Optimal Scheduling of Household Appliances in Off-Grid Hybrid Energy System using PSO Algorithm for Energy Saving

Abderraouf Bouakkaz*‡, Salim Haddad*, Juan Andrés Martín- García **, Antonio Jose Gil-Mena**, Rafael Jiménez- Castañeda***

*Laboratoire de génie mécanique et matériaux, Université 20 aout 1955 Skikda. Bp26 route d'el Hadaik Skikda, Algérie

** Department of Electrical Engineering, University of Cádiz, Escuela Politécnica Superior de Algeciras, Avda. Ramón Puyol, s/n, 11202 Algeciras (Cádiz), Spain

*** Department of Electrical Engineering, Escuela Superior de ingeniería de Puerto real, Avda. de la Universidad de Cádiz, 10 / 15519 Puerto Real (Cádiz), Spain

(ab.bouakkaz@univ-skikda.dz, s.haddad@univ-skikda.dz, juanandres.martin@uca.es, antonio.gil@gm.uca.es, rafael.castaneda@uca.es)

‡ Corresponding Author; Abderraouf Bouakkaz, Tel: +213697092825, ab.bouakkaz@univ-skikda.dz

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Abstract- In a stand-alone renewables energy system (SRES), maintaining the balance of power between supply and demand with minimum cost in homes connected to these systems present one of the most important challenges to consider. In SRES, a large capacity of batteries is usually used to store the energy and reuse it when the absence or insufficient power supply to maintain energy balance. However, the batteries are costly, as well as a large amount of power lost during the charging and discharging process, represent big issues that should be avoided. One of the most important tools to redress these issues is the scheduling strategy for household appliances. In this paper, Particle Swarm Optimization Algorithm (PSO) is proposed to schedule the household appliances in the off-grid hybrid energy system (PV, Wind turbine, batteries, and diesel generator) with the objective of saving energy and reduce the energy consumption cost (i.e. energy of diesel) by maximizing the using the power of renewable energy sources and minimizing using the power of batteries. The scheduling algorithm is based on the data forecast of one day ahead of renewable energy and the daily load power consumption profile, a case study of meteorological data in the south of Spain are selected and tested for the simulation. Two scenarios of scheduling strategy are presented and compared with the scenario without scheduling of appliances. The simulation results show that the optimization of cost reached to 50% with 0.472 kWh of energy saved in scheduling with user preferences and can be reached up to 64% with 0.811 kWh of energy saved in case of optimal scheduling which considered the optimal for saving energy.

Keywords Off-grid renewable energy system, household appliance, Scheduling, Particle swarm optimization, Energy cost reduction, Energy saving.

1. Introduction

The demand for electricity increases dramatically in recent years due to population growth. Therefore, as a result of the geographic expansion of population, many people have not been accessed to the electricity grid, whereas, according to the latest statistics of the International Energy Agency (IEA) more than 1.1 billion people worldwide have not access to electricity[1]. Therefore, using renewable energy sources (RESs) such as solar and wind become a crucial and unavoidable solution for providing electricity especially when considering remote rural areas[2]. In general, to make the system more reliable and efficient, two or more different energy sources are combined in the form of a hybrid system[3].

The intermittency nature of RESs due to environmental factors, e.g., weather, is one of the most issues which represent a major challenge to maintain the power balance between demand and supply of home energy management system (HEMS)[4–6]. However, including of storage system and using diesel generator in SHRES can contribute to fill the gap of the intermittency problem in the system and make it more flexible[7–9]. However, employing a large of storage capacity is costly, as well as the power losses throughout energy conversion, transfer, and storage [10,11]. In addition, using diesel generator is costly and unfriendly for the environment[12]. Therefore, implementing efficient scheduling strategies for energy production, energy consumption and energy storage in HEMS will contribute to save energy and avoiding the peak of energy consumption by scheduling the time of use of appliances[13,14].

Many different strategies for scheduling of household appliances in home energy management system have been proposed to manage the energy consumption[15]. For instance, a real-time scheduling of household appliances was proposed in[16], to manage the energy consumption and avoid peak demand for power supply. In[17], mixed integer linear programming (MILP) under a time-of-use electricity tariff is used to schedule home appliances in order to minimize the electricity cost. In reference[18], an optimal scheduling for HEMS was proposed based on real-time pricing using Taguchi- genetic algorithm. An optimal scheduling based on the day-ahead real-time electricity pricing is proposed by [19] for minimizing energy consumption cost. [20] Has applied Multi-Swarm PSO for scheduling of appliance under day ahead prices and PV generation for minimizing the cost. Scheduling strategy of load consumption based on computing the optimal static load sizes and PV energy production using Mixed-Integer Linear Programming (MILP) in order to maximize solar energy utilization has proposed by[21].

