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Article *in* IET Renewable Power Generation · June 2015

DOI: 10.1049/iet-rpg.2015.0027

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IET Renewable Power Generation

Research Article

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ISSN 1752-1416
Received on 21st January 2015
Revised on 4th April 2015
Accepted on 28th April 2015
doi: 10.1049/iet-rpg.2015.0027
www.ietdl.org

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Abstract: In this study, two control strategies involving 'continuous' and 'ON/OFF' operation of the diesel generator in the solar photovoltaic (PV)-wind-diesel-battery hybrid systems are modelled. The main purpose of these developed models is to minimise the hybrid system's operation cost while finding the optimal power flow considering the intermittent solar and wind resources, 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 analysed and compared with the case where the diesel generator is used alone to supply the given load demand. The results show that using the developed PV-diesel-battery optimal operation control models, significant fuel saving can be achieved compared with 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 diesel generators (DGs) running continuously [1]. Compared with other supply option such as renewable energy (RE) 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, because of 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 sources [2].

RE generation is gaining consideration, because of advantages such as low operation and maintenance, and easy deployment to meet growing energy needs [1, 3, 4]. Solar photovoltaic (PV) and wind turbines (WT) are an established clean ways of generating energy and are currently extensively to supply power in several standalone applications [5–7].

However, except for its high capital cost, the other main disadvantage of PV and WT generation is the fact that their produced powers depend on the solar and wind resources which are highly non-linear and varies with the hours of the day and the seasons of the years. Therefore they cannot always match the load power demand.

Hybrid solar PV-WT-diesel-battery hybrid systems present a resolution to the time correlation of intermittent solar source as well as load demand fluctuations [8, 9]. In this configuration, the DG is used to balance the deficit of the power supply from the renewable sources and the battery system 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 RE-diesel-battery systems for standalone power generation. Dufo-lopez and Bernal-agustin [10] have developed the HOGA program (hybrid optimisation 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, minimising its total net present cost. For each vector of the main algorithm, the optimal strategy is obtained (minimising the non-initial costs, including operation and maintenance costs) by means of the secondary algorithm. In the paper, a PV-diesel system optimised 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 optimisation of hybrid systems such as the hybrid optimisation model for energy renewable and HYBRID2. In [11], 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 with 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 [12] developed and applied an operational control technique, based on using the fuzzy logic controller and the commonly used ON-OFF controller for a PV-diesel-battery hybrid energy system. This control technique aims to reliably satisfy the system's load, and at the same time to optimise the battery and diesel operation under all working atmospheric conditions. The proposed hybrid energy system is modelled 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.*, [13] reviewed an optimal control approach used in [14] to evaluate the differences in operating strategies and configurations during the design of a PV-diesel-battery model. However, Tiryono *et al.*, [14] 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 optimisation programs. The authors proposed several improvements to the current model to make it more representative to real systems.

Dispatch strategies for the operation of a PV-diesel–battery hybrid power system using ‘set points’ are presented in [15]. This includes the determination of the optimum set points values for the starting and stopping of the diesel generator to minimise 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.

Currently, the development of models for optimal scheduling and energy management of standalone or grid connected renewable systems is gaining attention. In [16], the authors developed a hybrid system model incorporating PV cells and diesel generator in which the daily energy demand fluctuations for different seasonal periods of the year to evaluate the equivalent fuel costs (FCs) 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 FCs reflecting fluctuations of power consumption behaviour patterns for any given hybrid system.

In [17], an energy dispatch model that satisfies the load demand, taking into account the intermittent nature of the solar and wind energy sources and variations in load demand, is presented for a solar PV-wind-diesel-battery hybrid power supply system. The emphasis in this work is on the co-ordinated management of energy flow from the battery, wind, PV and DGs when the system is subject to disturbances. The results show that the advantages of the approach become apparent in its capability to attenuate and its robustness against uncertainties and external disturbances.

In [18], a switching grid connected PV system is studied for simplifying system installation. Optimal switching control model is proposed to sufficiently utilise the solar energy and to minimise electricity cost under the time-of-use (TOU) program. The results showed that optimal scheduling of the PV system can achieve promising cost savings.

Sichilalu and Xia [19] developed an optimal control strategy for power dispatch of the grid-tied PV-battery-diesel system to power heat pump water heaters (HPWH). The objective function of the model is to minimise energy and FC while maximising PV energy trade-off for incentives. The optimal control shows a great potential to realise a practical net zero-energy building and demand side management. The optimal control problem is solved using a mixed integer non-linear program and the results show how TOU affects the power dispatch to the HPWH. The energy and cost savings are presented in this paper.

