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Energy Scheduling for Island Microgrid Applications

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Abstract: The paper considers the calculation of an effective energy schedule in an islanded microgrid. GridLab-D open source simulation tool is used for simulation of microgrid elements. Matlab environment is used to run an optimization solver. The product GridMat is used as an interface tool between Matlab and GridLab-D. An economic scheduling optimization problem for the considered microgrid is formulated and solved. Analysis of the obtained results is presented.

Key words: Microgrids, GridLab-D, GridMat, Matlab, energy scheduling optimization.

1. Introduction

A microgrid is a low-voltage distribution system, integrating DERs (distributed energy resources) or RES (renewable energy sources) and controllable loads, which can be used/controlled in either islanded or grid-connected mode [1]. In the first case the microgrid is disconnected from the main grid and it needs to integrate an IPP (independent power producer), for example a diesel generator. In the second case the microgrid is connected to the main grid (the Network) which allows to share the power generation through buying or selling energy.

DERs/RES may include for example energy storages/batteries, solar/photovoltaic panels, micro hydro, wind turbines, etc. The distributed/renewable energy resources (generators) and storage systems make the microgrid more secure and reliable, for instance, in case of disasters such as earthquake, which might cause a lengthy power outage in electrical power grid. On the other hand, the microgrid should be robust in controlling supply, demand, voltage and frequency [2].

The DERs/RES production plan can be estimated by using meteorological forecasts, which have an intrinsic uncertainty. In such a setup, adding energy storage gives flexibility to the energy system [3]. The timely produced satellite meteorological forecasts can ensure enough time for specialists in the area to formulate and to solve corresponding optimization tasks. The optimal battery schedule may lead to minimal energy consumption from the main grid and to reduced environment impact/pollution (for example minimizing the exploitation of diesel generators).

This paper is an extended version of Ref. [4]. Here the microgrid economic scheduling is studied, i.e. the problem to optimize the energy storage/battery schedule, as well as the schedule of the diesel generator used, covering the time-varying energy demand and operational constraints while minimizing the costs of internal generated energy.

The experimental setup consists in a simple microgrid, including photovoltaic system, wind turbine, diesel generator and three houses. In this study the microgrid's PCC (point of common coupling) is disconnected from the main grid and the microgrid operates in an island mode. When formulating an optimization task the amount of power demand and the supply for the next 24 hours period are presumed to be known and without any change. This is an unrealistic setup, especially in real world applications. For example, there could appear great fluctuations in the wind generators output. The solar radiation

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forecasts could also be inexact and could vary essentially. For this reason the energy, generated by the diesel generator should include a reserve rate (see Refs. [5, 6]) and the forecasted data for each microgrid element — for the renewable energy resources (wind turbine and photovoltaic system), and a safe margin should be added for the loads (houses). The optimized safe margins values obtained in Ref. [5] for a similar microgrid are used here, in the formulation of a realistic optimization problem.

The open source GridLab-D (see Ref. [7]) is used to simulate all the elements of the microgrid. The software product GridMat (see Refs. [2, 8]) is used as an interface tool between Matlab (see Ref. [9]) and GridLab-D. Climate data, available on the official website of GridLab-D, are used for the simulations. The optimization problem is formulated and solved in an efficient way by using the Matlab optimization toolboxes/solvers.

The paper is organized as follows: Section 2 considers the microgrid structure; Section 3 devotes to the simulation and optimization tools used in this study; Section 4 presents the optimization model for the economic energy scheduling; Section 5 presents the results obtained, from the simulation and the optimization; Some conclusions are drawn in Section 6.

2. The Experimental Microgrid

The microgrid studied in this work, is composed by several units which produce, exchange and consume energy. Essentially, the microgrid operates with a three-phase medium voltage AC (alternating current) transmission system, which can be connected or not, to the main grid (Network) through a transformer system, in order to buy the energy necessary to cover the demand, or sell the surplus energy produced by the RES. When the microgrid is used in an Island mode (disconnected from the Network), a diesel generator is considered in order to supply, together with the RES, the energy necessary to cover the loads. Two types of RES are considered connected in the Microgrid: 1) a photovoltaic system, composed by an inverter and a group of solar panels, and 2) a wind turbine. A group of batteries (energy storage system) is also interconnected to the microgrid through a DC/AC bi-directional inverter: these batteries can modify their own schedule of charge/discharge in order to meet the needs of the microgrid. This special part makes the microgrid under study a smart microgrid, since the schedule of batteries is based on the behavior of the loads and the energy production by the RES. The system configuration of the proposed microgrid is presented on Fig. 1.