However, most previous research work on HEMS, the scheduling strategy of energy consumption has most often been studied in terms of grid connected system which based on the price of electricity and peak demand. In this study, an optimal scheduling of household appliances based on day-ahead data forecast in stand-alone renewables energy systems using particle swarm optimization algorithm (PSO) proposed to manage the energy consumption by maximizing the utilization of RESs energy in order to minimize the peak load demand and energy production cost.

The main contribution of this paper is to propose a scheduling strategy based on the energy losses and energy cost. The rest of the paper organized as follows, the mathematical model of the system is given in section 2, in section 3 energy management strategy of the system and in section 4 the problem formulation, the PSO optimization algorithm is given in section 5, in section 6 the analyzing and discussing the simulation results and finally we conclude the paper in section 7.

2. Hybrid power system model

The system chosen in this study is designed to achieve a parallel operation of both sources (wind, photovoltaic) with energy storage system and a backup generator. The hybrid power system presented in Fig.1 is suggested as a stand-alone system for the local production of PV and wind power generation combined with energy storage system (ESS) to store excess energy and improve the reliability of the system and a diesel generator using as a backup system in case of power supply deficit. In this section, the design and modelling of different energy sources in the proposed system (PV generator, wind turbine and battery) is presented.

2.1. Photovoltaic power output

The power output of the PV generator (P_{pv}) at the maximum power point (MPP) can be calculated as a function of solar radiation G (W/m²) and ambient temperature T_{amb} (°C) Eq.(1)[22,23]:

$$Ppv = \left[P_{STC} \cdot \frac{G}{G_{STC}} \times \left[1 - \gamma \cdot \left(T_{cell} - T_{cell,STC} \right) \right] \right] \cdot Ns \cdot Np \qquad (1)$$

Where P_{pv} is the power output of PV at MPP, N_s and N_p is the number of PV arrays in series and in parallel, P_{STC}, G_{STC} and $T_{cell,\,STC}$ are the rated power, solar radiation and the cell temperature in standard test condition (STC), γ is the power temperature coefficient at MPP, *Tcell* is the cell temperature which obtained from Eq. (2).

$$T_{cell} = T_{amb} + \frac{G}{G_{NOCT}} \cdot \left(NOCT - T_{amb,\,NOCT} \right) \qquad (2)$$

Where G_{NOCT} and $T_{amb,NOCT}$ is solar radiation and the ambient temperature in nominal operating cell temperature (NOCT) and *NOCT* is a constant. The STC and NOCT measurement conditions are obtained from information in datasheet delivered by the manufacture which is presented in Table 1.

2.2. Wind power output

The power output of the wind turbine generator (P_w) can be calculated as a function of wind speed V *(m/s)* by the following formula[24]:

$$P_w = \begin{cases} 0 & V < V_{c.in} \text{ or } V > V_{c.out} \\ P_r \cdot \dfrac{V - V_{c.in}}{V_r - V_{c.in}} & V_{c.in} \le V \le V_r \\ P_r & V_r \le V \le V_{c.out} \end{cases} \qquad (3)$$

Where P_r is the rated power of the turbine, V, V_r, $V_{c.in}$ and $V_{c.out}$ represent wind speed, nominal wind speed, cut in wind speed and cut out wind speed respectively.

