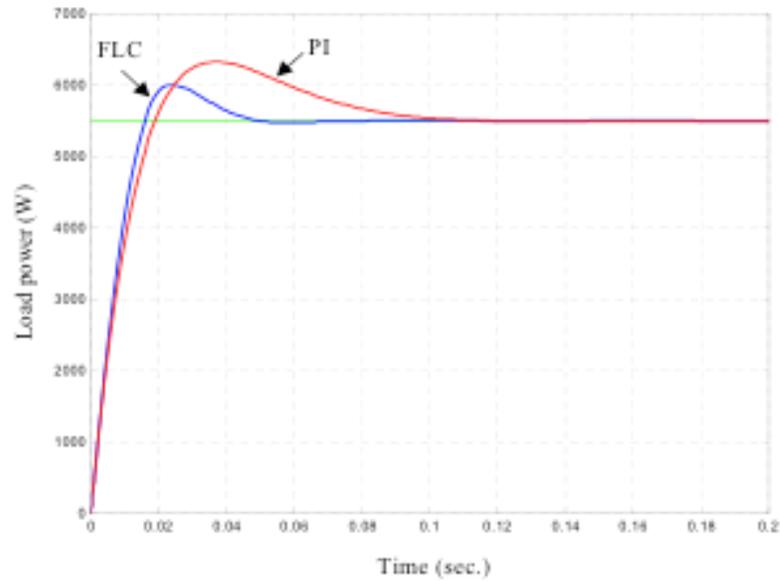


Fig. (8). Responses of the load power using the FLC and the PI controller.

Table 4. Time Domain Specifications

Controller	FLC	PI
Rise time (t_r)	0.016 sec.	0.019 sec.
Settling time (t_{ss})	0.042 sec.	0.086 sec.
Peak time (t_p)	0.024 sec.	0.037 sec.
Max. overshoot (M_p)	9.2 %	15 %
Integral of squared error (ISE)	123.763×10^3	151.904×10^3

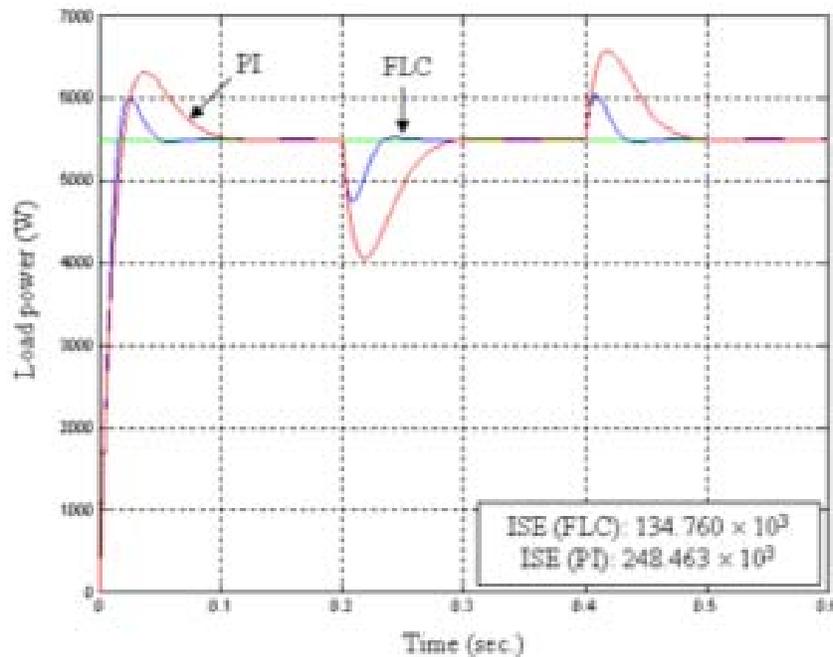


Fig. (9). Responses of the load power using the FLC and the PI controller at sudden variations in insolation.