Simulations performed and the formulated optimization task are considered only for a microgrid operating in Island (isolated) mode. Thus a diesel generator is included in the microgrid.

The components composing the microgrid are:

• *Houses*. Some parameters have been fixed, such as the floor area, cooling and heating systems and their set-points. The GridLab-D simulation tool, used in this study has the advantage to have default values for the systems used in the houses simulation; therefore,

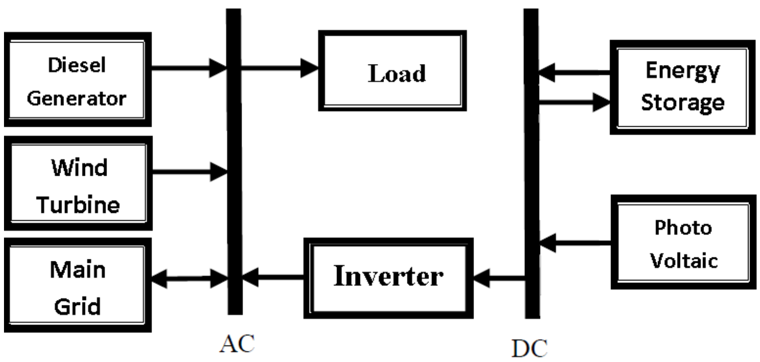

Fig. 1 Microgrid system configuration.

for all parameters, which are not explicitly defined, the default value is used. Here is used a group of three houses, each connected to one phase of the transmission system; this approach is used in order to reduce the imbalance of the load between the phases of the microgrid.

• *Photovoltaic*. The photovoltaic power system is composed by solar panels and inverter (for connecting the system to the AC network with the loads). The parameter which has the greatest impact on the power production is the area of the whole photovoltaic system. In the concrete case, the area of all solar panels is set to 1,500 ft^2. This value corresponds to a produced power with peak around 25-30 kW (the value is obtained from the simulations).

• *Wind turbine*. A specific model of the wind turbine is used here: "*Bergey 10 kW*". By means of command "*Turbine Model*" in the GridLab-D code, and specifying the concrete wind turbine model, the turbine parameters upload automatically their default values.

• *Battery*. For the simulations the battery block (batteries + AC/DC inverter) is considered as not connected to the microgrid, since the behavior of the battery system is unknown and the battery schedule should be calculated by a Matlab solver to solve the correspondent optimization task. The battery system is composed by a battery block (with maximum energy storable of 100 kWh) and an inverter for the charge/discharge of the battery (with maximum power of 10 kW).

• *Diesel generator*. Here is used a 35kw/44kVA KOHLER Systems diesel generator (engine type: 3029TF120, class G3). This diesel generator has a rated power of 38 kW and a rated voltage of 400/230 V (see http://www.kohlerpower.com.sg/industrial/detail.htm?sectionNumber=13261&categoryNumber=11961&prodnum=248461).

The experimental microgrid used is shown in Fig. 2.