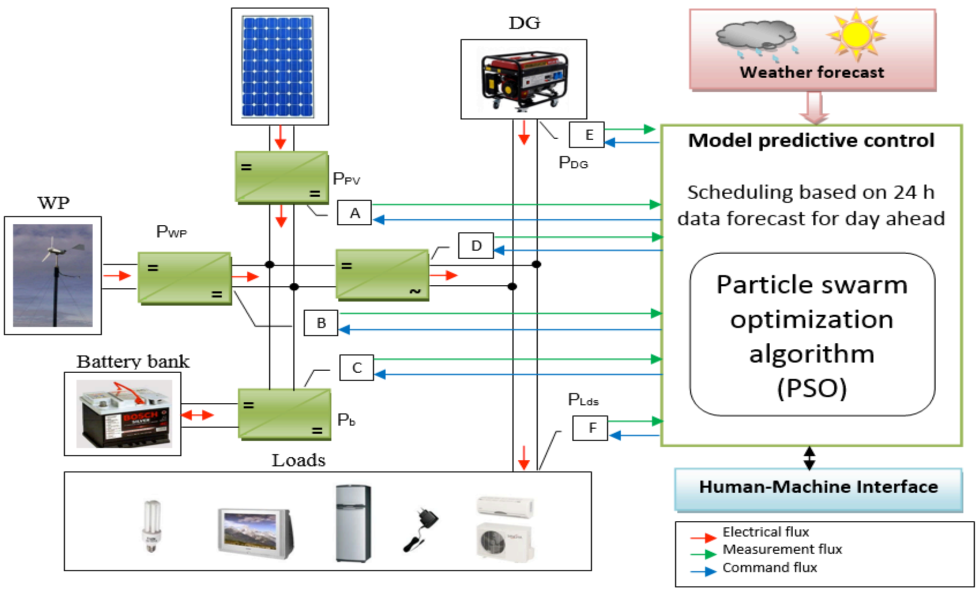

Fig.1. The architecture of studied stand-alone system.

2.3. Storage system power

The storage energy system plays a very essential role in the stand-alone energy system, in this study a lead-acid batteries is used. However, for a lead-acid battery model requiring consideration of the limitation of charge and discharge current, this limitation comes from the Kinetic battery model (KiBaM)[25]. The available and bound charge of the battery at any time given by Eq. (4) and (5).

$$q_1 = q_{1,0}\cdot e^{-k\cdot\Delta t} + \frac{(q\cdot c\cdot k - 1)(1-e^{-k\cdot\Delta t})}{k} - \frac{I\cdot c(k\cdot\Delta t - 1 + e^{-k\cdot\Delta t})}{k} \quad (4)$$

$$q_2 = q_{2,0}\cdot e^{-k\cdot\Delta t} + q(1-c)(1-e^{-k\cdot\Delta t}) - \frac{I(1-c)(k\cdot\Delta t - 1 + e^{-k\cdot\Delta t})}{k} \quad (5)$$

$$q = q_1 + q_2 \quad (6)$$

Where $q_{1,0}$ and $q_{2,0}$ are the amount of available and bound charge at the beginning of time step (Ah), c and k represent capacity ratio and rate constant respectively which can calculated from the datasheet provided by manufactures.

A. Maximum charging and discharging current

The maximum charge and discharge currents are given by the following equations:

$$I_{c,\max} = \frac{-k\cdot c\cdot q_{\max} + k\cdot q_{1,0}\cdot e^{-k\cdot\Delta t} + q\cdot c\cdot k(1-e^{-k\cdot\Delta t})}{1-e^{-k\cdot\Delta t} + c(k\cdot t - 1 + e^{-k\cdot\Delta t})} \quad (7)$$

$$I_{disc.\max} = \frac{k\cdot q_{1.0}\cdot e^{-k\cdot\Delta t} + q\cdot k\cdot c(1-e^{-k\cdot\Delta t})}{1-e^{-k\cdot\Delta t} + c(k\cdot t - 1 + e^{-k\Delta t})} \quad (8)$$

Where q_{max} is the maximum charge of battery (Ah). The transfer of charge of the battery should take on consideration of the maximum charge and discharge current as in (9) and (10):

$$I_{ch} = -\min\left(\left|\frac{P_b}{V_b}\right|, |I_{ch.\max}|\right) \quad (9)$$

$$I_{disc} = \min\left(\frac{P_b}{V_b}, I_{disc.\max}\right) \quad (10)$$

B. State of charge (SOC)

At each time step, the new capacity is obtained by Eq. (11) when the battery's operation is a charging and by Eq. (12) when the battery's operation is a discharge:

$$q_1(1+t) = q_1(t)\cdot e^{-k\cdot\Delta t} + \frac{(q(t)\cdot c\cdot k - 1)(1-e^{-k\cdot\Delta t})}{k} - \frac{c(k\cdot\Delta t - 1 + e^{-k\cdot\Delta t})\cdot I_{disc}}{k\cdot\eta_b} - q_{auto.disc}\cdot\Delta t \quad (11)$$

$$q_1(t+1) = q_1(t)\cdot e^{-k\cdot\Delta t} + \frac{(q(t)\cdot c\cdot k - 1)(1-e^{-k\cdot\Delta t})}{k} + \frac{-c(k\cdot\Delta t - 1 + e^{-k\cdot\Delta t})I_{ch}\cdot\eta_b}{k} - q_{auto.disc}\cdot\Delta t \quad (12)$$

Where η_b is the battery efficiency, $q_{auto,disc}$ represent the self-discharge charge of the battery which can be calculated as follow:

$$q_{auto.disc} = \frac{Q\cdot\partial}{V_b} \quad (13)$$

Where ∂ is the daily battery self-discharge rate (it assumed 2% per day).