Unlike the above-mentioned papers, the present work looks at the optimisation 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 characterised by the performance efficiency, the operation efficiency, the equipment efficiency and the technology efficiency as main components [20]. 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. Operation efficiency can be enhanced using mathematical optimisation and optimal control techniques [21]. Therefore the present paper focuses on the development of two models namely the ‘continuous’ and ‘ON/OFF’ control strategies to minimise 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 FC 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-WT-diesel-battery hybrid system is shown in Fig. 1. The load demand is primarily met by the sum of the PV, WT and the battery starts discharging within its operating limits as soon as the PV and WT do not meet the demand. If the sum of the PV and WT output power is above the load demand, the excess of power is used to recharge the battery (a dump load can be used to dissipate this power in the case where the RE generation is more than the load and the required power to recharge the battery). The DG is used when the power from PV, WT and the battery cannot respond to the load 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 (power sources) are presented in the section below

2.1 PV system

When light strikes a silicon, gallium arsenide or cadmium sulphide cell an electric current is generated through the PV effect [22]. The power rating of a PV panel is expressed in peak watts (W_p) indicated at ‘standard test conditions’ conducted at a cell temperature of 25°C and irradiance of 1000 W/m^2. The output power of the solar PV system can be expressed as follows [23]

$$P_{\rm PV} = A_{\rm PV} \times \eta_{\rm PV} \times \int_{t_0}^{t} I(t) \times f(t) \times \mathrm{d}t \qquad (1)$$

where: $A_{\rm PV}$ is the total area of the PV generator (m^2); $\eta_{\rm PV}$ is the system’s efficiency; I is the hourly irradiation (kWh/m^2) and $f(t)$ is the radiance density.

2.2 Wind energy system

Wind energy systems convert the kinetic energy of moving air into mechanical then electrical energy [24]. The power output ($P_{\rm WT}$) of

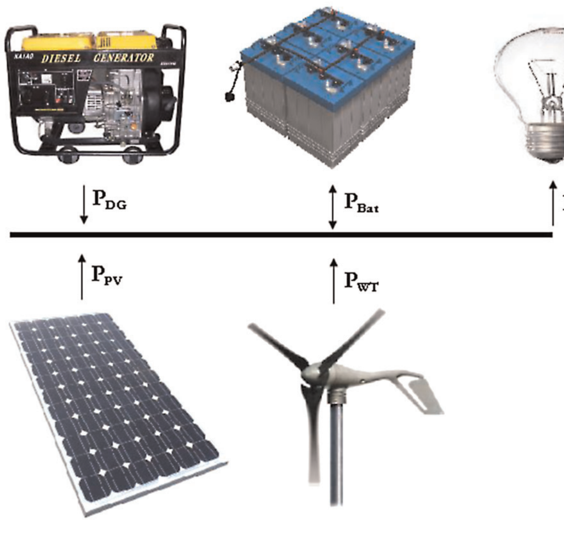

Fig. 1 *Proposed hybrid system layout and power flow*

the wind system within a sampling time interval can be expressed as is expressed as

$$P_{\mathrm{WT}} = \frac{1}{2} \times \rho_{\mathrm{a}} \times A_{\mathrm{WT}} \times C_{p,\mathrm{WT}} \times \eta_{\mathrm{WT}} \times \int_{t_0}^{t} v_{\mathrm{a}}^{3}(t) \times f(t) \times \mathrm{d}t \quad (2)$$

where ρ_{a} is the air of water (1 225 kg/m^3); $C_{p,\mathrm{W}}$ is the coefficient of the wind turbine performance; η_{WT} is the combined efficiency of the wind turbine and the generator; A_{WT} is the wind turbine swept area (m^2); v_{a} is the wind velocity (m/s); and $f(t)$ is the wind probability density function.

2.3 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 [25].

The FC is calculated for a day is given by the quadratic non-linear function below

$$C_{\mathrm{f}} \sum_{j=1}^{N} (aP_{\mathrm{DG}(j)}^{2} + bP_{\mathrm{DG}(j)} + c) \quad (3)$$

where: a, b, c are the parameters related to any DG's fuel consumption curve (available from the manufacturer); C_{f} is the price of one litre of diesel fuel; $P_{\mathrm{DG}(j)}$ is the output power or control variable from the DG in any sampling interval. It has to be highlighted that different DGs of different sizes as well as from different manufacturers present different fuel consumption curves and parameters.

2.4 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 state of charge (SOC) can be expressed in discrete-time domain by a first order difference equation as follows [26]

$$\mathrm{SOC}_{(j+1)} = (1 - d_{\mathrm{b}}) \times \mathrm{SOC}_{(j)} - t_{\mathrm{s}} \times \frac{\eta_{\mathrm{Bat}}}{E_{\mathrm{nom}}} \times P_{\mathrm{Bat}(j)} \quad (4)$$

where SOC is the SOC of the battery; d_{b} is the self-discharging rate of the battery storage system; η_{Bat} is the battery charging or discharging efficiency; E_{nom} is the battery system nominal energy, $P_{\mathrm{Bat}(j)}$ is the power flowing from the battery system.

By induction reasoning, the dynamics of the battery SOC at jth sampling interval can be expressed in terms of its initial value $\mathrm{SOC}_{(0)}$ as follows

$$\mathrm{SOC}_{(j)} = (1 - d_{\mathrm{b}}) \times \mathrm{SOC}_{(0)} - t_{\mathrm{s}} \times \frac{\eta_{\mathrm{Bat}}}{E_{\mathrm{nom}}} \times \sum_{i=1}^{j} P_{\mathrm{Bat}(j)} \quad (5)$$

3 Optimisation models and proposed algorithm

The optimisation problem addressed in this work aims at finding the optimal scheduling of energy production at any given time that minimises 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 modelling

In this case the DG is ON most of the time and its output power continuously controlled, depending on the demand, to minimise 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 minimise the fuel consumption cost from the DG during the operation time. This can be expressed as

$$\min C_{\mathrm{f}} \times \sum_{j=1}^{N} (aP_{\mathrm{DG}(j)}^{2} + bP_{\mathrm{DG}(j)} + c) \quad (6)$$

