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Operation cost minimization of photovoltaic–diesel–battery hybrid systems

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A R T I C L E I N F O

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A B S T R A C T

In this paper, two control strategies involving "continuous" and "ON/OFF" operation of the diesel generator in the solar photovoltaic–diesel–battery hybrid systems are modeled. The main purpose of these developed models is to minimize the hybrid system's operation cost while finding the optimal power flow considering the intermittent solar resource, the battery state of charge and the fluctuating load demand. The non-linearity of the load demand, the non-linearity of the diesel generator fuel consumption curve as well as the battery operation limits have been considered in the development of the models. The simulations have been performed using "fmincon" for the continuous operation and "intlinprog" for the ON/OFF operation strategy implemented in Matlab. These models have been applied to two test examples; the simulation results are analyzed and compared to the case where the diesel generator is used alone to supply the given load demand. The results show that using the developed photovoltaic–diesel–battery optimal operation control models, significant fuel saving can be achieved compared to the case where the diesel is used alone to supply the same load requirements.

1. Introduction

The lack of reliable electrical power supply, the high cost of AC grid extension and rough topography are some of the severe challenges faced in the rural electrification of a good number of developing countries. In most of the cases, loads in those rural areas are powered by small DGs(Diesel Generators) running continuously [11]. Compared to other supply option such as renewable energy sources, DGs have low initial capital costs and generate electricity on demand. They are easily transportable, modular, and have a high power-to-weight ratio. DGs can also be integrated with other sources and energy storage in hybrid system configurations making it an ideal option for standalone power generation. However, due to the long running times and the highly non-linearity in the daily load demand profiles, DGs are usually operated inefficiently resulting in higher cost of energy produced.

The global warming, the ozone layer's depletion and other environmental impacts from using DGs (or other fossil fuels) have led to the use of RE (renewable energy) sources [13].

RE generation such as solar PV (photovoltaic) are gaining consideration, due to advantages such as low operation and maintenance, and easy deployment to meet growing energy needs [1,5,9]. Solar PV technology is an established clean way of generating energy and is currently extensively to supply power in several standalone applications [3,16,19].

However, except for its high capital cost, the other main disadvantages of PV generation is the fact that the power produces depends on the solar resources which is highly non-linear and varies with the hours of the day and the seasons of the years. Therefore the PV cannot always match the load power demand.

Hybrid solar PV–diesel–battery hybrid systems present a resolution to the time correlation of intermittent solar source as well as load demand fluctuations [4,14]. In this configuration, the DG is used to balance the deficit of the power supply from the PV and the battery when the load demand is high. This combination enhances the efficiency and the output capability of the entire hybrid system.

Several authors have discussed the optimal operation control of hybrid PV–diesel–battery systems for standalone power generation [6]. Have developed the HOGA program (Hybrid Optimization by Genetic Algorithms) used to design a PV–Diesel system (sizing and operation control of a PV–Diesel system). The program has been developed in C++. Two algorithms are used in HOGA. The main algorithm obtains the optimal configuration of the hybrid system, minimizing its Total Net Present Cost. For each vector of the

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main algorithm, the optimal strategy is obtained (minimizing the non-initial costs, including operation and maintenance costs) by means of the secondary algorithm. In the paper, a PV–Diesel system optimized by HOGA is compared with a standalone PV system that has been dimensioned using a classical design method based on the available energy under worst-case conditions. HOGA is also compared with a commercial program for optimization of hybrid systems such as the HOMER (Hybrid Optimization Model for Energy Renewable) and HYBRID2. In Ref. [7]; the same authors have presented a study of the influence of mathematical models in the optimal design of PV–Diesel systems. For this purpose, HOGA has been used. The mathematical models of some hybrid system elements have been improved in comparison to those usually employed in hybrid systems' design programs. Furthermore, a more complete general control strategy has been developed, one that also takes into account more characteristics than those usually considered in this kind of design.

Nafeh [15] developed and applied an operational control technique, based on using the FLC (fuzzy logic controller) and the commonly used ON–OFF controller for a Photovoltaic–Diesel–Battery 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 under all working atmospheric conditions. The proposed hybrid energy system is modeled and simulated using MATLAB/Simulink and FUZZY toolbox. The FLC is mainly designed to overcome the non-linearity and the associated parameters variation of the components included in the hybrid energy system, therefore yielding better system's response in both transient and steady state conditions.

Woon et al. [23] reviewed an optimal control approach used by Ref. [22] to evaluate the differences in operating strategies and configurations during the design of a PV–diesel–battery model. However Ref. [22], did not capture all realistic aspects of the hybrid power system. In this paper, the optimal control model was analysed and compared with three different simulation and optimization programs. The authors proposed several improvements to the current model to make it more representative to real systems.

Ashari and Nayar [2] presented dispatch strategies for the operation of a PV–diesel–battery hybrid power system using 'set points'. This includes the determination of the optimum set points values for the starting and stopping of the diesel generator in order to minimize the overall system costs. A computer program for a typical dispatch strategy has been developed to predict the long-term energy performance and the life cycle cost of the system.