Table1. The input parameters of the system

Parameter	value	Unit
Pv (ac-250p/156-60s)		
Rated power	250	Watt
G_{stc}	1000	Watt/m²
G_{noct}	800	Watt/m²
Noct	45	°C
$T_{amb,noct}$	20	°C
γ	0.043	%/°C
Ns	2	
Np	5	
Wind turbine (x600)		
Rated power	600	Watt
Vr	12.5	m/s
Vc.in	2.0	m/s
Vc.out	45	m/s
Battery (BAE Secura 6 PVS 660)		
Capacity	595	Ah
Voltage	12	v
Number of cycle (DOD =70)	1800	cycle
Efficiency	80	%
Soc_{min}	30	%
Soc_{max}	100	%
Number of battery	2	
Cost of battery	2 110,05	$
Diesel generator		
Rated power	4	kW

The estimation of state of charge (SOC) of the battery at any time is defined by following equations:

$$Q(t+1) = q_1(t+1)V_b \tag{14}$$

$$SOC(t+1) = \frac{Q(t+1)}{Q} \cdot 100 \tag{15}$$

Where Q is the battery capacity and V_b is the battery voltage.

2.4. Diesel generator

The diesel generator in stand-alone system generally used as a backup power when there is deficit in power supply in the system. In this paper, the cost of fuel consumption for diesel generators is considered in the optimization problem and taken into account for formulating the objective function.

The fuel consumption of DG is depending on the amount of energy produced, which can be calculated as follows[26]:

$$CON_{DG}(t) = \left(A \cdot P_{DG}(t) + B \cdot P_n\right) \tag{16}$$

Where CON_{DG} (l/h) the fuel consumption of diesel, P_n and P_{DG} represent nominal and output power of diesel generator. The parameters A and B are coefficients of fuel consumption (A = 0.246 and B = 0.08415).

3. Power management strategy

In this section, we present the power management strategy proposed in this study, which can predict a day ahead for the appropriate times for the operation of the shiftable household appliances, based on particle swarm optimization algorithm.

3.1. Supply and demand data forecast

In our study, we chose one of the households in south of Spain (Cadiz: Puerto Real), where we considered eight household appliances used daily. Fig. 2 represent the daily distribution of the household appliances, the energy consumption and time of use of each electric appliance are summarized in Table 2.

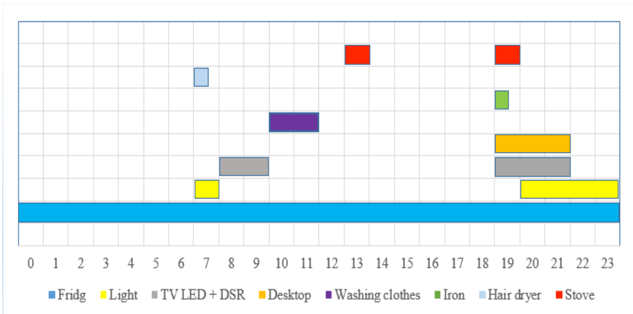

Fig. 2. Daily distribution of household appliances.

Concerning wind speed and solar radiation data for the simulation in this study, one-day data with time steps of five minutes are used. Fig. 3 shows the estimation of generation profiles solar and wind power systems.

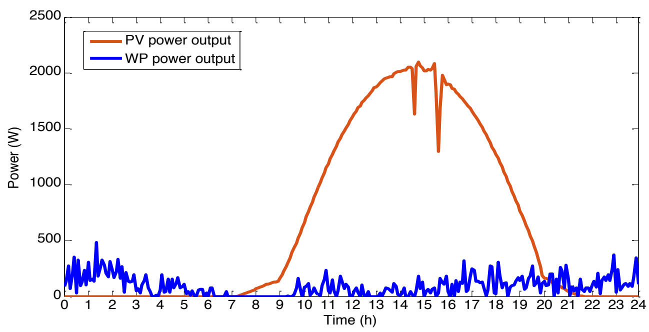

Fig. 3. PV and WP power output used in simulation.

Table 2. The list of service usage in the considered home.

