Economic Energy Scheduling of an Islanded Microgrid

Galia Marinova[1] and Vassil Guliashki[2]

Abstract – **This paper considers the calculation of an effective energy schedule in an islanded microgrid. GridLab-D open source simulation tool is used to 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 on the considered microgrid is formulated and solved.**

Keywords – **Microgrids, GridLab-D, GridMat, Matlab, Energy scheduling optimization.**

I. Introduction

A microgrid represents a low-voltage distribution system consisting of distributed energy resources (DERs) or renewable energy resources (RES) and controllable loads, which can be used/controlled in either islanded or grid-connected mode. The microgrid should be robust in controlling supply, demand, voltage, and frequency. The DERs/RES production plan can be evaluated by using meteorological forecasts, which have an intrinsic uncertainty. In such a setup, energy storage can help in meeting the hourly production plan [2].

In this paper the microgrid economic scheduling is studied, i.e. the problem to optimize the energy storage/battery schedule, as well 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 microgrid includes a photovoltaic system, a wind turbine, a diesel generator and three houses. The microgrid's point of common coupling (PCC) is disconnected from the main grid and the microgrid operates in an island mode. Formulating an optimization task the amount of power demand and supply for the next 24 hour period may be assumed to be known without any change. This is an unrealistic setup, especially in real world applications.. Also the solar radiation forecasts could be inexact and could vary essentially. For this reason the energy, generated by the diesel generator should include a reserve rate (see [5, 6]) and the forecasted data for the renewable energy resources (wind turbine and photovoltaic system), as well as for the loads (houses) should be taken adding a safe margin for each microgrid elemet.

The open source GridLab-D (see [3]) is used to simulate all the elements of the microgrid. The software product GridMat (see [1]) is used as an interface tool between Matlab (see [4]) 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.

[1]Galia Marinova is with the Faculty of Telecommunications at Technical University of Sofia, 8 Kl. Ohridski Blvd, Sofia 1000, Bulgaria, E-mail: gim@tu-sofia.bg.

[2]Vassil Guliashki is with the Institute of Information and Communication Technologies – BAS, “Acad. G. Bonchev” Str. Bl. 2, 1113 Sofia, Bulgaria, E-mail: vggul@yahoo.com.

II. 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 alternating current (AC) 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 type 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. This is exactly the part that 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:

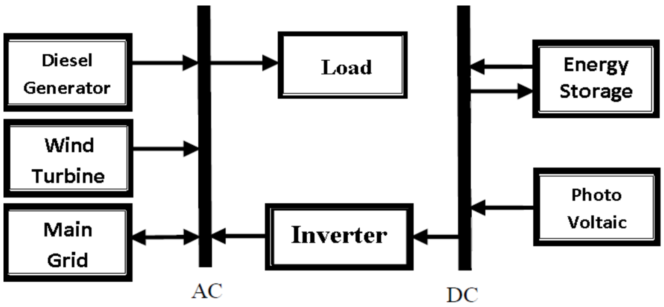

Fig. 1. Microgrid system configuration

The microgrid with all its components is shown on Fig 2.

III. Economic scheduling optimization model

It 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 a forecasted data.

In [5] are given energy safety margins necessary to cover the uncertainty of the forecasted data. Taking into account these margin values, in the created optimization model are assumed the following values: Wind turbine: (–30%) ;

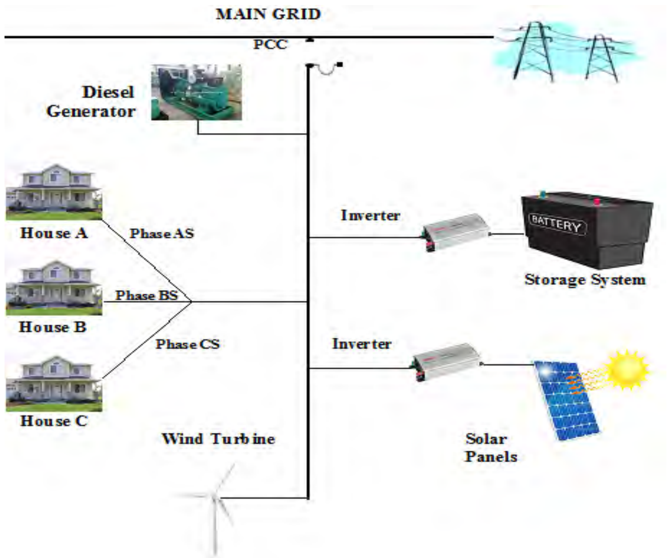

Fig. 2. The experimental microgrid

Photovoltaic: (–37%); Houses: (+25%); Diesel generator: (+20%). Having available correct forecasted data for the RES production and houses consumption one day before for the next day, it is possible to optimize the microgrid behavior for a whole year, solving one day ahead the correspondent scheduling optimization problem for the next day.