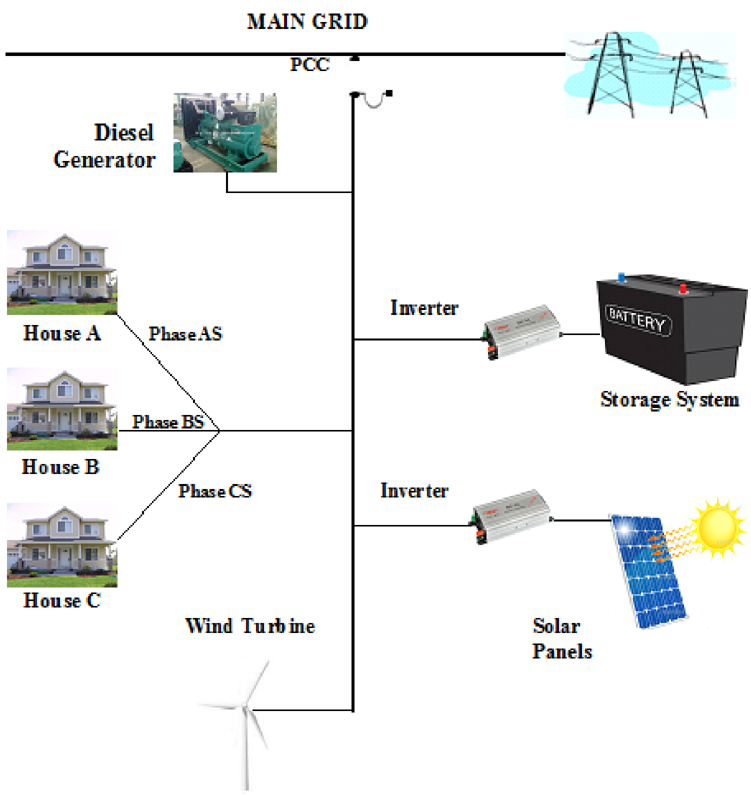

Fig. 2 The experimental microgrid.

3. Simulation and Optimization Tools

3.1 MATLAB Environment for Microgrid's Analysis

In this study the solver "**fmincon**" from "Optimization Toolbox" in the software environment MATLAB is used.

3.2 Simulation Tool GridLab-D

Modeling complex, large-scale, heterogeneous, multiphysics, multi-domain, and distributed system, such as a microgrid, requires heterogeneous composition of physical, computational and communication sub-systems [8, 10]. Simulation tool, corresponding to these needs, is GridLab-D. It was developed by the U.S. DOE (Department of Energy) at PNNL (Pacific Northwest National Laboratory) under funding for Office of Electricity in collaboration with industry and academia [7] and it is a sponsored open-source, multi-domain modeling (power, weather, market) and simulation (it uses discrete event-based model of computation) tool for power systems (particularly suitable for distribution grid). GridLab-D incorporates the most advanced modeling techniques, with high-performance algorithms to deliver the best in end-use modeling. For the above reasons this tool is used here.

3.3 The Tool GridMat

GridLab-D is limited in supporting advanced control algorithm development and does not provide a user friendly interface for modeling the structural and behavioral aspects of a residential Microgrid. Therefore, a new Matlab toolbox is created (see Ref. [8]) to integrate the capabilities of domain-specific modeling and simulation tools for power system (GridLab-D) and control (Matlab). The new toolbox, called GridMat, is an open-source tool, used for academic and research activities. This tool supports user friendly model creation, robust debugging, and intelligent grid impact analysis utilities [8, 11]. It can be used to facilitate the control engineers in developing advanced and hierarchical control algorithms for a residential microgrid. For these reasons it is used here.

4. Economic Scheduling Optimization Model

In this study the behavior of the RES and houses has been simulated from historical climate data of a particular geographical position: Seattle (USA); the data for solar radiation and wind speed, as well for the houses energy consumption are real data for a given winter day. They are taken as forecasted data.

The experimental results in Ref. [5] about the energy safety margins, used to cover the uncertainty of the forecasted data are presented in Table 1 as follows.

Taking into account these margin values, the following values are assumed in the defined optimization model: Wind turbine: (−30%); Photovoltaic: (−37%); Houses: (+25%); Diesel generator: (+20%). This means that (the energy produced by the diesel generator + the energy of battery discharge) should be equal to 120% of the energy necessary to cover the difference between the 125% of (houses forecast + energy of battery charge) and (70% of wind forecast + 63% of solar forecast), in order to cover the energy fluctuations due to forecast uncertainty, which could eventually arise. Having available correct forecasted data for the RES production and houses consumption a day before, it will be possible to optimize the microgrid behavior for the whole year, solving one day ahead the correspondent next day scheduling optimization problem.

The time interval being analysed (one day and one night) is divided by 24 time steps, each with 1 hour length. Formulated optimization problem has the form:

Table 1 Safety margin combination.

Margins [%]	Wind turbine margin	Photovoltaic margin	Demand margin	Reserve margin
Obtained by trial and error	30.2	36.6	25.5	20.0

The balance power P_B of the studied microgrid should satisfy the following equations (see Ref. [6]):

$$P_{RES} + P_B = P_L \quad (1)$$

$$P_B = P_{Bat\_d} + P_{DG} \quad (2)$$

where P_{RES} is the output power of renewable energy sources, P_B is the balance power, P_{Bat_d} is the power from discharging the battery system, P_{DG} is the output of the diesel generator, and P_L is the microgrid load, equal to houses consumption energy plus battery system charging energy.