N°	Service	Rated power (kW)	Start (h)	Finish (h)	Time of use (h)	Nature of service
1	Refrigerator	0.25	[00:00]	[24:00]	24	Non shiftable
2	Light	0.12	[7:00 & 20:00]	[8:00 & 24:00]	5	Non shiftable
3	Washing machine	2.2	[10:00]	[12:00]	2	Shiftable
4	Iron	2	[20:00]	[20:30]	0.5	Shiftable
5	TV + DSR	0.08	[08:00 & 19:00]	[10:00 & 22:00]	5	Non shiftable
6	Desktop	0.13	[19:00]	[22:00]	3	Non shiftable
7	Hair dryer	2.2	[07:00]	[07:30]	0.5	Shiftable
8	Electric Stove	1.5	[12:00 & 19:00]	[13:00 & 20:00]	2	Non shiftable

3.2. Power balancing

The balance of power in stand-alone energy systems is to maintain the equivalence between the power supply and demand at any time and under all constraints. The power balancing for the studied system shown in Fig.4 is presented by the equation (17):

$$P_{pv}(t)+P_{wp}(t)+\alpha.P_b(t)+\beta.P_{DG}(t)-P_{lds}(t)-P_{loss}(t)=0 \quad (17)$$

Where P_{pv}, P_{wp}, P_b, P_{DG}, P_{lds} and P_{loss} represent respectively the available power output of PV and wind turbine, the power from/to batteries, the output power of diesel generator, power demand of loads and the power losses in the system due to energy conversion and storage. α and β are indices which indicates the state of battery (1: charging, -1: discharging and 0: disconnecting) and the state of diesel generator (1: on, 0: off).

In this study, the power balancing of the system is shown in Fig. 5, the Fig. 6 illustrate the state of battery storage charging and discharging.

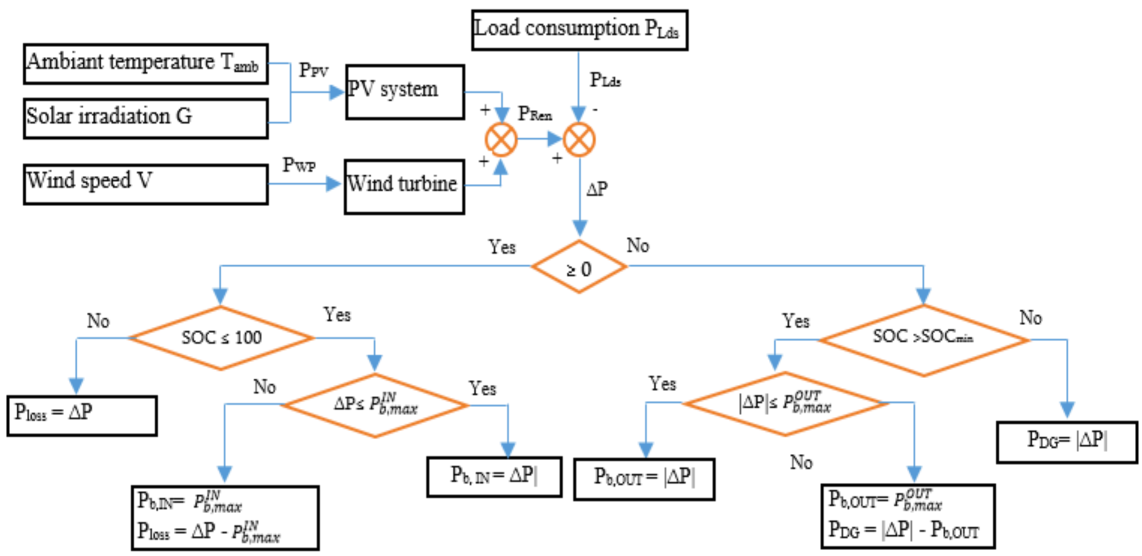

Fig. 4. Flowchart of power balance strategy of the hybrid energy system.