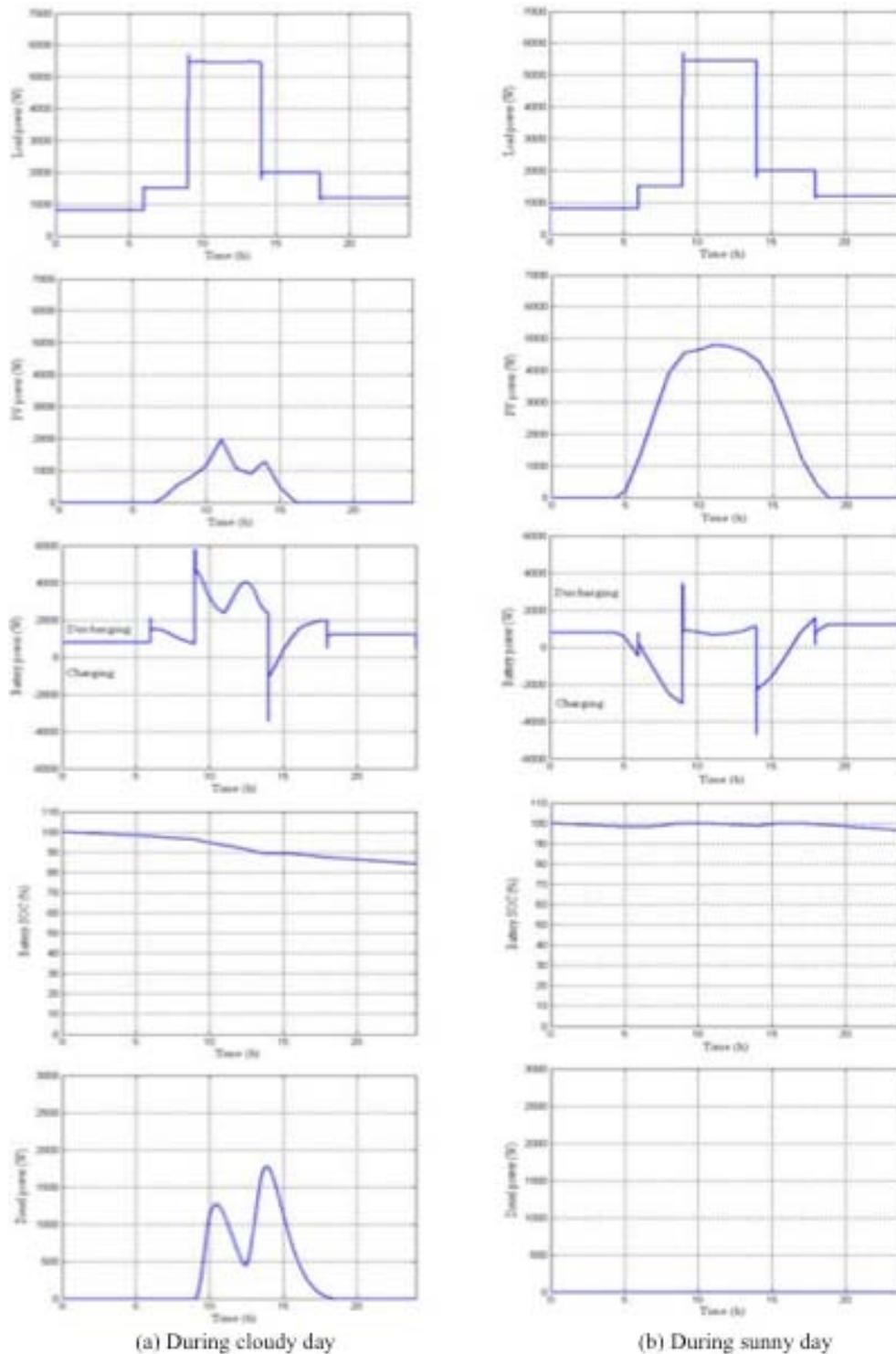


Fig. (10). Performance of the PVDB hybrid system during two different days.

the battery (i.e., increases the battery state of charge SOC), especially during the sunny days. Moreover, the diesel generator is shown to operate only during the cloudy days; to supply the deficit in peak load power in conjunction with the system battery.

6. CONCLUSION

An operational control technique, based on using the FLC and the commonly used ON-OFF controller, is devel-

oped and applied to the proposed PVDB hybrid energy system. This control technique aims to reliably satisfy the system's load, and at the same time to optimize the battery and diesel operation at all working atmospheric conditions. The proposed PVDB hybrid energy system is modeled and simulated using MATLAB-SIMULINK and FUZZY toolbox. The FLC is, mainly, designed to overcome the nonlinearity and the associated parameters variation of the components included in the PVDB hybrid energy system; therefore yield-

ing better system's response at both transient and steady-state conditions. Through simulation work, the proposed PVDB hybrid energy system with using the FLC is compared to that with using the conventional PI controller. Where, the obtained simulation results indicate that the response of the load power in case of using the FLC is better and faster than that obtained in case of using the PI controller at all atmospheric conditions. Also, the obtained performance of the PVDB hybrid energy system, using the designed FLC, during two different days indicates that the load is continuously satisfied at all working days through optimizing the battery and diesel operation.

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