Tazvinga et al. [20] developed a hybrid system model incorporating photovoltaic cells and diesel generator in which the daily energy demand fluctuations for different seasonal periods of the year in order to evaluate the equivalent fuel costs as well as the operational efficiency of the system for a 24 h period. The results show that the developed model can give a more realistic estimate of the fuel costs reflecting fluctuations of power consumption behavior patterns for any given hybrid system.

Unlike the above-mentioned papers, the present work looks at the optimization of the daily operation cost of hybrid PV–diesel–battery systems from an energy efficiency point of view, as one of the main attributes of energy efficiency is seeking for optimality. Energy efficiency can be defined as the ratio of the output to the input energy and is characterized by the performance efficiency, the operation efficiency, the equipment efficiency, and the technology efficiency as main components [25]. Operation efficiency is a system-wide measure, which is assessed by taking into consideration the optimal sizing and matching of all system components, time control and human coordination [24]. Operation efficiency can be enhanced using mathematical optimization and optimal control techniques [24,25].

Therefore, the present paper focuses on the development of two models namely the "continuous" and "ON/OFF" control strategies to minimize the operation cost of PV–diesel–battery hybrid systems during a 24 h period. Considering a short time horizon, the battery and PV's operation costs are negligible, therefore only the fuel cost of the DG is considered. The non-linearity in the fluctuation of the solar resource and the load demand, the non-linearity of the diesel generator fuel consumption curve as well as the battery operation limits have been considered in the development of the models. The simulations of two control strategies have been performed under the summer and winter load and weather conditions; the results have been compared with the case where the DG is used alone to supply the load demands.

2. Hybrid system components description and operation

The power flow of the proposed PV–diesel–battery hybrid system is shown in Fig. 1. The load demand is primarily met by the sum of the PV and the battery starts discharging within its operating limits as soon as the PV do not meet the demand. If the PV output power is above the load demand, the excess of power is used to recharge the battery. The DG is used when the power from PV and the battery cannot respond to the load energy requirements. Depending on the operation strategy selected, the DG can only supply the deficit of power needed by the load or even at the same time recharge the battery. The mathematical models of the system's different components are presented in the subsection below:

2.1. Photovoltaic system

When light strikes a silicon, gallium arsenide or cadmium sulphide cell an electric current is generated through the photovoltaic effect [17]. The power rating of a PV panel is expressed in Wp (peak Watts) indicated at "standard test conditions" conducted at a temperature of 25 °C and irradiance of 1000 W/m^2. The output power of the solar PV system can be expressed as follows [21]:

$$P_{PV} = A_{PV} \times \eta_{PV} \times \int_{t_0}^{t} I(t) \times f(t) \times dt \tag{1}$$

where: A_{PV} is the total area of the photovoltaic generator (m^2); η_{PV} is the module efficiency; I is the hourly irradiance (kWh/m^2) and *f(t)* is the radiance density.

2.2. Diesel generator

A DG is normal diesel engine coupled to an electrical generator. DGs are usually designed in such a way that they always operate close to their power rating to achieve high efficiency; this condition can be used later as an operation constraint. With this operation strategy as well as operation constraint, the DG is expected to run at high load factors, which will result a decrease of the fuel consumption, of the Carbone footprint and increase of the DG lifespan [10].

The FC (fuel cost) is calculated for a day is given by the quadratic non-linear function below:

$$C_f \sum_{j=1}^{N} \left(aP_{DG(j)}^2 + bP_{DG(j)} + c \right) \tag{2}$$

where:

N = the number of sampling intervals within the operation range or period of the system;