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 (control variables) from the PV, WT, DG and from the battery must be equal to the demand. This can be expressed as

$$P_{\mathrm{DG}(j)} + P_{\mathrm{Bat}(j)} + P_{\mathrm{PV}(j)} + P_{\mathrm{WT}(j)} = P_{L(j)} \quad (7)$$

- *Variable limits:* The DG and battery modules are modelled 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

$$0 \le P_{\mathrm{DG}(j)} \le P_{\mathrm{DG}}^{\max} \quad (1 \le j \le N) \quad (8)$$

$$-P_{\mathrm{Bat}}^{\mathrm{rated}} \le P_{\mathrm{Bat}(j)} \le P_{\mathrm{Bat}}^{\mathrm{rated}} \quad (1 \le j \le N) \quad (9)$$

$$0 \le P_{\mathrm{PV}(j)} \le P_{\mathrm{PV}(j)}^{\max} \quad (1 \le j \le N) \quad (10)$$

$$0 \le P_{\mathrm{WT}(j)} \le P_{\mathrm{WT}(j)}^{\max} \quad (1 \le j \le N) \quad (11)$$

- *Battery SOC:* The available battery bank SOC in any sampling internal must not be less than the minimum allowable and must not be higher than the maximum allowable SOC. This can be expressed as

$$\mathrm{SOC}^{\min} \le \mathrm{SOC}_{(j)} \le \mathrm{SOC}^{\max} \quad (12)$$

Equation (5) can be replaced in (12) to link the battery dynamics to its operation limits; this gives

$$\mathrm{SOC}^{\min} \le (1 - d_{\mathrm{b}}) \times \mathrm{SOC}_{(0)} - t_{s} \times \frac{\eta_{\mathrm{Bat}}}{E_{\mathrm{nom}}} \times \sum_{i=1}^{j} P_{\mathrm{Bat}(j)} \le \mathrm{SOC}^{\max} \quad (13)$$

3.1.3 Proposed algorithm: The objective functions have been modelled as a non-linear function of the DG output power. The non-linear optimisation problem can be solved using the 'fmincon' function in MATLAB [27]. This function solves problems in the form

$$\min_{x} f(x) \text{ Subject to: } \begin{cases} \boldsymbol{c}(\boldsymbol{x}) \le 0 \\ \boldsymbol{c}_{\mathrm{eq}}(\boldsymbol{x}) = 0 \\ \boldsymbol{A} \cdot \boldsymbol{x} \le \boldsymbol{b} \\ \boldsymbol{A}_{\mathrm{eq}} \cdot \boldsymbol{x} = \boldsymbol{b}_{\mathrm{eq}} \\ \boldsymbol{l}_{\mathrm{b}} \le \boldsymbol{x} \le \boldsymbol{u}_{\mathrm{b}} \end{cases} \quad (14)$$

where $\boldsymbol{x}$, $\boldsymbol{b}$, $\boldsymbol{b}_{\mathrm{eq}}$, $\boldsymbol{l}_{\mathrm{b}}$ and $\boldsymbol{u}_{\mathrm{b}}$ are vectors; $\boldsymbol{A}$ and $\boldsymbol{A}_{\mathrm{eq}}$ are matrices; $\boldsymbol{c}(\boldsymbol{x})$ and

Table 1 Resources and load data

Time, h	Summer			Winter		
	Global solar, kW/m^2	Load, kW	Wind speed, m/s	Global solar, kW/m2	Load, kW	Wind speed, m/s
00:00	0.000	0.3	0.821	0.000	0.3	0.871
01:00	0.000	0.2	1.665	0.000	0.2	0.381
02:00	0.000	0.1	0.998	0.000	0.1	0.947
03:00	0.000	0.0	0.956	0.000	0.0	1.425
04:00	0.000	0.3	2.549	0.000	0.3	1.575
05:00	0.000	0.0	2.558	0.000	0.0	1.463
06:00	0.000	2.4	2.775	0.000	3.0	0.932
07:00	0.002	0.6	3.754	0.000	0.7	1.560
08:00	0.141	4.3	2.948	0.145	8.0	1.337
09:00	0.417	5.6	2.828	0.244	5.6	1.761
10:00	0.687	3.2	2.870	0.306	2.6	2.611
11:00	0.940	1.6	2.522	0.512	3.0	3.542
12:00	1.062	0.3	1.766	0.611	0.5	3.956
13:00	1.061	2.0	2.576	0.614	3.4	4.698
14:00	0.978	0.4	2.017	0.568	0.7	4.898
15:00	0.846	0.8	2.282	0.428	1.3	4.089
16:00	0.679	3.9	3.116	0.460	1.4	5.544
17:00	0.464	1.8	2.626	0.266	1.5	4.404
18:00	0.208	1.7	3.427	0.000	3.8	4.547
19:00	0.043	1.9	2.972	0.000	4.6	4.711
20:00	0.000	2.2	2.543	0.000	5.9	3.881
21:00	0.000	0.9	2.336	0.000	2.1	4.610
22:00	0.000	0.7	1.863	0.000	0.8	2.537
23:00	0.000	0.3	1.231	0.000	0.3	2.370

$\boldsymbol{c}_{\text{eq}}(\boldsymbol{x})$ are functions that return vectors and $f(x)$ are function that returns a scalar. $f(x)$, $\boldsymbol{c}(\boldsymbol{x})$ and $\boldsymbol{c}_{\text{eq}}(\boldsymbol{x})$ 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 minimises its operation cost. The PV and WT are 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 RE sources and the battery system; the DG is turned 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, WT and battery bank are smoothly controlled to meet the demand, the problem is therefore formulated as a mixed-integer programming one. The mathematical optimisation model is given in the sections below.

