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Optimal scheduling for distributed hybrid system with pumped hydro storage

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ABSTRACT

Photovoltaic and wind power generations are currently seen as sustainable options of in rural electrification, particularly in standalone applications. However the variable character of solar and wind resources as well as the variable load demand prevent these generation systems from being totally reliable without suitable energy storage system. Several research works have been conducted on the use of photovoltaic and wind systems in rural electrification; however most of these works have not considered other ways of storing energy except for conventional battery storage systems. In this paper, 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 demand, is presented for a hybrid system consisting of a photovoltaic unit, a wind unit, a pumped hydro storage system and a diesel generator. The main purpose of the developed model is to minimize the hybrid system's operation cost while optimizing the system's power flow considering the different component's operational constraints. The simulations have been performed using "fmincon" implemented in Matlab. The model 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 control model for the proposed hybrid system, fuel saving can be achieved compared to the case where the diesel is used alone to supply the same load patters.

1. Introduction

Stability and reliability are main requirements for industrial and domestic power supply. Sometimes, these requirements are not easily achievable due to the remote location of the demand or due to the weak grid supply. Critical loads need to be supplied with power from in-plant generators either to complement the grid or as an emergency source which can tolerate very little or no interruptions. Diesel generators (DGs) are useful in these circumstances because of their simplicity and ease of maintenance. They can be started easily without external supply assistance, available in variety of ratings [1]. DGs can also be integrated with renewable energy sources (RE) such as solar photovoltaic (PV) and wind turbines (WT), making the combination ideal for isolated power generation [2].

Hybrid solar PV–WT–diesel systems present a resolution to the time correlation of intermittent solar source as well as load demand fluctuations [3]. 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 [4].

Energy storages are one of the few responses to the integration with variable energy production due to the fluctuation of their resources [5]. Storage system can decrease the effects of variable output power from renewable energy sources, and assure that power can be reliably dispatched in response to the fluctuating load requirements [6]. At this present time, PHS is the most widespread energy storage system not dealing with the conversion of chemical energy to electricity. This technology can be implemented with a roundtrip efficiency of 70–80%, and its capacity is not influenced by the seasonal variation of the water flow [7].

Currently, the development of models for optimal scheduling and energy management of standalone or grid connected renewable systems is gaining attention as a way to minimize the operation cost of hybrid systems. Several papers have discussed the optimal operation control of hybrid renewable energy sources with diesel systems for isolated power generation, but very few considered PHS as energy storage system.

In Ref. [8], two control strategies involving 'continuous' and 'ON/OFF' operation of the diesel generator in a PV–diesel–battery hybrid system have been modeled and used to demonstrate the

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Nomenclature

Abbreviations

DG	diesel generator
HKT	hydrokinetic turbine
PHS	pumped hydro storage
PV	photovoltaic
WT	wind turbine

Symbols

δ	evaporation and leakage loss
η_{DG}	diesel generator efficiency
η_{M-P}	overall pumping efficiency
η_{T-G}	overall efficiency of the turbine–generator set
ρ_a	air density (kg/m^3)

Subscripts

A	turbine area (m^2)
$C_{p,HKT}$	coefficient of the wind turbine performance
E_{DG}	energy from the diesel generator (kW h)
E_{PV}	energy from the photovoltaic system (kW h)
E_{WT}	energy from the wind generation system (kW h)
E_{Load}	load energy demand (kW h)
E_{M-P}	charging energy from the hydrokinetic system to the pump (kW h)
E_R	potential energy of the water stored in the upper reservoir (kW h)
E_{T-G}	energy generated from the turbine–generator (kW h)
g	gravity (m/s^2)
h	net pumping head (m)
j	sampling interval considered (s)
N	number of sampling intervals
P_{DG}	power from the diesel generator (kW)
P_{PV}	power from the photovoltaic system (kW)
P_{WT}	power from the wind generation system (kW h)
P_{Load}	load energy demand (kW)
P_{M-P}	charging power from the hydrokinetic system to the pump (kW)
P_{T-G}	power generated from the turbine–generator (kW)
Q_{M-P}	water flow rate from the pump (m^3/s)
Q_{T-G}	water volumetric flow rate from the reservoir onto the turbine (m^3/s)
t	time (s)
V	storage capacity of the water reservoir (m^3)
v_a	wind current velocity (m/s)

cost effective character of the proposed system compared to the DG alone. In Ref. [9], the author has taken the study further by adding a WT to the PV–diesel–battery hybrid system proposed in Ref. [8]. In Ref. [10], the optimal energy management of a more comprehensive system composed of a hydrokinetic (HKT) in combination with PV, WT, DG and battery storage system has been studied under different loads and weather conditions with the aim of minimizing the operation cost. In Ref. [11], an optimal energy management model of a PV, DG–battery hybrid power supply system for off-grid applications is presented. The proposed model minimizes fuel and battery wear costs and finds the optimal power flow, taking into account photovoltaic power availability, battery bank state of charge and load power demand.