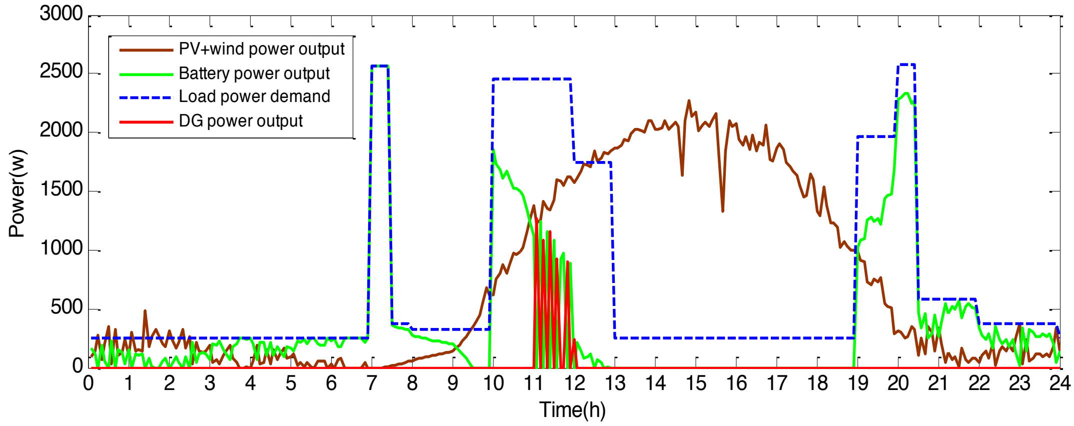

Fig. 5. Power balance of the system in simple day.

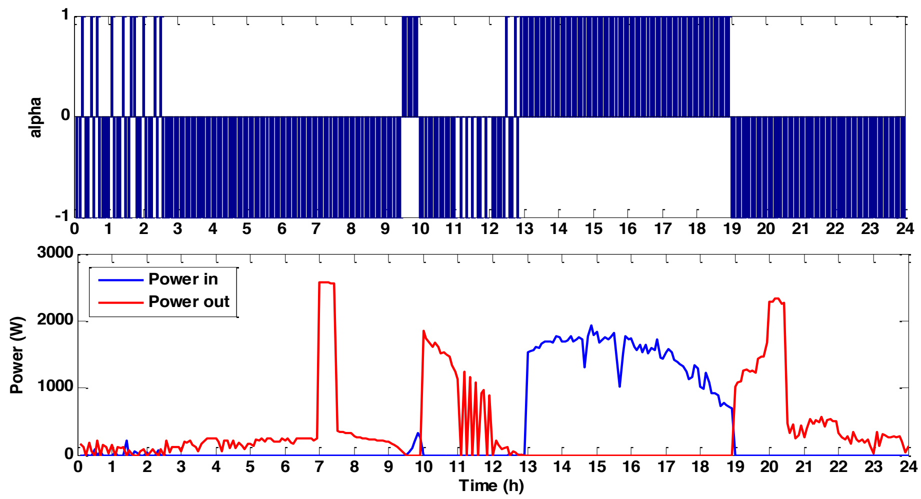

Fig. 6. Battery charging and discharging.

4. Problem formulation

The purpose of household appliances scheduling strategy is to maintain the power balance as given in the Eq. (17) with the minimum cost taking into account the following limitations:

$$SOC_{\min} \le SOC(t) \le SOC_{\max} \tag{18}$$

$$P_b(t) \le P_{disc.\max}(t) \tag{19}$$

$$P_b(t) \le P_{ch.\max}(t) \tag{20}$$

In this paper, when calculating the total cost of energy, it assumed that the cost of energy from renewable sources is free and only on the cost of energy from batteries and diesel generators are considered, with the objective of maximizing the utilization of RESs when the production of energy is high and minimizing using the power of batteries. The objective function of the scheduling strategy is expressed by Eq. (21)

$$Min(Cost) = Min\sum_{t=0}^{288} C_B(t) + C_{DG}(t) \tag{21}$$

Where C_B, C_{DG} present the utilization cost of batteries and diesel generator which can calculated as follow:

$$C_B(t) = P_b(t) \cdot \frac{C_b^a}{E_b^n \cdot N_{cycle}} \tag{22}$$

$$C_{DG}(t) = CON_{DG}(t) \cdot C_f \cdot \Delta t \tag{23}$$

Where Cf is the price of 1 liter of fuel, the average price of diesel around the world is 1.01 \$/L. C_b^a is the acquisition costs of the battery, E_b^n is nominal energy of battery and N_{cycle} is the life cycle of battery.