3.2.1 Objective function:

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

$$\min C_{\text{f}} \times \sum_{j=1}^{N} (aP_{\text{DG-rated}}^2 + bP_{\text{DG-rated}} + c) \times S_{(j)} \tag{15}$$

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.

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

3.2.2 Constraints:

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

$$P_{\text{DG-rated}} S_{(j)} + P_{\text{Bat}(j)} + P_{\text{PV}(j)} + P_{\text{WT}(j)} = P_{L(j)} \quad (1 \leq j \leq N) \tag{16}$$

- *Control variable limits:* As explained above, '$S_{(j)}$' can only take two values [0, 1] which are its lower and upper limits. The PV, WT and battery modules are modelled as variable power sources; the (8) to (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 modelled as a function of the switch controlling the DG and the variable battery output power. This mixed-integer optimisation problem can be solved using '*Intlinprog*' function from MATLAB Optimisation toolbox [28]. This function solves problems in the form

$$\min_{x} f^{\text{T}} x \text{ Subject to: } \begin{cases} x(intcon) \\ \boldsymbol{A} \cdot \boldsymbol{x} \leq \boldsymbol{b} \\ \boldsymbol{A}_{\text{eq}} \cdot \boldsymbol{x} = \boldsymbol{b}_{\text{eq}} \\ \boldsymbol{l}_{\text{b}} \leq \boldsymbol{x} \leq \boldsymbol{u}_{\text{b}} \end{cases} \tag{14}$$

where $\boldsymbol{f}$, $\boldsymbol{x}$, $\boldsymbol{intcon}$, $\boldsymbol{b}$, $\boldsymbol{b}_{\text{eq}}$, $\boldsymbol{l}_{\text{b}}$ and $\boldsymbol{u}_{\text{b}}$ are vectors; $\boldsymbol{A}$ and $\boldsymbol{A}_{\text{eq}}$ are matrices.

4 Application example

4.1 Daily load demand

The solar radiation data used in this study are calculated from stochastically generated values of hourly global and diffuse irradiation using the simplified tilted-plane model of [29]. This is calculated for a South African rural area close to Bloemfontein. Wind speed data measured at 10 m height at the site over a period of two years is used in this work. Two typical summer and winter load demand profiles for institutional applications based on an energy demand survey carried out in rural communities in South Africa are used and the methodology for calculating the load demand profile is as described in [30]. The load and RE data for the selected summer and winter days are as shown in Table 1.

The two daily load profiles are used to analyse the benefit of the hybrid system operating under the two control strategies compared with the DG alone. These renewable resources and data are used as input to the optimisation models developed in Section 3 above. It has to be noted that these data have been collected for a summer

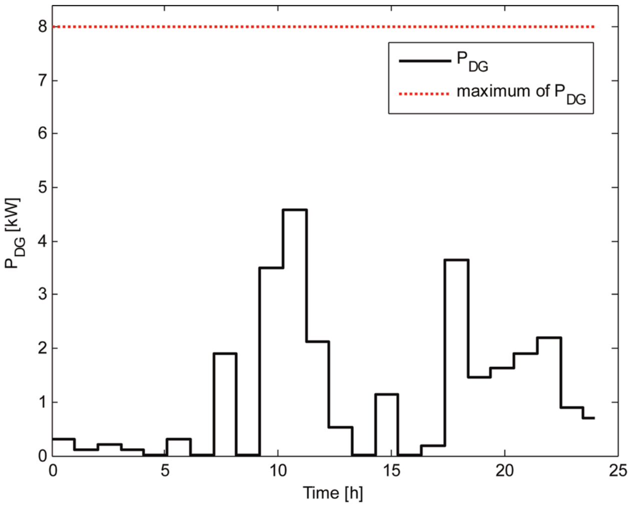

Fig. 2 *DG 'alone' optimal scheduling and output power in summer*

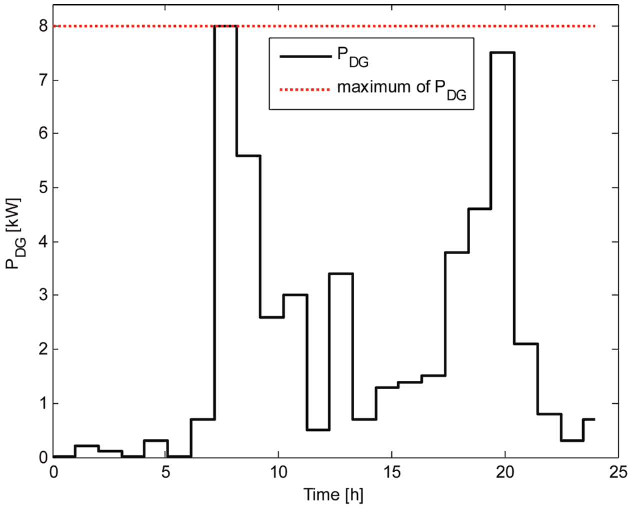

Fig. 3 *DG 'alone' optimal scheduling and output power in winter*

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 hybrid system is designed such that the load power demand is met at any given time. This study emphasises mainly on the optimal energy management of the given hybrid system. The different parameters used in the simulations are given on the Table 2 [30].