In Ref. [12], an optimization model for the operation of a hybrid energy system consisting of a hydrokinetic system, a battery bank and diesel generator is developed. The optimization approach is aimed at minimizing the cost function subject to the availability of water resource, total load energy requirements as well as the diesel generator and the battery operational constraints. The effect of using a PHS instead the battery bank, in the system studied in Ref. [12], has been investigated in Ref. [13].

Based on the potential benefits of decentralized energy sources and storage systems in rural electrification as exposed in the different research discussed in the sections above, the combination of hybrid renewable energy systems with PHS is proposed in the present study. This arrangement can be seen as an attractive and interesting alternative for isolated power generation and storage problems with several benefits such as lowered cost of energy produced; lowered environmental impacts and increased reliability and availability of the electrical power supply.

Therefore, this paper develops a model to optimize the daily operation of a system consisting of a PV, WT, DG and PHS. The optimization approach aims at minimizing the operation cost function subject to the load energy requirements as well as to the operational constraints of the hybrid system's components. Considering a short time horizon, the PV, WT and PHS's daily operation costs are not taken into account, thus only the cost of the DG's fuel consumed is considered. Therefore, the main purpose of the developed control algorithm is to minimize the DG's operation cost while maximizing the use of PV, WT and PHS in the electricity generation process.

The main contribution is the consideration of PHS in the architecture of the proposed system, as PHS can have a great impact on the hybrid system's operation cost and environmental impacts; and these have not been considered in the optimization of renewable energy based distributed hybrid systems.

2. Hybrid system's components and operation description

The power flow of the proposed PV–WT–DG–PHS system is shown in Fig. 1. The load energy requirement is principally covered by the PW and WT units. When there is more than enough energy to supply the load directly from the PW and WT units, the surplus of generated energy is used to drive the motor–pump set to fill-in the upper reservoir of the PHS. However, when there is an insufficient energy to supply the load directly from the PW and WT units, the extra energy is provided from the water flowing down from the PHS's upper reservoir and driving the turbine–generator set. If the PW and WT units and the turbine–generator set from the PHS cannot respond to the load energy requirement, the DG is turned on as a last resort, in order to balance the shortage of energy needed by the load. The flowchart illustrating the simulation and optimization procedure is presented in Fig. 2.

2.1. Photovoltaic system

Solar panels convert light into electrical energy through the photovoltaic effect [14]. The output power of the solar PV system can be expressed as follows [15]:

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

where A_{PV} is the total area of the photovoltaic generator (m^2); η_{PV} is the system's efficiency; I is the hourly irradiation (kW h/m^2) and $f(t)$ is the radiance density.

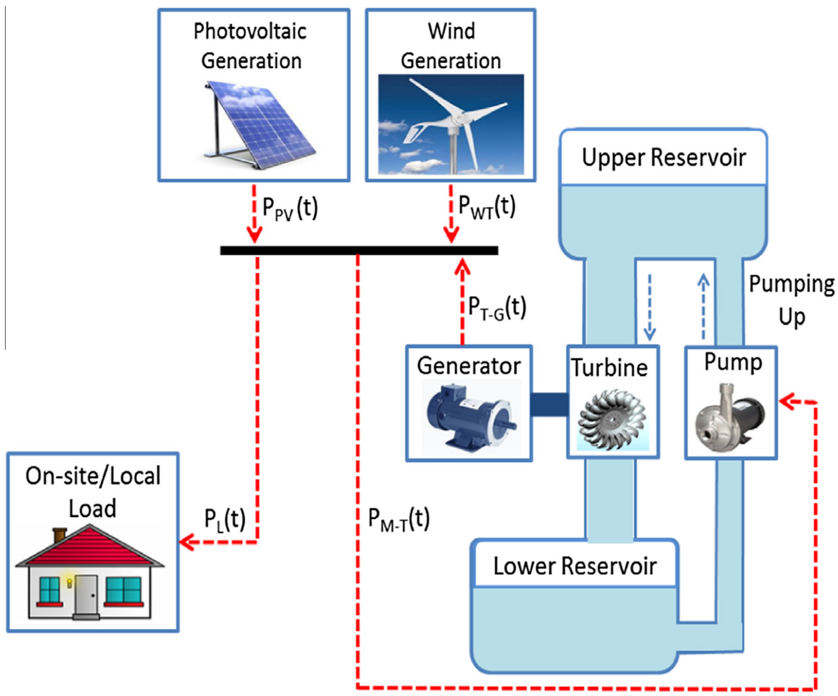

Fig. 1. Proposed hybrid system layout and power flow.