The parameters and the decision variables used in the proposed formulation are presented in Table 2.

The objective function, which has to be minimized, consists of the cost of microgrid balance power.

Objective function:

$$F = \sum_{t=1}^{24}(C_t.P_{Bt}) = \sum_{t=1}^{24} CC_{DG}(t) + OM_{DG}(t) + FC_{DG}(t) + + EC_{DG}(t) + \sum_{t=1}^{24} OM_{Bat}(t) + RC_{Bat}(t) + CC_{Inv}(t) \quad (3)$$

where P_{Bt} is the balance power for hour t and C_t is the cost of this power. In C_t are included the deprecations costs of each microgrid energy generation element (unit), of individual units' operational costs, of the fuel cost (for the fuel consumed by the diesel generator), and of emission cost. It should be taken into account that the photovoltaic area, the wind turbine capacity, as well as the house energy consumption, cannot be subject to optimization since their schedules are independent. F is calculated only for the hours, when the diesel generator operates and when the battery system is charging/discharging. In Refs. [12, 13] formulas for calculating the correspondent annual values are given. Hence, the hourly capital cost of microgrid units, which do not need a replacement during the project life time, such as diesel generator and inverter, is calculated as follows:

$$CC_{DG} = \frac{Ccap_{DG}.\mathrm{CRF}(i, \mathrm{y})}{5375} \quad (4)$$

Assuming, that the diesel generator is used in average 15 hours per 24 h period, the denominator is: 5,375 = 15 × 365.

$$\mathrm{CRF}(i, \mathrm{y}) = \frac{i.(1+i)^{\mathrm{y}}}{(1+i)^{\mathrm{y}} - 1} \quad (5)$$

where, $Ccap_{DG}$ is the capital cost (US$), y is the project life time, and i is the annual interest rate.

The annual interest rate is calculated as follows [14]:

$$i = \frac{i' - f}{1 + f} \quad (6)$$

where: i' is the loan interest (%), and f is the annual inflation rate (%).

The operation maintenance cost per hour is:

$$OM = \frac{Ccap_{DG}.(1-\lambda)}{5375.\mathrm{y}} \quad (7)$$

for the diesel generator, and

$$OM = \frac{Ccap_{Bat}.(1-\lambda)}{6570.\mathrm{y}} \quad (8)$$

for the battery, where: λ is the reliability of the correspondent unit.

Assuming, that the battery bank is used in average for 18 hours per 24 h period (i.e. 365 × 18 = 6,570 hours annually), one hour battery bank replacement cost is:

$$RC = \frac{Crep_{Bat}.\mathrm{SFF}(i, y_{rep})}{6570} \quad (9)$$

where: $Crep$ is the replacement cost of battery bank, and SFF is the sinking fund factor, which is calculated as follows [14]:

$$\mathrm{SFF} = \frac{i}{(1+i)^{\mathrm{y}} - 1} \quad (10)$$

The fuel cost of diesel generator per hour for the hour t is:

$$FC = Cf.G(t)$$

Table 2 Parameters.

Parameter	Description
CC	Capital cost for interval of 1 hour
OM	Operation maintenance for 1 hour
RC	Replacement cost (of the battery)
FC	Fuel cost for interval of 1 hour
EC	Emission cost for interval of 1 hour
CRF	Capital recovery factor for 1 hour
SFF	Sinking fund factor for 1 hour

where: Cf is the fuel cost per liter, and $G(t)$ is the hourly consumption of diesel generator. $G(t)$ is calculated in Refs. [12, 13, 15, 16] as follows:

$$G(t) = (0.246P_{DG}(t) + 0.08415.P_R) \quad (11)$$

where: $P_{DG}(t)$ is the diesel power at time t, and P_R is the rated power of the diesel generator.

The hourly emission cost (CO_2 emission) is:

$$EC(t) = \frac{E_f.E_{cf}.P_{DG}(t)}{1000} = 0{,}0187.P_{DG}(t) \quad (12)$$

where: E_f is the emission function (kg/kWh), and E_{cf} is the emission cost factor ($/ton).

The economic data are given in Table 3.