Using the sampling time in minutes, the daily number of sampling intervals used in the simulation can be calculated as

$$N = \frac{24 \times 60}{\Delta t} \tag{15}$$

5 Simulation results and discussion

In this section, simulation results of the PV-wind-diesel-battery hybrid systems operation under the continuous operation and ON/OFF strategy in different climatic situations are presented. The results are also compared with the case where the DG is used alone to supply the load.

5.1 Diesel generator alone

In this scenario, the DG is used alone to supply the load demand. Figs. 2 and 3 illustrate the DG's power curve for the 24 h period where it is used as the only option to supply the fluctuating load demand (summer and winter cases). It can be seen that the DG continuously adjusts its power output, using the load following principle, to respond to the demand.

5.2 Hybrid system: continuous operation

Fig. 4 shows how the load demand as well as the maximum and optimum output power flows from the PV, WT, DG and battery during the selected day in summer. It can be seen that the PV system constitute the major contribution of the power supplied by the renewable systems, therefore has a primary role in the DG daily operation cost minimisation and the battery charging/

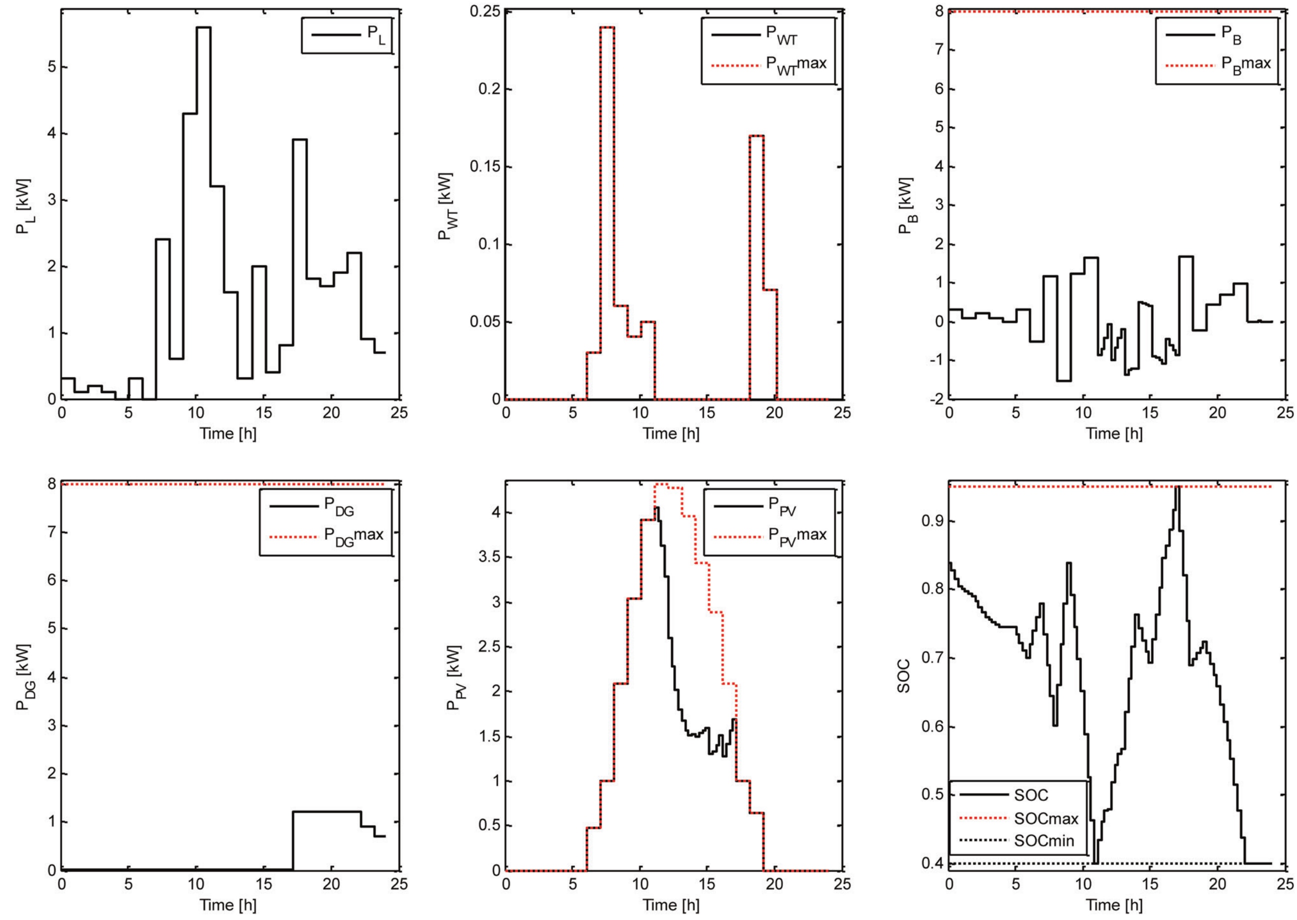

Fig. 4 *Continuous control: load profile, components output power and battery SOC (summer case)*