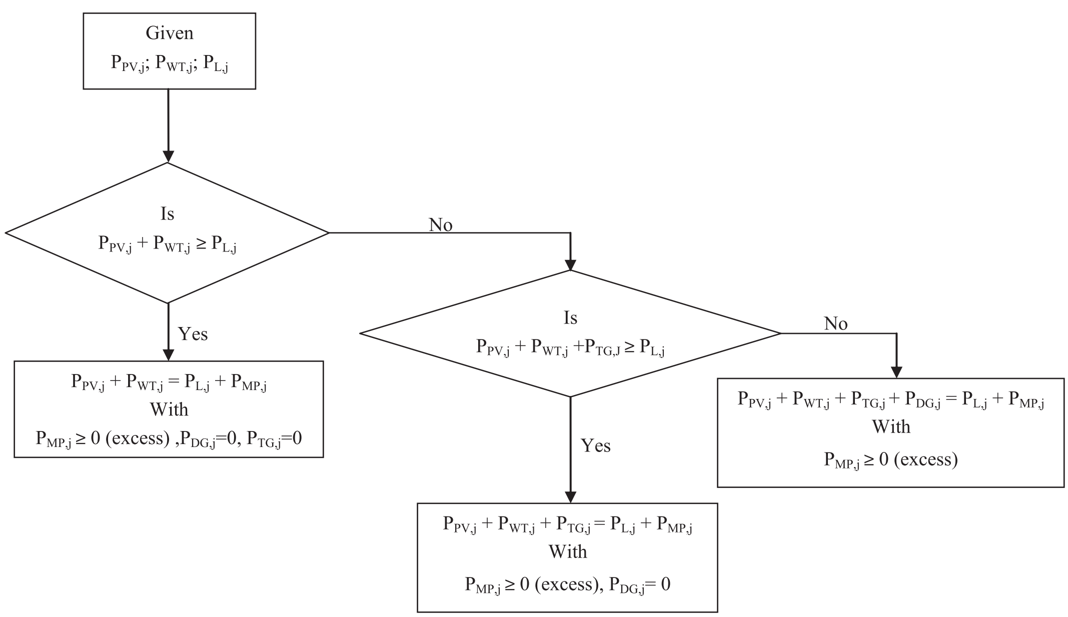

Fig. 2. Simulation and optimization procedure flowchart.

2.2. Wind energy system

Wind energy systems convert the kinetic energy of moving air into mechanical then electrical energy [16]. The power output (P_{WT}) of the wind system within a sampling time interval can be expressed as is expressed as:

$$P_{WT} = \frac{1}{2} \times \rho_a \times A_{WT} \times C_{p,WT} \times \eta_{WT} \times \int_{t_0}^{t} v_a^3(t) \times f(t) \times dt \tag{2}$$

where ρ_a is the air of water (1225 kg/m^3); $C_{p,W}$ 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 a 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 in the developed model 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 in a decrease of the fuel consumption and carbon footprint and also in an increase of the DG lifespan [17,18].

The fuel cost (FC) is calculated for a day and is given by the quadratic non-linear function shown in Eq. (2):

$$C_f\sum_{j=1}^{N}(aP_{DG(j)}^2 + bP_{DG(j)} + c) \tag{3}$$

where a, b, c are the parameters related to any DG's fuel consumption curve (available from the DG's manufacturer); C_f is the price of one liter of diesel fuel; $P_{DG(j)}$ is the output power or control variable from the DG in any sampling interval.

2.4. Pumped hydro storage

2.4.1. Motor–pump set

The energy required by the motor–pump set to suck water from the river up to the reservoir can be expressed in Eq. (4) [7]. This energy is directly supplied by the hydrokinetic system.

$$E_{MP} = \frac{\rho_W \times g \times h \times Q_{MP}}{\eta_{M-P}} \tag{4}$$

where E_{MP} is the charging power from the hydrokinetic system to the pump (W); Q_{MP} is the water flow rate from the pump (m^3/s); h is the net pumping head (m); g is the acceleration due to gravity (9.8 m/s^2) and η_{MP} is the overall pumping efficiency.