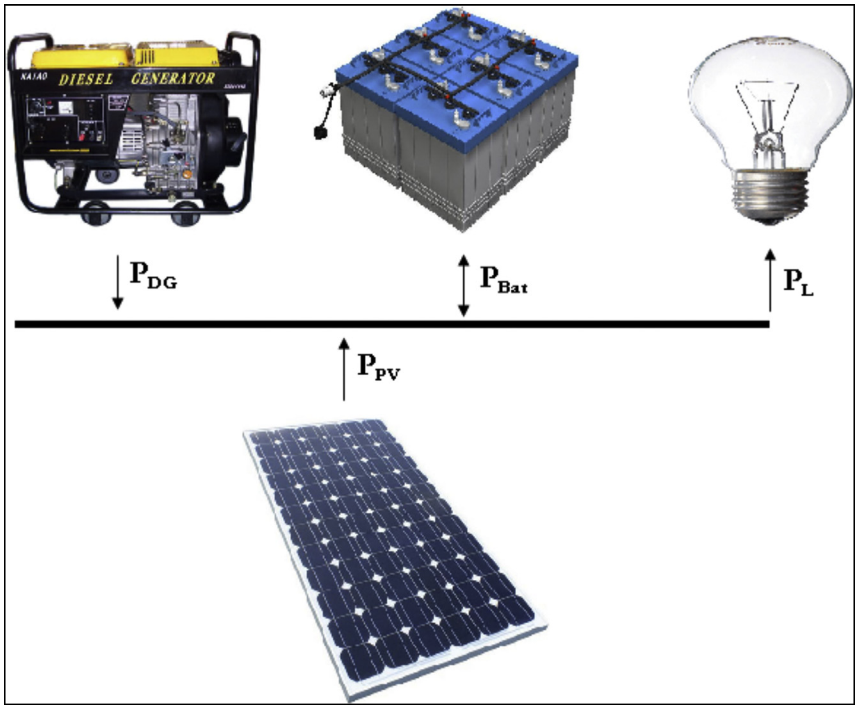

Fig. 1. Proposed hybrid system layout and power flow.

a,b, c = the fuel cost coefficients;
j = the jth sampling interval;
$P_{DG(j)}$ = the output power from the DG at jth sampling interval;
C_f = the price of 1 L of fuel.

2.3. Battery storage system

The output power from the DG and the load demand at any given sampling interval j, determine whether the battery is charging or discharging. The dynamics of the battery SOC (state of charge) can be expressed in discrete-time domain by a first order difference equation as follows [18]:

$$SOC_{(j+1)} = SOC_{(j)} - t_s \frac{\eta_{Bat}}{E_{nom}} \times P_{Bat_{(j)}} \tag{3}$$

where: SOC is the state of charge of the battery; η_{Bat} is the battery charging or discharging efficiency; E_{nom} is the battery system nominal energy, P_{Bat} is the power flowing from the battery system.

By induction reasoning, the dynamics of the battery state of charge at jth sampling interval can be expressed in terms of its initial value $SOC_{(0)}$ as follows:

$$SOC_{(j)} = SOC_{(0)} - t_s \frac{\eta_{Bat}}{E_{nom}} \sum_{i=1}^{j} P_{Bat_{(j)}} \tag{4}$$

3. Optimization models and proposed algorithm

The optimization problem addressed in this work aims at finding the optimal scheduling of energy production at any given time that minimizes the DG fuel expenses while totally responding to the load energy requirements within the system's operating limits and constraints. As stated in the introduction, the control of the hybrid system can be implemented using two different strategies, namely "*continuous operation*" and "*ON/OFF*" control.

3.1. Continuous operation control modeling

In this case the DG is ON most of the time and its output power continuously controlled, depending on the demand, to minimize the fuel usage resulting in operation cost. The DG is used as back up to supply the deficit of power, from the other sources, needed by the load.

3.1.1. Objective function

The objective is to minimize the fuel consumption cost from the DG during the operation time. This can be expressed as:

$$\min C_f \times \sum_{j=1}^{N} \left(a P_{DG(j)}^2 + b P_{DG(j)} + c \right) \tag{5}$$

3.1.2. Constraints

The different constraints on the operation are as follows:

- Power balance:

At any sampling interval j, the sum of the supplied powers from the PV, DG and from the battery must be equal to the demand. This can be expressed as:

$$P_{DG(j)} + P_{Bat(j)} + P_{PV(j)} = P_{L(j)} \tag{6}$$

- Variable limits:

The DG and battery modules are modeled as variable power sources controllable in the range of zero to their rated power for the 24 h period. Therefore the variable limits are the output limits of these different power sources as well as of the battery storage system at any time t. These constraints depend on the characteristics of each power source and can be expressed as:

$$0 \le P_{DG(j)} \le P_{DG}^{\max} \quad (1 \le j \le N) \tag{7}$$

$$-P_{Bat}^{rated} \le P_{Bat(j)} \le P_{Bat}^{rated} \quad (1 \le j \le N) \tag{8}$$

$$0 \le P_{PV(j)} \le P_{PV(j)}^{\max} \quad (1 \le j \le N) \tag{9}$$

- Battery state of charge:

The available battery bank state of charge in any sampling internal must not be less than the minimum allowable and must not be higher than the maximum allowable state of charge. This can be expressed as:

$$SOC^{\min} \le SOC_{(j)} \le SOC^{\max} \tag{10}$$

Equation (4) can be replaced in Equation (10) to link the battery dynamics to its operation limits; this gives:

$$SOC^{\,\min} \le SOC_{\,(0)} - t_s \frac{\eta_{Bat}}{E_{nom}} \sum_{i=1}^{j} P_{Bat_{(j)}} \le SOC^{\max} \tag{11}$$

3.1.3. Proposed algorithm

The objective functions have been modeled as a non-linear function of the DG output power. The non-linear optimization problem can be solved using the “fmincon” function in MATLAB [12]. This function solves problems in the form:

$$\min_x f(x) \text{Subject to}: \begin{cases} c(x) \le 0 \\ c_{eq}(x) = 0 \\ A \cdot x \le b \\ A_{eq} \cdot x = b_{eq} \\ l_b \le x \le u_b \end{cases} \tag{12}$$

where:
x, b, b_{eq}, l_b, and u_b = vectors;
A and A_{eq} = matrices;
$c(x)$ and $c_{eq}(x)$ = functions that return vectors;
$f(x)$ = function that returns a scalar.
$f(x)$, $c(x)$, and $c_{eq}(x)$ can be non-linear functions.