Other parameters to be defined are the Pbt_max, fixed to 10 kW for charging and discharging, and E_{bt_max}, fixed to 100 kWh. The data in Table 3 are taken from Ref. [12], only the fuel cost value is taken from Ref. [13]. Since P_R = 38, hence $Ccap_{DG}$ = 19,000 $. In Ref. [6] is stated, that the high speed (3,600 r/min), air-cooled diesel can be used for about 20,000 h. Hence y in Eqs. (5), (7) and (8) is: y = 3.721. The annual interest rate i = 0.53846154. Hence CRF(i, y) = 0.6742. CC_{DG} = 2.38 $/h. OM_{DG} = 0.095 $/h. OM_{Bat} = 0.0061 $/h. $Crep_{Bat}$ = 20,000 $. SFF = 0.1357. RC = 0.413 $/h. $Ccap_{Inv}$ = 10,000. The inverter hourly capital cost is: CC_{Inv} = 1 $/h.

Hence, the objective Eq. (3) is presented in the form:

$$F = \sum_{t=1}^{24} 2{,}38_{DG}(t) + 0{,}095_{DG}(t) + 0{,}1845.P_{DG}(t) + 2{,}398_{DG}(t) + \\ + 0{,}0187.P_{DG}(t) + \sum_{t=1}^{24} 0{,}274_{Bat}(t) + 0{,}413_{Bat}(t) + 1_{Inv}(t) \quad (13)$$

Constraints:

The constraints concerning the diesel generator are [17]:

$$0.3.P_R \le P_{DG}(t) \le P_R \quad (14)$$

Taking into account the modified values from Table 1, the following constraint is obtained:

$$P_{DG}(t) = \begin{cases} 1{,}2.(1{,}25.P_L - 0{,}63.P_{PV} - 0{,}7.P_{WT} - P_{Bat\_d}) \\ \quad if\ 0{,}63.P_{PV} + 0{,}7.P_{WT} + P_{Bat\_d} < 1{,}25.P_L \\ 0. \quad \text{otherwise} \end{cases} \quad (15)$$

The constraints for the battery system are:

$$-P_{BT\_MAX} \le P_{\mathrm{BAT}}(T) \le +P_{BT\_MAX} \quad (16)$$

$$SOC_{MIN} \le SOC(I) \le SOC_{MAX} \quad (17)$$

$$\sum_{t=1}^{24} P_{Bat}(t) = 0; \quad t = 1,...,24; \quad (18)$$

where: $P_L(t)$ is the power absorbed by the houses during the hour "t"[kW]; $P_{PV}(t)$ is the power delivered by photovoltaic panels during the hour "t" [kW]; $P_{WT}(i)$ is the power delivered by wind turbine during the hour "t" [kW]; $P_{Bat\_d}(t)$ is the power delivered by the battery block (discharging) during the hour "t" [kW]. *Pbt_max* is the maximum power that the battery system can deliver/absorb [kW]; *SOC(t)* is the State Of Charge of the battery during the hour "t" [%] SOC_{min} = lower limit for the State Of Charge of the battery [%] SOC_{max} = upper limit for the State Of Charge of the battery [%].

Finally, taking into account the energy balance of the microgrid (see Eqs. (1) and (2)), the last constraint obtained is:

$$P_{Bat}(t) + P_{DG}(\mathrm{t}) \ge P_H(t) - P_{PV}(t) - P_{WT}(t)\ , t = 1, ...,24 \quad (19)$$

where $P_H(t)$ is the house consumption energy. The energy $P_{Bat}(\mathrm{t})$ is considered positive when the battery is discharging and negative when is charging. Therefore, Eq. (16) represents the power limit, which can be delivered or absorbed by the inverter tie to the battery system; the system cannot supply or absorb a power more than the *Pbt_max*.

The SOC of the battery represents the amount of energy stored in the battery system. Therefore, Eq. (17) means that, for each time step, the SOC must be

Table 3 The economic data.

Description	Value
Interest rate i' (%)	3
Inflation rate (%)	1.6
Inverter life time (years)	20
Battery life time (years)	10
Reliability of inverter (%)	0.98
Reliability of battery (%)	0.98
Reliability of diesel (%)	0.9
Cost of diesel generator (US$/KW)	500
Cost of battery bank (US$/KWh)	200
Cost of inverter (US$/KW)	1000
Fuel cost (*Cf*) (US$/l)	0.75
Emission function (kg/kWh)	0.34
Emission cost factor (US$/ton)	55

included between a minimum and a maximum value, depending by the system used to store the energy and agrees with the physical limit of maximum SOC of 100%. In this case, the minimum and maximum levels of SOC are fixed to 20% and 100% respectively.