2.4.2. Turbine–generator set

In the situation where there is a shortage of energy, water from reservoir is used to operate the turbine driving the micro hydro generator [7]. The energy generated from the turbine–generator E_{TG} set can be expressed as:

$$E_{T-G} = \rho \times g \times h \times Q_{TG} \times \eta_{TG} \tag{5}$$

where η_{TG} is the overall efficiency of the turbine–generator set; Q_{TG} is the water volumetric flow rate from the reservoir onto the turbine (m^3/s).

2.4.3. Upper reservoir

The volume of water stored in the reservoir should be sufficient to meet the load power demand in a situation whereby there is an insufficient power from the hydrokinetic [7]. The potential energy is directly proportional to the volume of the water stored in the reservoir can be expressed as:

$$E_R = \rho \times V \times g \times h \tag{6}$$

where E_R is potential energy in the reservoir (kW h); V is the storage capacity of the water reservoir (m^3).

3. Optimization model and proposed algorithm

In this work, an optimum operation scheduling to minimize the 24-h operational cost of the proposed hybrid power plant is desired. For this purpose, an optimization problem is formulated, through the minimization of the operation cost that results from the energy supplied to the load, considering the main operational restrictions of each of the hybrid system's components. The solution of this problem provides an operational strategy to be followed by the PV, WT, DG and PHS system during 24 h.

3.1. Objective function

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

$$\min C_f \times \sum_{j=1}^{N}(aP_{DG(j)}^2 + bP_{DG(j)} + c) \tag{7}$$

where N is the number of sampling intervals within the operation range or period of the system; j is the jth sampling interval.

3.2. Variable constraints

3.2.1. Power balance

At any sampling time interval (j), the sum of the supplied power for the different sources must be equal to the demand.

$$P_{Load(j)} = P_{PV(j)} + P_{WT(j)} + P_{TG(j)} - P_{MP(j)} + P_{DG(j)} \tag{8}$$

3.2.2. Variable limits

The PV, WT, DG and PHS modules are modeled as variable power sources controllable in the range of zero to their maximum available power, or their rated power (for the DG and battery) for the 24 h period. These constraints depend on the characteristics of each power source and can be expressed as:

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

$$0 \leqslant P_{WT(j)} \leqslant P_{WT(j)}^{max} \quad (1 \leqslant j \leqslant N) \tag{10}$$

$$0 \leqslant P_{DG(j)} \leqslant P_{DG}^{max} \quad (1 \leqslant j \leqslant N) \tag{11}$$

$$0 \leqslant P_{MP(j)} \leqslant P_{M-P}^{max} \quad (1 \leqslant j \leqslant N) \tag{12}$$

$$0 \leqslant P_{TG(j)} \leqslant P_{TG}^{max} \quad (1 \leqslant j \leqslant N) \tag{13}$$

$$V_R^{min} \leqslant V_{R(j)} \leqslant V_R^{max} \tag{14}$$

$$V_{R(j)} = V_{R(0)} \times (1-\delta) + t_s \times \left(\eta_{MP} \times \sum_{i=1}^{j} P_{MP(j)} - \frac{\sum_{i=1}^{j} P_{TG(j)}}{\eta_{TG}}\right) \tag{15}$$

Eqs. (9)–(14) describe the operational restrictions of the PV, WT, DG, PHS units and storage capacity.

Eq. (15) describes the water volume dynamics in the upper reservoir. At the beginning of any sampling interval, the volume $V_{R(0)}$ in the reservoir is the initial level plus the pumped volume, minus the volume used by the turbine–generator set during that same interval. The PHS can either pump or generate, not both at the same time. In this equation δ is the evaporation and leakage loss.

3.3. Proposed algorithm

In the presented formulation, Eqs. (7)–(15) represent a non-linear optimization problem. The non-linear optimization problem can be solved using the "fmincon" interior point method in MATLAB. The solver fmincon has been selected for the following reasons [19]:

- Fmincon is state-of-the-art optimization method.
- It can solve larger-scale constrained optimization problems.
- It has the ability to supply Hessian information.
- Interior-Point Algorithm improves the robustness of the solver.