3.2. DG ON/OFF operational model

In this case, the philosophy is to obtain an optimal ON/OFF schedule of the DG that minimizes its operation cost. The PV is acting as the main supply of energy with the battery bank considered as a back-up energy source. When there is a deficit of power from the PV and the battery system the DG is on, it is forced to run at its rated output power with a high load factor in its most efficient operating zone. Since the DG is switched ON/OFF and the PV and battery bank are smoothly controlled to meet the demand, the problem is therefore formulated as a mixed-integer programming one. The mathematical optimization model is given in the sections below:

3.2.1. Objective function

The binary switching variables may be introduced in the objective function as:

$$\min C_f \times \sum_{j=1}^{N} \left(aP_{DG-rated}^2 + bP_{DG-rated} + c \right) \times S_{(j)} \tag{13}$$

where: $S_{(j)}$ is a discrete-switching function that takes the value of either 0 or 1. $S_{(j)} = 0$ means that the DG is switched off during the jth sampling interval, while $S_{(j)} = 1$ means that the DG is switched on. The output power of the DG is therefore a constant.

3.2.2. Constraints

- Power balance:

In this case, the power balance can be expressed as:

$$P_{DG-rated} S_{(j)} + P_{Bat(j)} + P_{PV(j)} = P_{L(j)} \quad (1 \le j \le N) \tag{14}$$

- Control variable limits:

As explained above the switch can only take two values [0, 1] which are its lower and upper limits. The PV and battery modules are modeled as variable power sources; the Equations (8)–(11) linked to their operations limits as well as to the battery dynamic developed in section 3.1.2 are also used in the present case.

3.2.3. Proposed algorithm

The objective function has been modeled as a function of the switch controlling the DG and the variable battery output power. This mixed-integer optimization problem can be solved using “*Intlinprog*” function from MATLAB Optimization toolbox [8]. This function solves problems in the form:

$$\min_x f^T x \quad \text{Subject to}: \begin{cases} x(\text{intcon}) \\ A \cdot x \le b \\ A_{eq} \cdot x = b_{eq} \\ l_b \le x \le u_b \end{cases} \tag{15}$$

where: f, x, intcon, b, b_{eq}, l_b, and u_b are vectors;
A and A_{eq} are matrices.

4. Application example

4.1. Daily load demand

Two typical daily load profiles (summer and winter) of a South African rural household are used to analyze the benefit of the hybrid system operating under the two control strategies compared to the DG alone. These data are used as input to the energy optimization models developed in section 3 above. The hourly renewable resources as well as load demands for a 24 h period are shown in Table 1. It has to be noted that these data have been collected for a summer day as well as for a winter day; this is to show how the daily and seasonal variation of the load and solar resources also affect the operation cost of the system.

4.2. Component size and model parameters

The sizes of the components as well as the different parameters used in the simulations are given on Table 2.

5. Simulation results and discussion

In this section, the simulations of the two control strategies, namely continuous operation and on/off control are presented and compared to the case where the DG is used alone to supply the load.

Table 1
Resources and load data.

Time (h)	Summer		Winter	
	Global solar (kW/m^2)	Load (kW)	Global solar (kW/m^2)	Load (kW)
00:00	0.000	0.3	0.000	0.3
01:00	0.000	0.2	0.000	0.2
02:00	0.000	0.1	0.000	0.1
03:00	0.000	0.0	0.000	0.0
04:00	0.000	0.3	0.000	0.3
05:00	0.000	0.0	0.000	0.0
06:00	0.000	2.4	0.000	3.0
07:00	0.002	0.6	0.000	0.7
08:00	0.141	4.3	0.145	8.0
09:00	0.417	5.6	0.244	5.6
10:00	0.687	3.2	0.306	2.6
11:00	0.940	1.6	0.512	3.0
12:00	1.062	0.3	0.611	0.5
13:00	1.061	2.0	0.614	3.4
14:00	0.978	0.4	0.568	0.7
15:00	0.846	0.8	0.428	1.3
16:00	0.679	3.9	0.460	1.4
17:00	0.464	1.8	0.266	1.5
18:00	0.208	1.7	0.000	3.8
19:00	0.043	1.9	0.000	4.6
20:00	0.000	2.2	0.000	5.9
21:00	0.000	0.9	0.000	2.1
22:00	0.000	0.7	0.000	0.8
23:00	0.000	0.3	0.000	0.3

5.1. Continuous operation

The load profile for the selected summer is presented in Fig. 2. Fig. 3 shows the optimal power flow from the PV, DG, battery as well as the battery SOC during the selected 24 h period the hybrid system is supplying the load in summer.