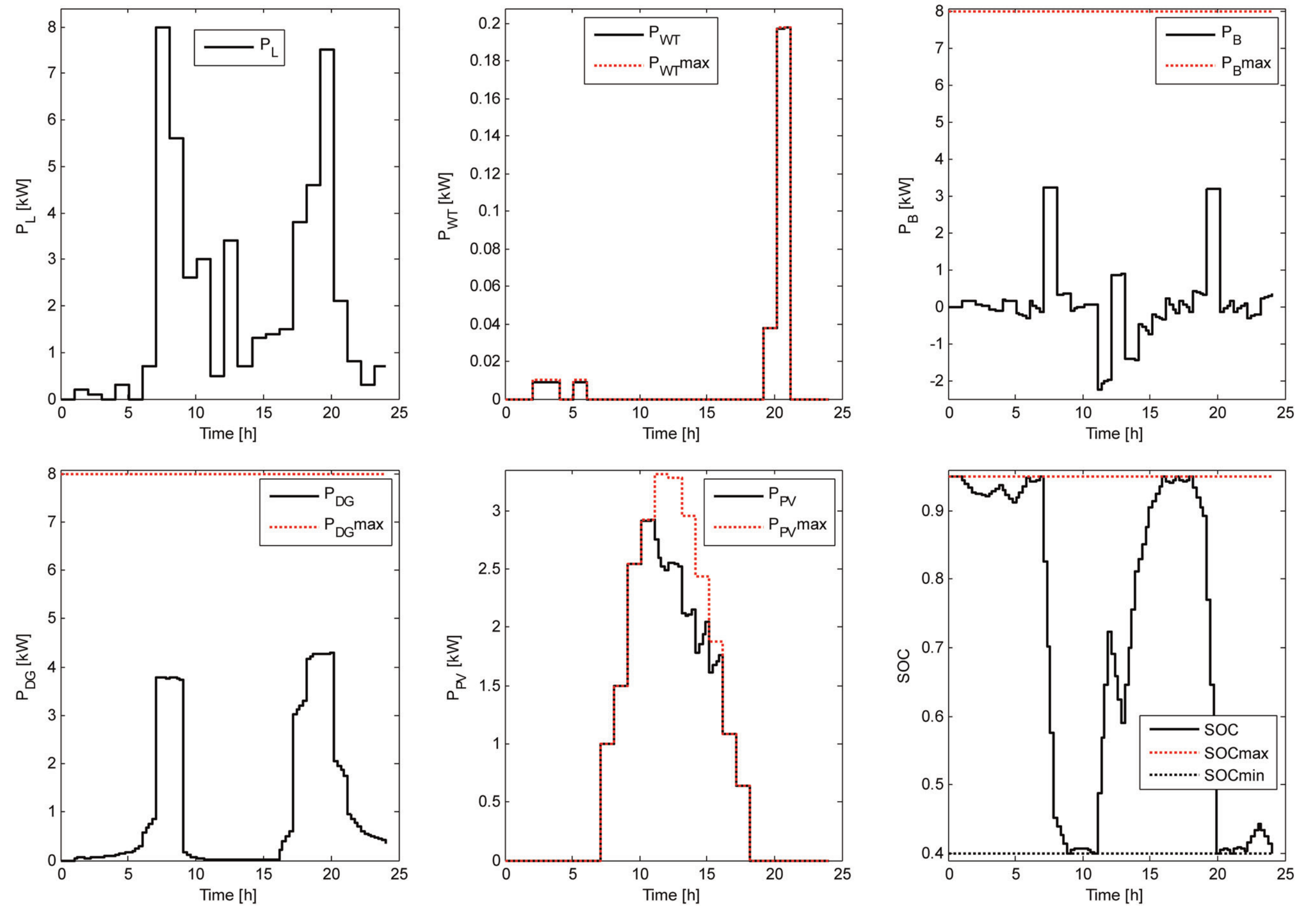

Fig. 5 *Continuous control: load profile, components output power and battery SOC (winter case)*

discharging process. The following observations on the hybrid system operation can be made after analysing Fig. 4:

- From this figure, it can be noted that during the night and early morning the load demand is low; therefore it is successfully met mainly by the battery system while the DG is kept off. The WT and PV systems are not able to generate during these periods because of the lack of wind and solar resources.
- The first morning peak load demand occurs between 07h00 and 08h00; therefore the PV and WT are used at their maximum output powers 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 to supply the load and to recharge the battery at the same time.
- The second increase in load demand occurs from 09h00 and reaches a peak at 11h00 where 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. 4, where the negative part of the battery power flow (P_B) represents the charging process. It can also be noted that during this period the sum of the power needed to supply the load and to recharge the battery is less than the maximum instantaneous power produced by the PV system. Therefore the excess of energy produced by the PV system is dissipated by a dump load as explained in Section 4.
- 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 to 19h00, the PV is used at its maximum output in conjunction with a contribution of the battery. After 19h00 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 on 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 and WT. It can be seen that the DG is not used to charge the battery but only to supply the load. A poor WT output is notable in the afternoon and in the evening, this power is also used to supply the load and contributes to the battery charging power requirement.

For this specific case, the total operating time of the DG running under this condition is 6.5 h.

In winter, the RE resource are lower and the load demand is higher compared with a typical summer day as shown in Fig. 5. From this figure, the following observations can be made:

- The power contributions of the PV and WT systems are low; therefore the hybrid system relies also on the use of the battery and on the DG which is running non-stop from 00h00 to 12h00 then 16h00 to 00h00 to supply the deficit of energy needed from the battery and RE systems needed by the load. This increases the fuel consumption as well as the DG operating time compared with the summer case.