However, any other non-linear optimization methods could also be used. Fmincon solves problems in the form:

$$\min_x \quad f(x)$$

$$\text{Subject to}: \begin{cases} c(x) \leqslant 0 \\ c_{eq}(x) = 0 \\ A \cdot x \leqslant b \\ A_{eq} \cdot x = b_{eq} \\ l_b \leqslant x \leqslant u_b \end{cases} \tag{16}$$

where x, b, b_{eq}, l_b, and u_b are vectors; A and A_{eq} are matrices; $c(x)$ and $c_{eq}(x)$ are functions that return vectors and $f(x)$ is a function that returns a scalar.

4. Case studies

4.1. Resource and load data

A typical summer and winter load demand profile for institutional applications based on an energy demand survey carried out in rural communities in South Africa close to Bloemfontein are used and the methodology for calculating the load demand profile is as described in [19]. The load and renewable energy data for the selected summer and winter days are as shown in Table 1.

4.2. Component sizes and model parameters

The hybrid system is designed such that the load power demand is met at any given time. This study emphasizes mainly on the optimal energy management of the given hybrid system. The different parameters used in the simulations are given in Table 2 [19].

5. Simulation results and discussion

In this section, simulation results of the hybrid systems operation under different load and climatic conditions are presented. The results are also compared to the case where the DG is used alone to supply the load.

5.1. Winter case

5.1.1. DG alone

Fig. 3 shows the load profile for the selected winter day. It can be observed that the demand is highly nonlinear; low during the night with high peaks in the morning and in the evening.

Fig. 4 shows the simulation results of the case where the DG is used alone to supply the same load demand of Fig. 3. It can be seen that the DG output and the load profile have the same pattern.

Table 2
Simulation parameters.

Item	Household
Sampling time (Δt)	30 min
PHS nominal capacity	5.6 kW h
PHS maximum volume	100%
PHS minimum volume	0%
PHS overall efficiency	50%
PV rated power	4 kW
WT rated power	1 kW
DG rated power	8 kW
Diesel fuel price	1.4 $/l
a	0.246
b	0.0815
c	0.4333

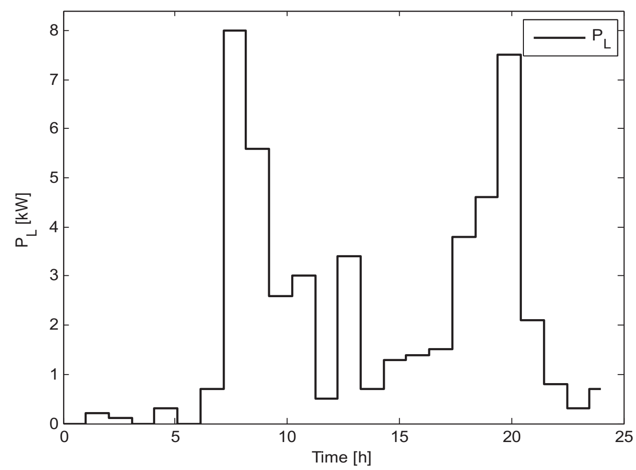

Fig. 3. Daily load profile in winter.

5.1.2. Hybrid system

Fig. 5 shows how the load demand as well as the maximum and optimum output power flows from the PV, WT, DG and PHS during the selected day in winter. It can be seen that the PV system constitute the major contribution of the power supplied by the

Table 1
Resources and load data.

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

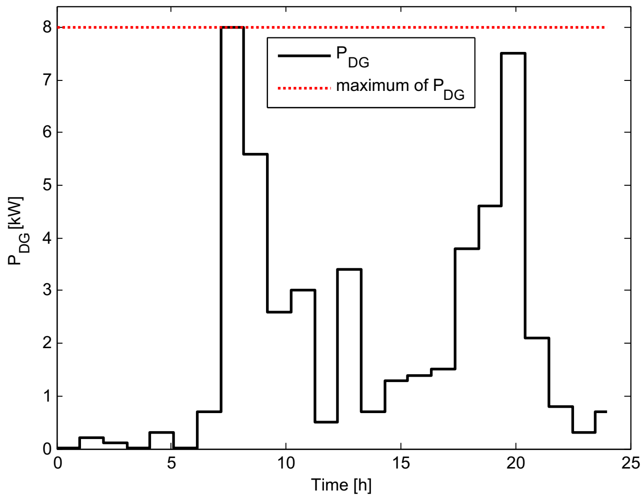

Fig. 4. DG “only” optimal scheduling and output power in winter.