It can be noticed that from midnight and early morning the load demand is low, therefore it is successfully met mainly by the battery storage system; the PV system is not able to generate during this period because in solar resource.

The first morning peak load demand occurs between 7h00 and 8h00; therefore the PV is used at its maximum output to supply the load in conjunction with the battery while the DG is kept off. The load demand decreases between 8h00 and 9h00; because of the availability of the solar resources, the PV is used by itself to supply the load and to recharge the battery at the same time.

After the morning peak, the SOC of the battery is at its minimum operation limit (40%); therefore, between 11h00 and 17h00, the PV produces more power than the load requirement. This surplus is used to charge the battery bank to a SOC of 95% which is reached at the end of the afternoon as shown in Fig. 3, where the negative part of the battery power flow (P_B) represents the charging process.

Table 2
Simulation parameters.

Item	Figure
Sampling time	30 min
Battery nominal capacity	5.6 kWh
Battery maximum SOC	95%
Battery minimum SOC	40%
Battery charging efficiency	85%
Battery discharging efficiency	100%
Diesel fuel price	1.4$/l
a	0.246
b	0.0815
c	0.4333

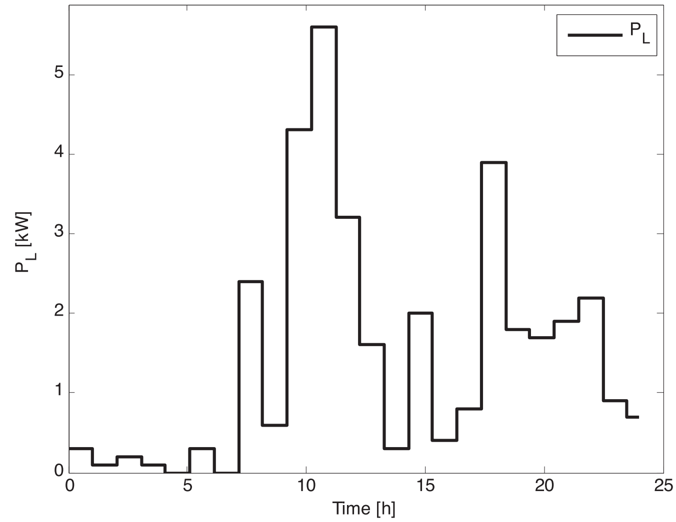

Fig. 2. Daily load profile for the selected summer day.

In the evening the demand gradually increases from 17h00 and reaches the peak between 19h00 and 20h00 then finally decreases at 21h00. Therefore from 17h00–18h00, the PV is used at its maximum output in conjunction with a contribution of the battery. After 18h00 the PV system can no more provide energy and the load demand is increasing; therefore the contribution of the battery is increased and the DG is switched to balance the energy needed by the load. The DG operating time and output power depends on the load demand, battery SOC and the amount of power from the PV. It can be seen that the DG is not used to charge the battery but only to supply the load. For this specific case, the total operating time of the DG running under this condition is 6.5 h.

In winter, the solar resource is lower and the load demand is higher compared to a summer day as shown in Fig. 4. From Fig. 5, it can be seen that the contribution of the PV system is very low; therefore the hybrid system relies also on the use of the battery and on the DG which is running nonstop all through the day to supply the deficit of energy needed from the battery and PV system needed by the load. This increases the fuel consumption as well as the DG operating time compared to the summer case.

5.2. ON/OFF operation

Fig. 6 shows the state of the switch controlling the DG (on or off), the PV power, the battery power flow as well as the battery SOC during a 24 h period in the selected summer day (Fig. 2).

As for the continuous case, the load is met by the PV, when available, and the battery bank. When the load demand increases during the day, and if the PV operating in conjunction with the battery power cannot meet the demand, the DG is switched on, giving its rated power of 5.6 kW. The load demand is therefore satisfied primarily by the DG and the surplus, which is not used by the load, is used to recharge the battery, allowing high load factor and high efficiency operation for the DG. Depending on the variation of the demand when the DG is ON, the battery can be recharged up to its maximum SOC.

While analyzing Fig. 6, it can be noticed that for the DG operating time is sensibly reduced; giving a total of 1.5 h in the selected summer day; and is OFF for the rest of the day. This can help the DG to have a long calendar life; however the impact of excessive ON and OFF cycles on the DG lifespan should be studied.