The SOC is depending on the value of P_{Bat}(t) for each time step; the relation between these variables is shown below [18]:

$$SOC(t) = SOC(t-1) - \frac{P_{Bat}(t)}{E_{bt\_\max}}.\Delta t \qquad (20)$$

where: Δt is the time step [h], $SOC(0)$ = Initial charge of the battery (it is an input value of the problem). In this optimization problem, the initial value of the SOC is fixed to 50%. It means that, at the optimization start, the battery system is charged to the half of its full charge.

The constraint, shown in Eq. (18), is used in order to get, at the end of the 24 h period, the same value of SOC like at the begin of the period. Therefore, this value can be used as an input for the optimization task of the next day.

5. Test Results Obtained by Means of Simulation and Optimization Tools

5.1 Simulation Results

The simulations with GridLab-D give the results for the consumption of the houses, the production of the solar panels and wind turbine and the power flow from the diesel generator (in this case the battery system is not presented there). The results obtained from the simulations in a winter day, are shown on Fig. 3.

For simulation purposes, the user can upload the climate data of a particular zone or city, given from an external file with extension "*.TMY2*", where TMY is the acronym of "Typical meteorological year". In this study data are taken for one winter day for the city Seattle (USA)—see HTTPS://SOURCEFORGE.NET/P/gridlab-d/code/4252/tree/course/ThreeDayCourse_v22/Day2/Demos/4.4%20Generator%20Examples/. They correspond to the real data but here they are considered as forecasted data.

The graphics of houses consumption energy, photovoltaic produced energy and wind generated energy are presented on Fig. 4.

5.2 Optimization Results

Eqs. (13)-(19) have 48 variables: $P_{DG}(t)$ and $P_{Bat}(t)$, t= 1, … , 24; to solve this optimization problem, the Matlab solver *FMINCON* has been used. In the "*HELP*" menu in Matlab, in the "Optimization Toolbox" the

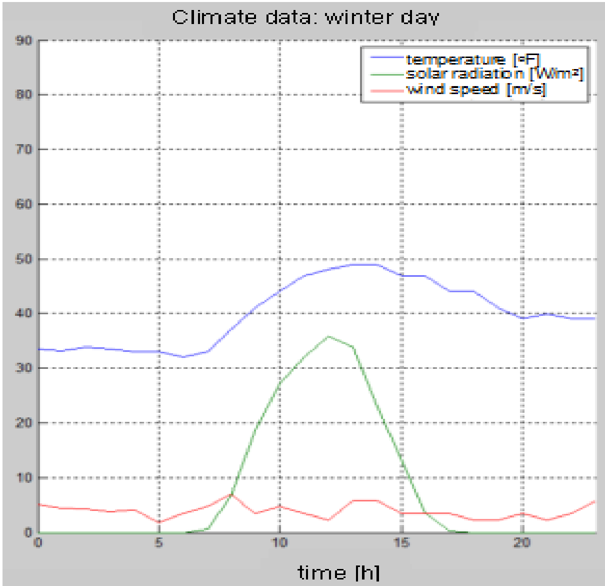

Fig. 3 Climate data trend (temperature, solar radiation and wind speed) in a winter day.

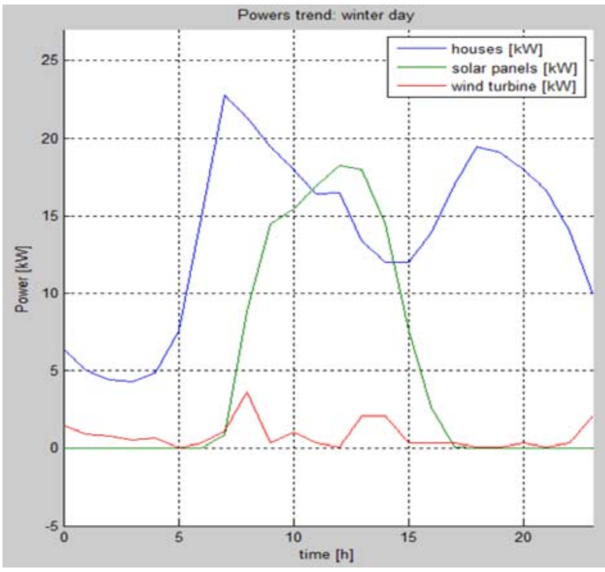

Fig. 4 Houses consumption, solar panels and wind turbine energy generation in a winter day.

description and explanation how to run it is given.

fmincon: It finds the minimum of constrained nonlinear multivariable problem, it accepts a vector x for input and returns a scalar *f* at output.