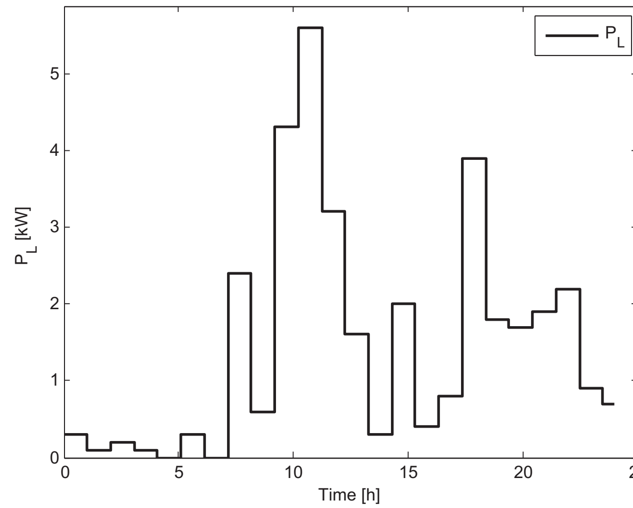

Fig. 6. Daily load profile in summer.

renewable systems, therefore has a major impact on the DG daily operation cost minimization and the PHS operation. The following observations on the hybrid system operation can be made after analyzing Fig. 5:

- From this figure, it can be noticed that during the night and early morning the load demand is low; therefore it is successfully met mainly by the PHS 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 09h00; therefore the PV is used at its maximum output power to supply the load in conjunction with the PHS and a small contribution of the DG.
- Between 11h00 and 17h00, the PV produces more power than the load requirement. This surplus is used to pump water into the PHS's reservoir up to 100% of its capacity, which is reached at the end of the afternoon as shown in Fig. 5, where the negative part of the PHS power flow (P_{PHS}) represents the pumping process.
- 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 PHS and the DG is also switched on. After 19h00 the PV system can no more provide energy while the load demand is increasing; therefore the contribution of the PHS and the DG