5. PSO optimisation algorithm

PSO algorithm is a meta-heuristic optimization algorithm inspired by the social behavior of birds and fish which was introduced by Kennedy and Eberhart[27].The algorithm base on the movement of particles in the swarm in multidimensional search space, each particle characterized by a position X (k) and velocity V (k). The algorithm begins with a random initial position for the particles. In each iteration, the position and velocity of each particle of the swarm are updated according to the current best position according to the following equations:

$$V_i(k+1) = w \cdot V_i(k) + c1 \cdot r1\left(X_{i,best}(k) - X_i(k)\right) + c2 \cdot r2\left(X_{g,best}(k) - X_i(k)\right) \quad (24)$$

$$X_i(k+1) = X_i(k) + V_i(k+1) \quad (25)$$

Where, $X_{i,best}$ is the best personal position in the current iteration, $X_{g,best}$ represent the global best position which represents the optimal fitting solution in the current iteration, C_1, C_2 are the personal and social acceleration coefficients. Parameters r_1 and r_2 are random numbers from [0; 1], w represent the inertia weight coefficient for particles which calculated as follows:

$$w(k) = w_{max} - \frac{\left(w_{max} - w_{min}\right)}{N_{iter}} \quad (26)$$

Where w_{max} and w_{min} represent the maximum and minimum weight inertia, N_{iter} is the number of iteration. Table 3 present the PSO algorithm parameters used in the scheduling strategy.

Table 3. The input parameters of PSO algorithm

Parameter	Scheduling with user preference	Optimal scheduling
w_{min}	0.4	0.4
w_{max}	0.9	0.9
C1	1.2	1.2
C2	1.2	1.2
Lower bound	[120,216,192]	[0,0,0]
Upper bound	[144,264,216]	[288,288,288]
Population	10	10
Max iteration	500	500

The policy of the proposed scheduling strategy is to shift the household appliance into a period when the energy production is high for maximizing the using of renewable energy and avoiding using energy from battery as possible. The structure of PSO algorithm adopted in the scheduling strategy is given below:

Step 1) Initialization
Load meteorological data;
Load system component parameters, Table.1;
Load list of appliances, Table.2;
Set the initial PSO parameters Table.3;
Set the initial velocity;
Step 2) Set random initial solution
For each particle i of the population {
Set the initial random particles, X_i gbest;
Call cost function;
$X_{i.best} = X_i$;
$P_{i.best}$ = fitness(X(i));
If ($P_{i.best}$ < gbest)
gbest = $P_{i.best}$; }
Step 3) Update initial solution
For each iteration k {
Update inertia weights, Eq.(26);
Update velocity (V_i), Eq.(24);
Update position (P_i), Eq.(25);
For each particle i of the population {
Call cost function;
$X_{i.best} = X_i$;
$P_{i.best}$ = fitness(X(i));
If ($P_{i.best}$ < gbest)
gbest = $P_{i.best}$ } }
Step 4) Set final solution
gbest is the solution

6. Simulation results and discussion

In this study, three different scenarios are considered, the first scenario without shifting the appliance, the second scenario is a scheduling of household appliances with user preferences, and the third scenario is an optimal scheduling without user preferences. The convergence process of PSO algorithm is shown in Fig.7, two scheduling optimization techniques are manipulated by the PSO, a scheduling with user preferences which allow the user to select the time slot to run the shiftable appliances according to his desire, and the second is optimal scheduling, in this case, the PSO algorithm has not any restriction of time by the user and will select the possible optimum solution and give the appropriate time for running the appliances. The obtained results of the PSO for the scheduling strategy are summarized in Table 4.

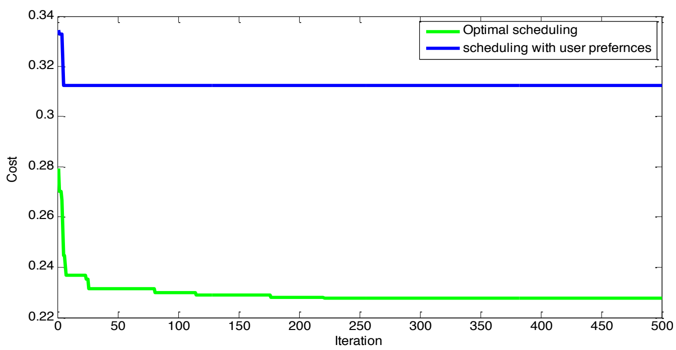

Fig. 7. The simulation result of PSO algorithm.

The first and second column present the cost reduction which present the objective function, the energy of the diesel generator produced is displayed in the third column, the column 4 shows the energy stored in the batteries at the end of day, while column 5 provides the amount of energy saved befor and after scheduling the household appliances and the last column present the total CO2 gas emission.