5.3 Hybrid system ON/OFF operation

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

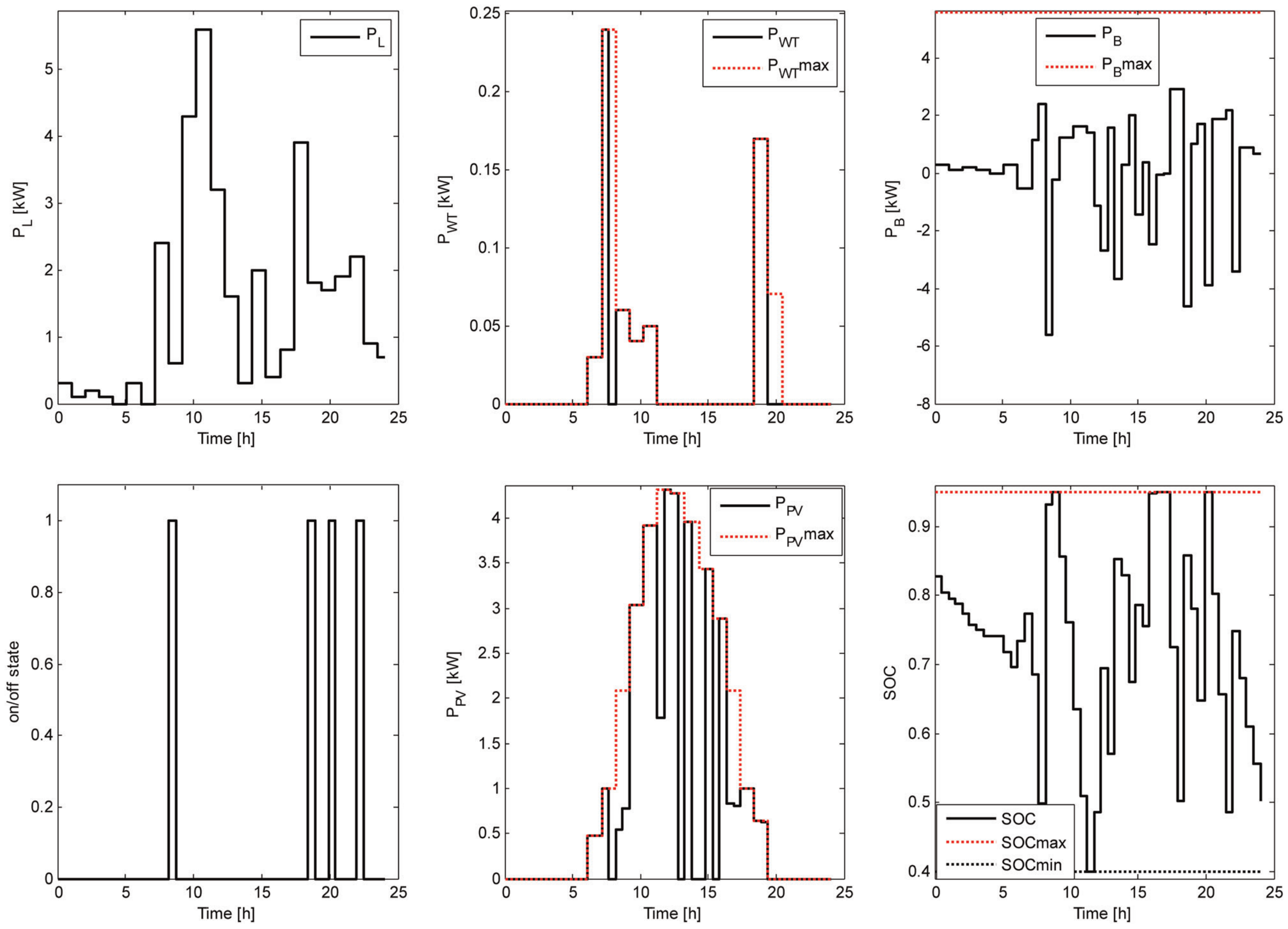

Fig. 6 *ON/OFF control: load profile, components output power and battery SOC (summer case)*

As for the continuous case, the supply priority is such that the load is initially met by the PV and WT; and the battery comes in when the RE generators' output is not enough to respond to the load demand, provided it is within its operating limits. The DG is switched ON, giving its rated output power, when the RE and/or the battery cannot meet the load. The battery is charged when the total generated power is above the load requirements.

While analysing Fig. 6, the following observations can be made:

- It can be noted that from 00h00 to 06h00 and from 22h00 to 00h00, the load demand is successfully met by the battery. The contribution of the PV and WT are not available while the one from the DG is not needed because the battery is operation within its SOC limits.
- From 06h00, soon as the PV and WT are able to produce power, they are used to supply the load and/or charge the battery depending on the instantaneous magnitude of the load demand and the battery SOC.
- When the RE and/or the battery cannot meet the load, the DG is then switched ON, giving its rated output power. As soon as the DG is ON, its generated energy is used to supply the load and the surplus is used in conjunction with the power from the RE to recharge the battery. In this case, any excess of energy generated by the RE, not used by the load or the battery charger, is dissipated by the dummy load.
- In general the DG operating time is sensibly reduced compared with the continuous operation control strategy; giving a total of 2 h in the selected summer day; and is OFF for 22 h. 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.

The contribution of the DG is important during the selected winter day as shown in Fig. 5; this is because of the high load demand and to the low solar and wind resources. This increase the amount of fuel consumed as well as the DG operating time compare with the summer case.