This solver can use several algorithms to optimize the problem, such as interior point, active set etc. In this case, it has been used the *Active set* algorithm.

After 18 iterations the optimal value of objective Eq. (13), which represents the costs for the diesel generator and the battery system (including the inverter) in [US$] is: $F^* = 205.037$.

The results of running "*FMINCON*" for a winter day using the "*optimtool*" command in Matlab are shown on Fig. 5.

5.3 Analysis of Optimization Results

The first 24 variables on Fig. 5 represent the battery schedule, and the next 24 variables correspond to the diesel generator schedule.

The calculated optimal schedule for the battery system is:

[-10. -10. -100 1.3786 10. -10. -1.1083 10. 10. -10. -10. -10. 9.7297 -10. -10. 10. 10. 10. 10. -10. 10. 10. 10. -10.]

The calculated optimal schedule for the diesel generator is:

[11.4 11.4 11.4 11.4 0. 11.4 22.0169 32.5701 22.3065 17.9062 14.4096 11.5544 0. 11.4 11.4 0. 18.4714 25.1381 29.1214 28.5803 26.6152 24.9310 20.7732 13.0999].

The correspondent energy graphics are presented on Fig. 6.

The optimization result shows, that the total cost for 24h period for a winter day, based on the objective Eq. (13) is: $F = 205.037$. Without optimization for an initial battery schedule: $P_{Bat}(0)$ = [0 0 0 -0.8 -0.8 -0.8 -0.8 -0.8 -1 0 1 1 1 1 1 -0.8 -0.8 -0.8 -0.8 -0.8 -1 1 2 2] the objective function value is $F = 226.717$. Hence, the simultaneous optimization of battery schedule and diesel generator schedule leads to about 10.574% reduction of the costs.

The safety margins in the presented optimization model are necessary to cover the uncertainty of the data in the meteorological forecast, as well as in the data for the load (houses consumption). The graphics of the load (houses consumption) energy and the sum

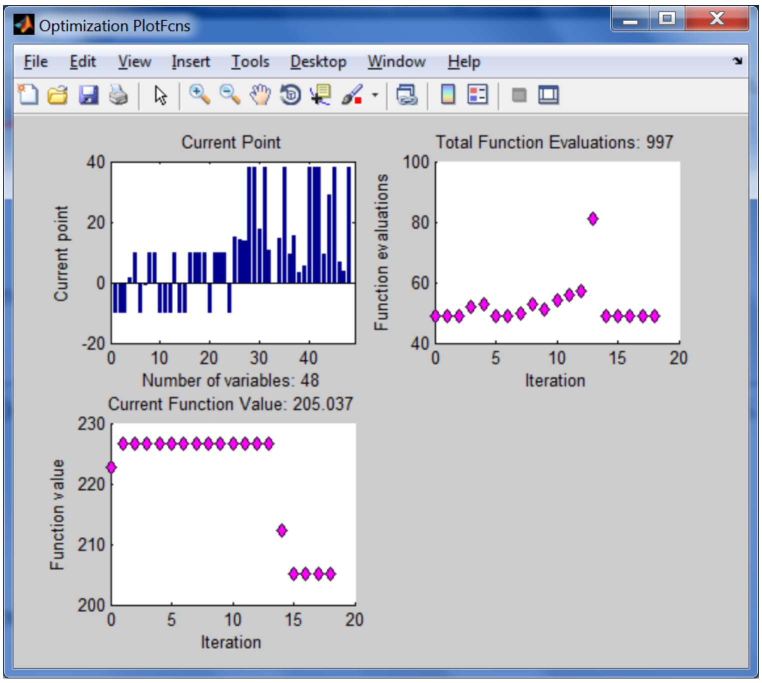

Fig. 5 Optimization results from "fmincon" solver.