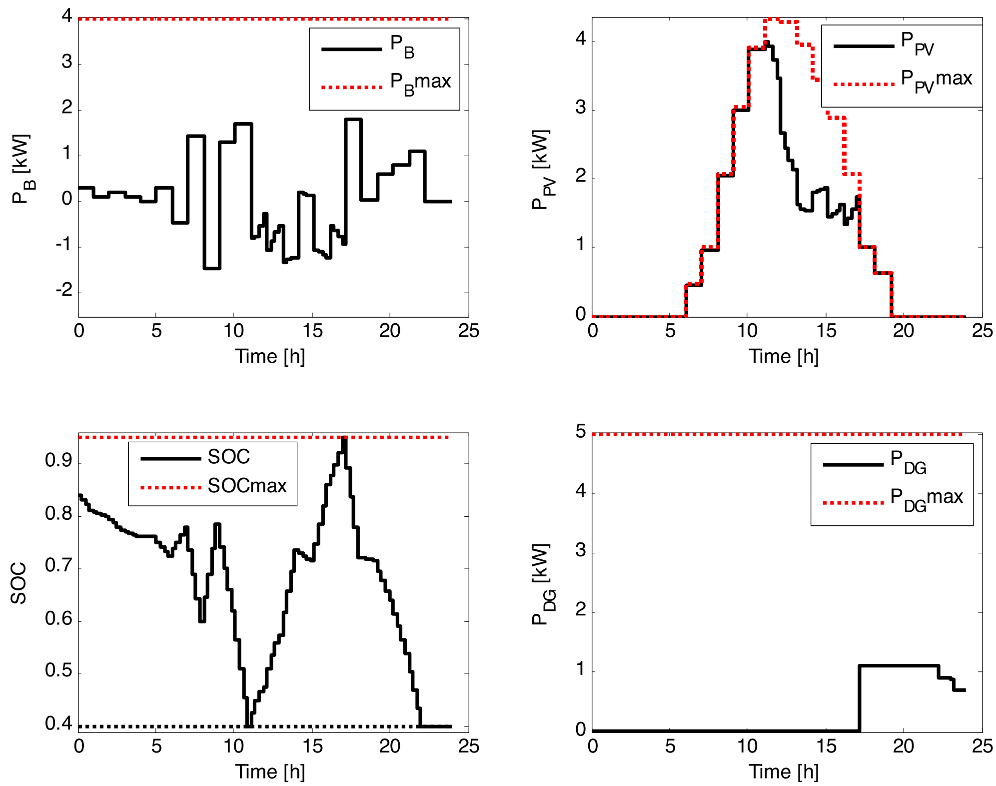

Fig. 3. Continuous control: components output powers and battery SOC (summer case).

The contribution of the DG is important during the selected winter day as shown in Fig. 7; this is due to the high load demand and to the low solar resource. This increase the amount of fuel consumed as well as the DG operating time compare to the summer case.

5.3. Comparison of the two control strategies

The actual operation cost for the continuous or ON/OFF operation control strategy can be found by multiplying the diesel price

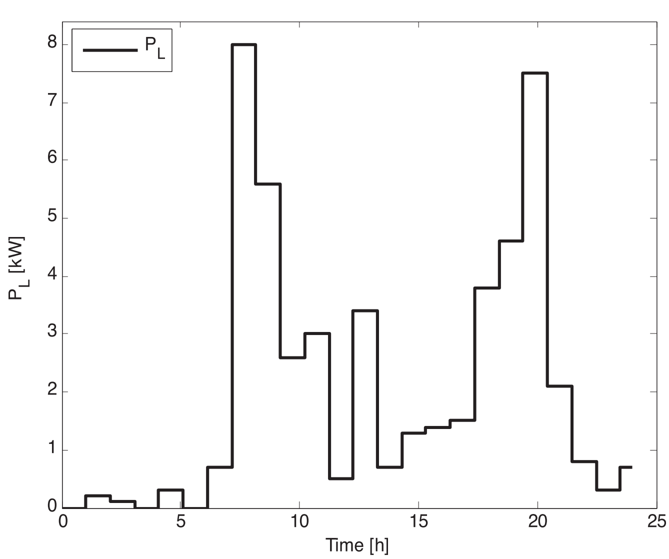

Fig. 4. Daily load profile for the selected winter day.

($/L) by the amount of fuel used in selected summer or winter day (L/day). It has to be highlighted that this daily fuel expense is highly dependent on the size, type and control settings of the battery storage system as well as the DG (fuel cost curve and fitting parameters from the manufacturer) used in the simulation.

Tables 3 and 4 show how much operation fuel can be saved and DG operating time can be reduced by using the hybrid system instead of the selected DG in a summer and a winter day respectively using the different control strategies.

From Table 3 it can be seen that the photovoltaic–diesel–battery model achieves 81% and 74% fuel savings for the selected summer day using the continuous and the ON/OFF operation strategy respectively. It can also be seen that the DG operating time is significantly reduced; it runs for 6.5 h when continuously control, and for only 1.5 h when the ON/OFF control is used.

From Table 4 it can be seen that the photovoltaic–diesel–battery model achieves 20% and 12% fuel savings for the selected winter day using the continuous and the ON/OFF operation strategy respectively. However when the DG is continuously control, it runs for 24 h while it runs for 7.5 h when the ON/OFF control is implemented.

These results also demonstrate that it is very important to take into account the variations of the load and solar energy resources with seasons when calculating the system's daily operation cost.