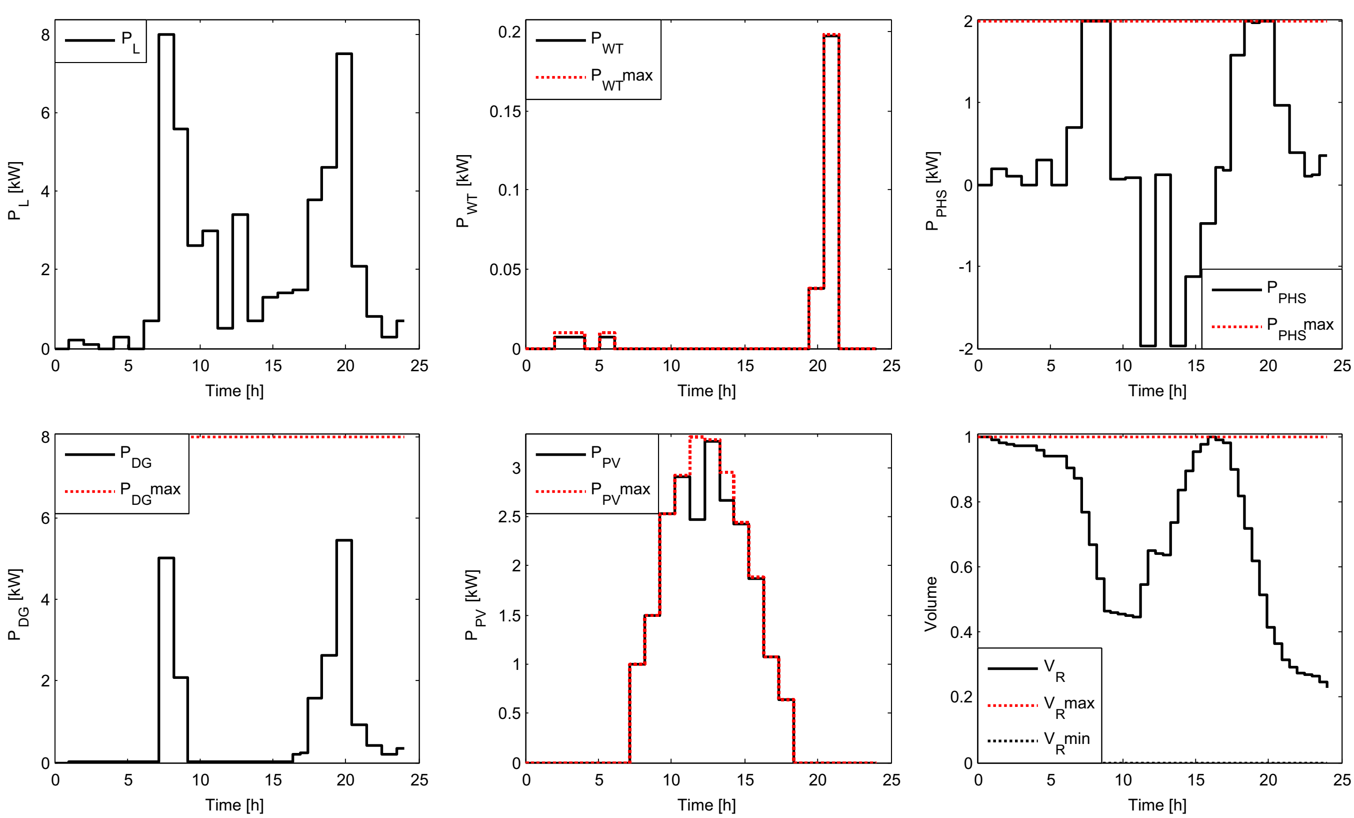

Fig. 5. Load profile, components output power and PHS volume dynamics (winter case).

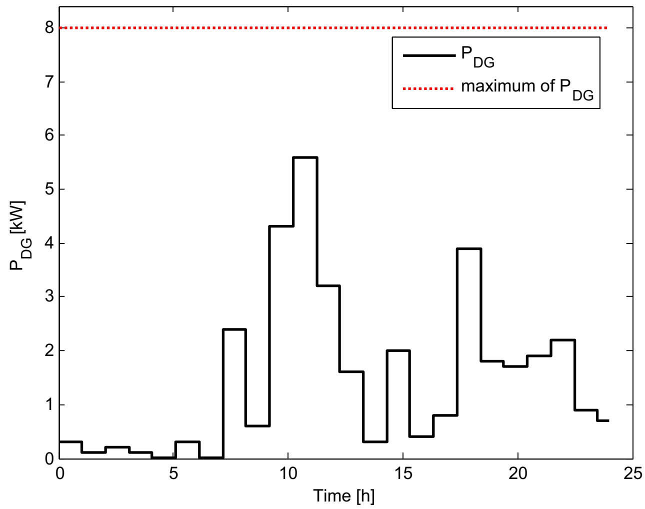

Fig. 7. DG "only" optimal scheduling and output power in summer.

are increased to balance the energy needed by the load. It can be seen that the DG is not used pump water into the reservoir but only to supply the load demand. A poor WT output is noticeable in the night and in the evening; this power is also used to supply the load.

5.2. Summer case

The developed model can also be used to analyze the difference in power flow during summer and winter due to different climatic conditions and load requirements which have significant effects on the diesel dispatch strategy and fuel consumption.

5.2.1. DG alone

Using the data from Section 4, the simulation results reveals that the DG supplies less power in summer than in winter, which is due to lower load demand in summer than in winter as shown in Figs. 6 and 7.

5.2.2. Hybrid system

The PV, WT, DG and PHS output powers during the selected summer day are presented in Fig. 8. From this figure, it can be seen that the contributions from both the DG is lower compared to the one from the selected winter day. This is due to the fact that the renewable resources as higher and the load demand is lower compared to the selected winter day.

5.3. Costs summary

Table 3 shows how much operation fuel can be saved by using the hybrid system instead of the selected DG on a winter or a summer day. These results demonstrate that it is very important to take into account the variations of the load and seasons when calculating the system's daily operation cost.

Table 3
Costs comparison.

	Winter		Summer	
	Consumption (L)	Cost ($)	Consumption (L)	Cost ($)
DG only	55.96	73.34	38.26	53.56
Hybrid system	14.7	20.54	5.85	8.19
Savings	41.26	52.8	32.41	45.37