5.4 *Comparison of the two control strategies*

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

Table 3 Daily savings (summer)

	Continuous			ON/OFF		
	Consumption, L	Cost, $	Operation time, h	Consumption, L	Cost, $	Operation time, h
DG only	38.26	53.56	24	38.26	53.56	24
hybrid system	7.9	11.6	6.5	11.49	16.06	2
savings	30.36	41.96	17.5	26.27	37.5	22

Table 4 Daily FC savings (winter)

	Continuous			ON/OFF		
	Consumption, L	Cost, $	Operation time, h	Consumption, L	Cost, $	Operation time, h
DG only	55.96	73.34	24	55.96	73.34	24
hybrid system	27.05	32.87	24	32.58	45.61	4.5
savings	28.91	40.47	24	23.38	27.73	19.5

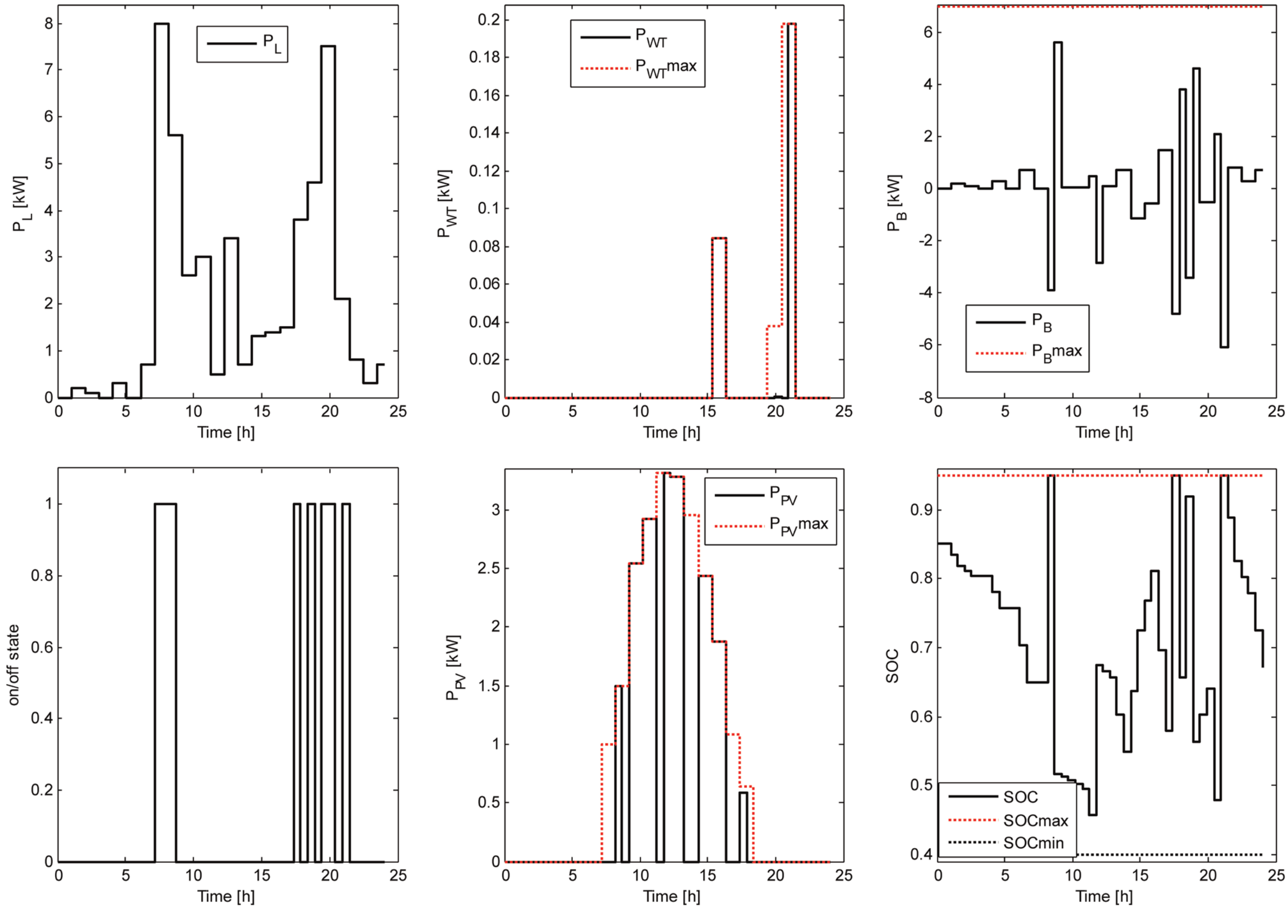

Fig. 7 *ON/OFF control: load profile, components output power and battery SOC (winter case)*

storage system as well as the DG (FC 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 PV-wind-diesel-battery system achieves 79.3 and 68.66% 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 (Fig. 7).

From Table 4 it can be seen that the PV-diesel-battery model achieves 51.6 and 41.7% 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 4.5 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 Conclusions

Two control strategies to minimise the daily operation cost of PV-diesel-battery hybrid systems have been modelled and simulated. As already mentioned, this work considered the fluctuation of the load demand, the intermittent solar resource as well as the non-linear diesel fuel consumption curve. The simulation results show that by using the PV-wind-diesel-battery hybrid system under the 'continuous' or the 'ON/OFF' operation strategy, significant operation cost can be saved compared with 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 with 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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