6. Conclusion

Two control strategies to minimize the daily operation cost of photovoltaic–diesel–battery hybrid systems have been modeled and simulated. As already mentioned, this work considered the fluctuation of the load demand, the intermittent solar resource as

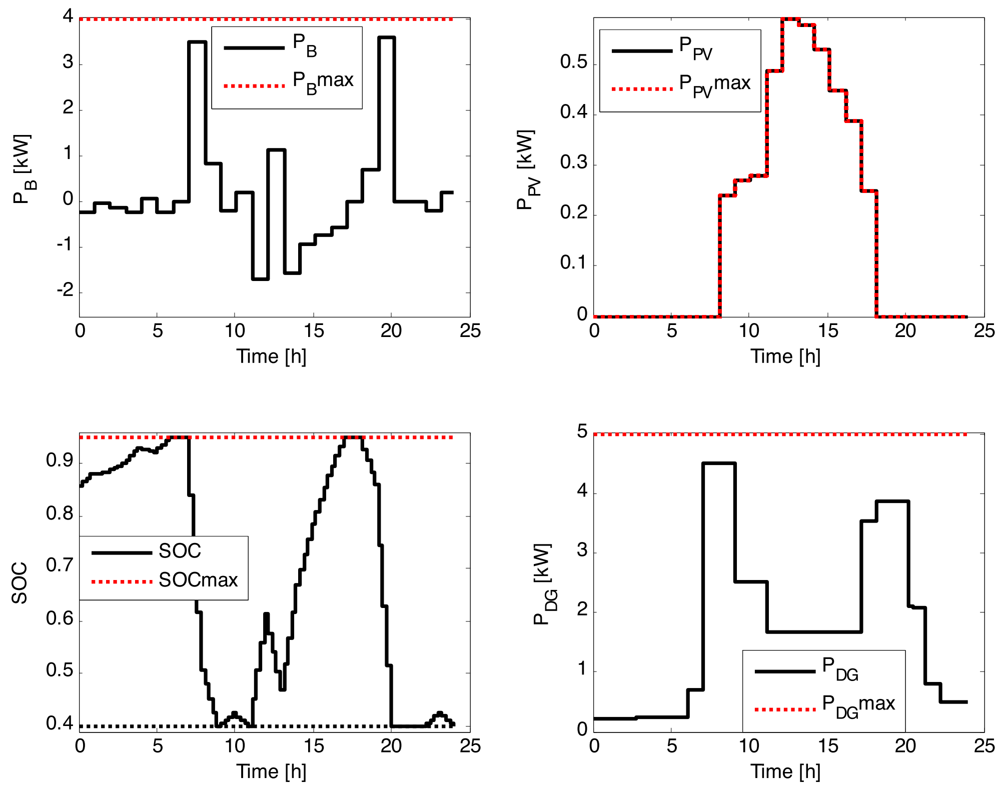

Fig. 5. Continuous control: components output powers and battery SOC (winter case).

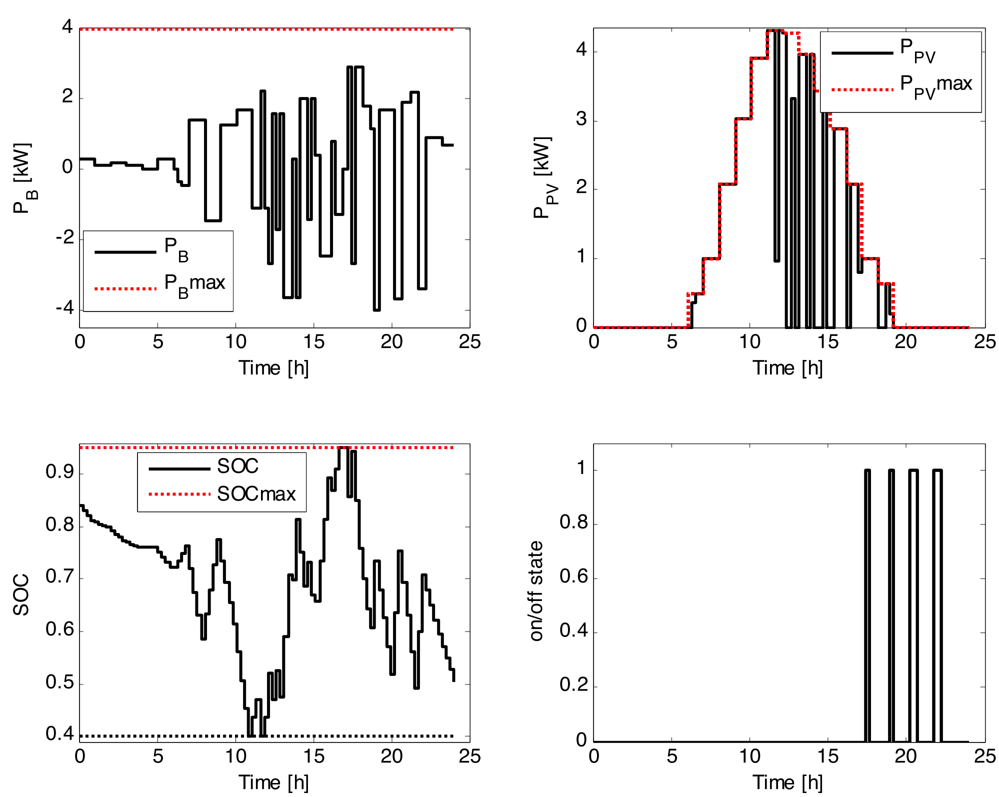

Fig. 6. ON/OFF control: components output powers and battery SOC (summer case).