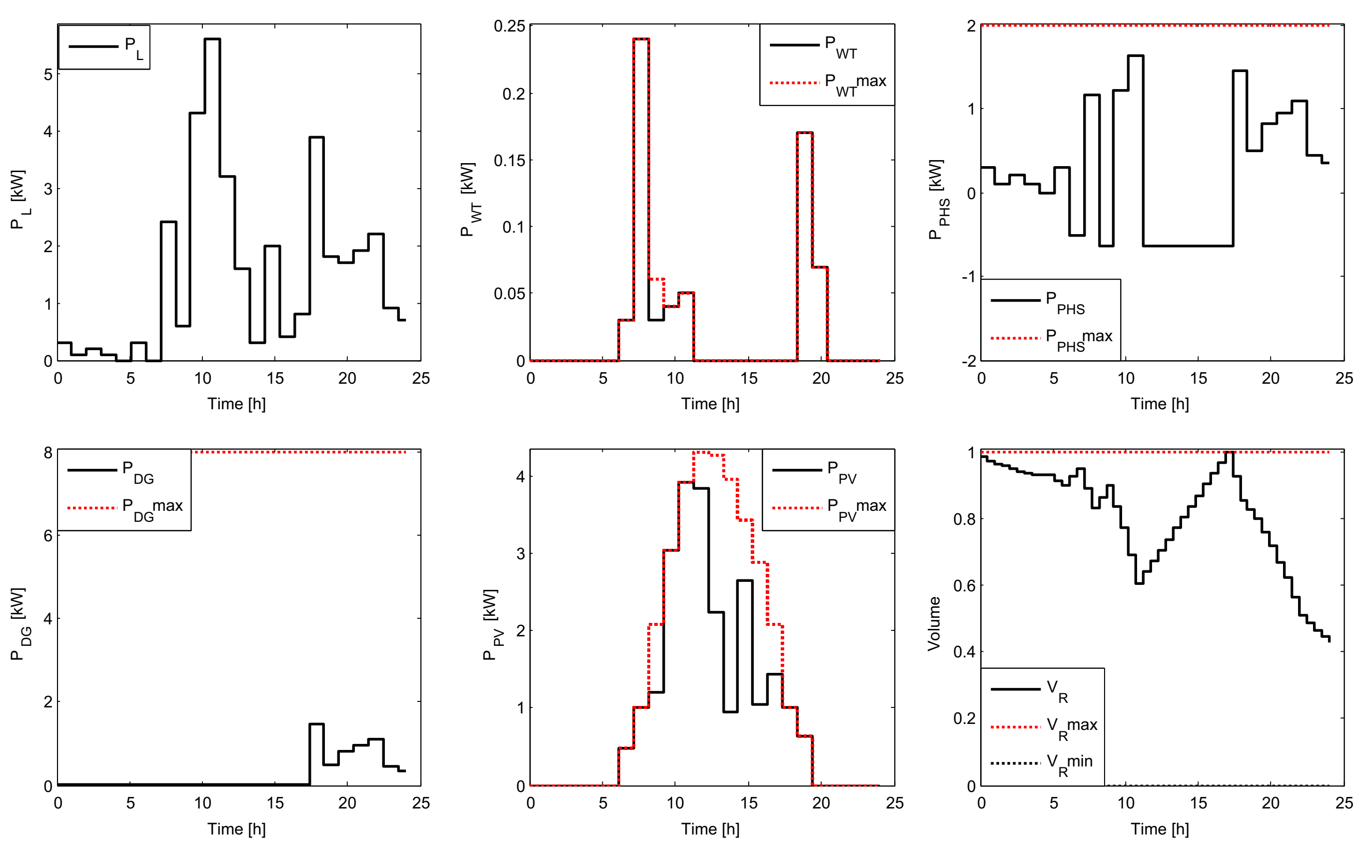

Fig. 8. Load profile, components output power and PHS volume dynamics (summer case).

6. Conclusion

In this paper, a model was developed to find the optimal daily operation scheduling to be implemented in a hybrid system composed of a photovoltaic unit, a wind unit, a pumped hydro storage system and a diesel generator. This model aims to minimize the use of the diesel generator while maximizing the use of the photovoltaic unit, wind unit and pumped hydro storage system.

The simulation results show that using the pumped hydro storage ability, it is possible to deal with any load operational constraints that usually require a rapid response from the power generation or storage system. For the two case studies, it has been demonstrated that using the proposed hybrid system and taking into account the non-linearity in daily and seasonal variations of the load demand, substantial reduction in the daily operational cost of the diesel fuel can be achieved. The difference in daily operation cost achieved highlight the potential of the proposed optimization model to reduce fuel consumptions for the proposed hybrid system compared to the diesel generator only scenario.

Pumped hydro storage also increases the penetration of the generation from variable renewable energy sources, aiming to improve the participation of the photovoltaic and wind systems in electricity markets. A decrease in the needs on diesel generator can also be obtained, since there will be an increase of the availability and reliability of power supply.

The developed model can also be used to show the effect of the PHS initial water level and allowable depth of discharge on the system's operational cost through sensitivity analysis. The results of this work allow users and practitioners to get an idea of the system operations and also to appreciate the necessity for optimal energy management of the system.

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