Table 4. Comparison of obtained results of PSO algorithm

Scenario	Cost ($)	Reduced cost (%)	Diesel power (kWh)	Energy saved on battery (kWh)	Energy saved (kWh)	Co2 emissions (kg)
Without scheduling	0.636	-	0.464	1.233	-	0.889
Scheduling with user preferences	0.307	52	0	1.241	0.472	0
Optimal scheduling	0.227	64	0	1.580	0.811	0

The comparison of the three scenarios shows that the PSO algorithm can provide an optimal solution for minimizing the cost of energy and saving the energy in the system. The reduced cost in scheduling with user preferences can reach 52% and save 0.472 kWh of energy while the reduced cost in optimal scheduling can reach 64% and saving 0.811 kWh of energy. Fig. 8 shows the load profile for the three scenarios. The time of use of appliance in the three scenarios are presented in Table 5.

Fig.9 shows the state of charge (SOC) and the output power of batteries for the three scenarios. It's noticed that in optimal scheduling of household appliances, the SOC ratios are convergent in all the time, which means less battery use, followed by scheduling with user preferences compared to the scenario without scheduling of appliances.

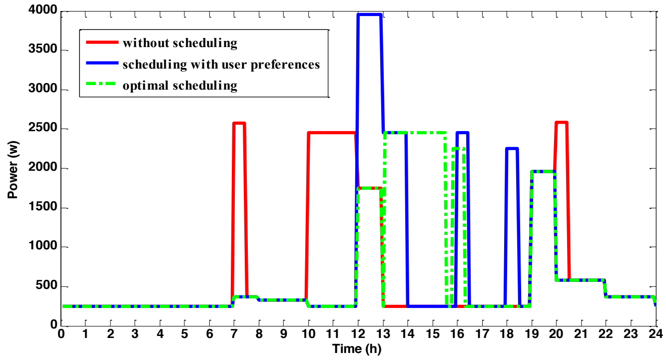

Fig. 8. Load profile for the three scenarios.

Table 5. The time of use shifting loads for the three scenarios

Scenario	Without scheduling		Scheduling with user preferences		Optimal scheduling	
Appliance	Start	finish	start	finish	start	finish
Washing machine	[10:00]	[12:00]	[12:00]	[14:00]	[13:35]	[15:35]
Iron	[20:00]	[20:30]	[18:00]	[18:30]	[15:50]	[16:20]
Hair dryer	[07:00]	[07:30]	[16:00]	[16:30]	[13:05]	[13:35]

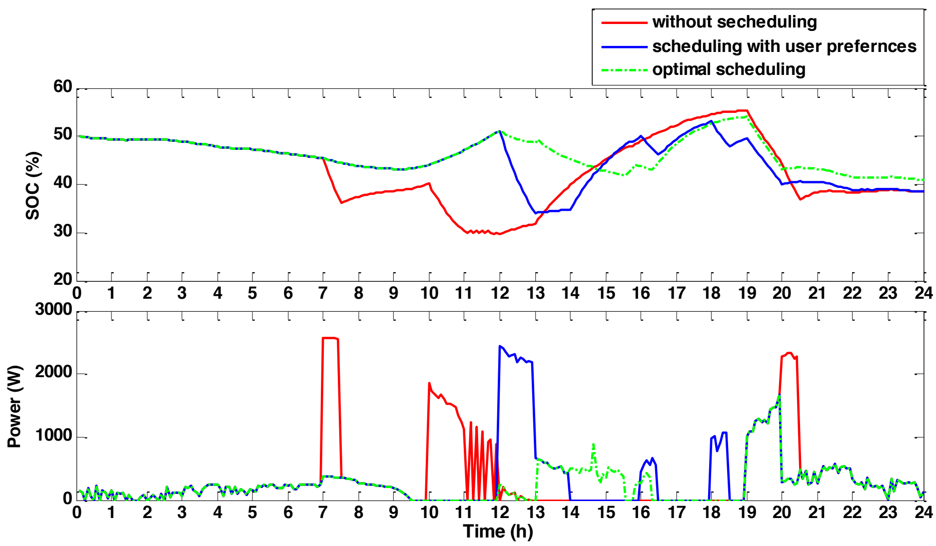

Fig. 9. The SOC and power output of batteries for the three scenarios.

7. Conclusion

In this paper, an optimal scheduling of household appliances in a home connected to a stand-alone renewable energy system (PV, wind turbines, batteries and diesel generators), using the PSO optimization algorithm is presented. Two scenarios of scheduling strategy are proposed and compared with the scenario without scheduling of household appliance. The simulation results showed that the optimal scheduling of the household appliances can save energy and reduce the energy cost of the system (avoiding the running of the diesel generator) by optimizing using the energy of batteries and maximizing using of renewable energy.

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