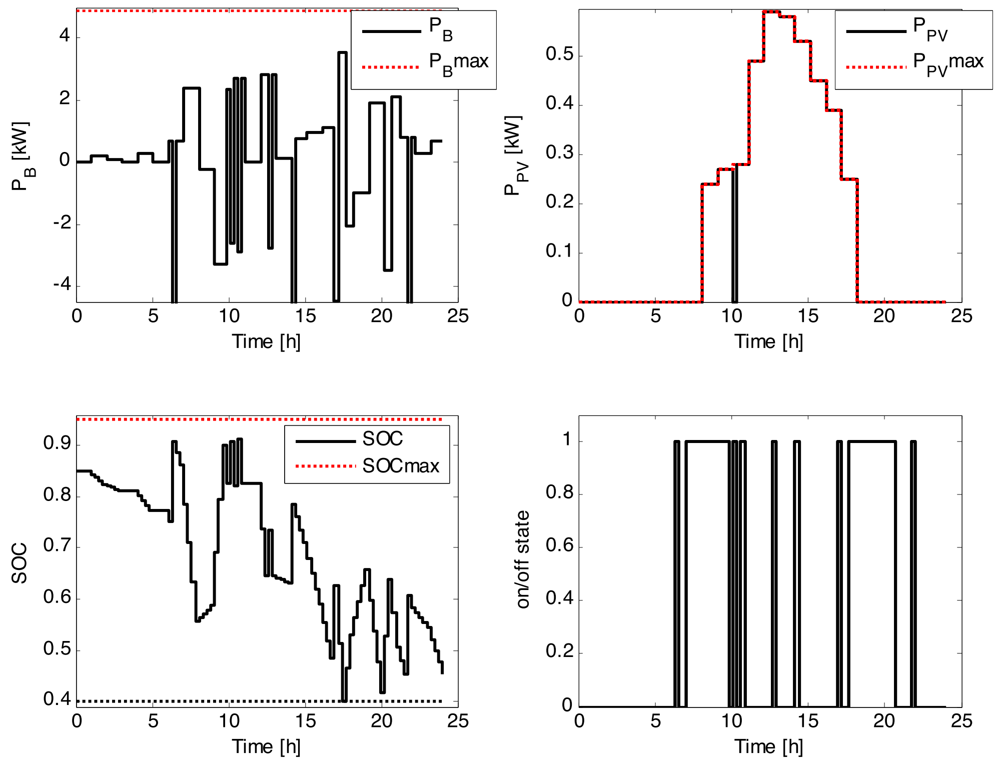

Fig. 7. ON/OFF control: components output powers and battery SOC (winter case).

Table 3
Daily savings (summer).

	Continuous			ON/OFF		
	Consumption (L)	Cost ($)	Operation time (h)	Consumption (L)	Cost ($)	Operation time (h)
DG only	38.26 L	53.56$	24 h	38.26 L	53.56$	24 h
Hybrid system	7.28 L	10.2$	6.5 h	9.84 L	25.77$	1.5 h
Savings	30.98 L	43.36$	17.5 h	28.42 L	27.79$	22.5 h

Table 4
Daily fuel cost savings (winter).

	Continuous			ON/OFF		
	Consumption (L)	Cost ($)	Operation time (h)	Consumption (L)	Cost ($)	Operation time (h)
DG only	55.96 L	73.34$	24 h	55.96 L	73.34$	24 h
Hybrid system	44.87 L	62.8$	24 h	49.24 L	68.94$	7.5 h
Savings	11.09 L	15.52$	24 h	6.72 L	9.4$	16.5 h

well as the non-linear diesel fuel consumption curve. The simulation results show that by using the photovoltaic–diesel–battery hybrid system under the continuous or the ON/OFF operation control strategy, significant operation cost can be saved compared to the case where the DG is used alone.

When comparing the two control strategies, it has been demonstrated that more fuel saving is achieved using the continuous control than using the ON/OFF control strategy. However the ON/OFF control achieves more DG daily operating time reduction compared to the case where the continuous control is implemented.

For further research, the impacts of long running time as well as the impact of several starts and stops of the DG should be investigated to find out which of the two control strategies will achieve the lower hybrid system's lifecycle cost.

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