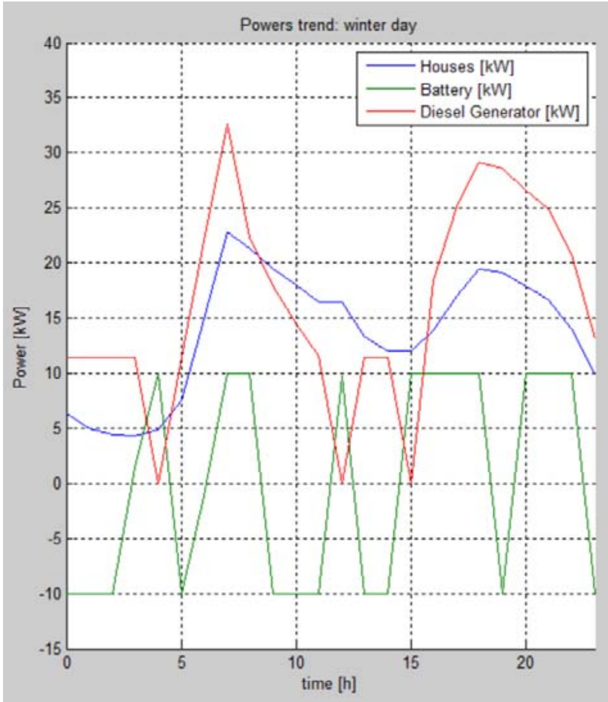

Fig. 6 Graphics of houses consumption, optimized Battery schedule and optimized Diesel generator schedule.

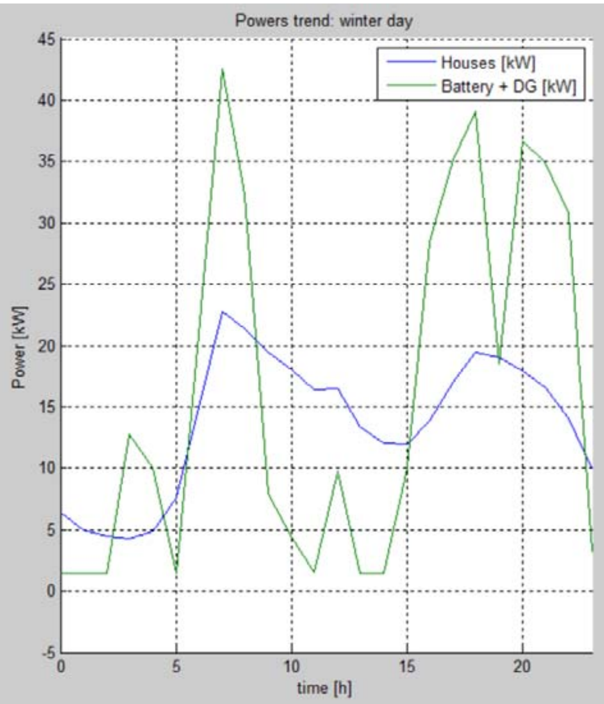

Fig. 7 Graphics of houses consumption, and of sum of Battery and Diesel generator energy.

of both: battery discharging and diesel generated energy are presented on Fig. 7 as a final comparison. The intervals, where the Load energy exceeds the sum of Battery + Diesel generator are covered by the energy generated by the photovoltaic system and by the wind turbine.

The connection of a battery system to the microgrid can provide benefits (absorbing energy when the production from RES is more than the consumption, and supplying energy to the main grid when the consumption is less than the produced by RES and stored by the battery energy). In case the microgrid operates in a grid connection mode, this may lead to economic benefits by selling energy to the main grid in case of surplus of production by the RES. This possibility can be taken into account and new optimization tasks could be formulated. This is one direction for further research activities. In the case considered here, the selling of energy to the main grid is impossible, because the experimental microgrid operates only in an isolated mode.

6. Conclusion

In this paper an optimization of a battery and diesel generator schedule in a microgrid is presented. Using the solution for the schedules two goals are achieved: 1) It is guaranteed that the load demand is covered by reserve high enough. 2) The optimization leads to 10.574% reduction of the costs. The result obtained shows, that by means of optimal battery and diesel generator schedules, a real safety margin concerning the system load is achieved. Additionally the costs for the end user are essentially reduced. Minimizing the objective function, the fuel consumption by the diesel generator is also minimized. In this way the harmful impact on the environment is reduced. The approach presented here is very promising and can be applied successfully, not only in rural regions, but also in big cities.

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