The time interval being analysed (one day and one night) is divided by 24 time steps, each with 1 hour length. The balance power P_B of the studied microgrid should satisfy the following equations (see [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 are presented in Table 1.

TABLE 1. PARAMETERS

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

Taking 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, the objective function includes the balance power:

$$\min\ \boldsymbol{F} = $$

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

$$+ \sum_{t=1}^{24} OM_{Bat}(t) + RC_{Bat}(t) + CC_{Inv}(t)$$

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 operational costs of individual units, of the fuel cost (for the fuel consumed by the diesel generator), and of emission cost. Calculating $\boldsymbol{F}$ only the hours, when the diesel generator operates and when the battery system is charging/discharging are taken into account. In [9, 10] are given formulas for calculating the correspondent annual values. Hence the one hour capital cost of microgrid units, which do not need a replacement during the project life time, such like 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 average 15 hours in a 24 h period, the denominator is: 5375 = 15 × 365;

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

Here $Ccap_{DG}$. is the capital cost (US$), y is the project life time, and i is the annual interest rate [11]:

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

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

The one hour operation maintenance cost 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 correspondent unit.

Assuming, that the battery bank is used average 18 hours in a 24 h period (i.e. 365 × 18 = 6570 hours annually), the 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 [11]:

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

The one hour fuel cost of diesel generator for hour t is:

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

where: Cf is the fuel cost per liter, and $G(t)$ is the hourly consumption of diesel generator [7, 8, 9, 10] 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:

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

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

The necessary economic data are given in Table 2:

Table 2. THE ECONOMIC DATA

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

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 [9], only the fuel cost value is taken from [10]. Since P_R = 38, hence $Ccap_{DG}$ = 19000 $. In [6] is stated, that the high speed (3600 r/min), air-cooled diesel can be used for about 20 000 h. Hence y in formulas (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. $Crep_{Bat}$ = 20000 $. SFF = 0,1357. RC = 0,413 $/h. $Ccap_{Inv}$ = 10000. The inverter one hour capital cost is: CC_{Inv} = 1 $/h.

Hence the objective function (3) is presented in the form:

$$\min \boldsymbol{F} =$$

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

$$+\ 0{,}0187.P_{DG}(t) + \sum_{t=1}^{24} 0{,}274_{Bat}(t) + 0{,}413_{Bat}(t) + 1_{Inv}(t)$$

The constraints concerning the diesel generator are:

$$0{,}3.P_R \le P_{DG}(t) \le P_R \quad (14)$$

Taking into account the modified values from [5], the following constraint is obtained:

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

The constraints concerning 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 equations (1)-(2)), the last constraint obtained is:

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

where $P_H(t)$ is the house consumption energy. The energy $P_{Bat}(t)$ is considered positive when the battery is discharging and negative when is charging. Therefore, the equation (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, the equation (17) means that, for each time step, the SOC must be included between a minimum and a maximum value depending by the system used to storage the energy and agree with physical limit of maximum SOC of 100%. In this case, the minimum and maximum level 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:

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

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 begin of the optimization, the battery system is charged to the half of its full charge.

The constraint, shown in equation (18), is used in order to get, at the end of the 24h period, the same value of SOC like at the begin of the period.

IV. TEST RESULTS OBTAINED BY MEANS OF THE SIMULATION AND THE OPTIMIZATION TOOLS

The simulations with GridLab-D give the results about the consumption of the houses, the production of the solar panels and wind turbine. The results obtained from the simulations, for a winter day, are shown on Fig. 3.

The problem (13)-(19) has 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 description and explanation how to run this solver is given.

The first 24 variables on Fig. 4 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 optimization result shows, that the total cost for 24h period for a winter day, based on the objective function (13) IS: $\boldsymbol{F}$ = 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

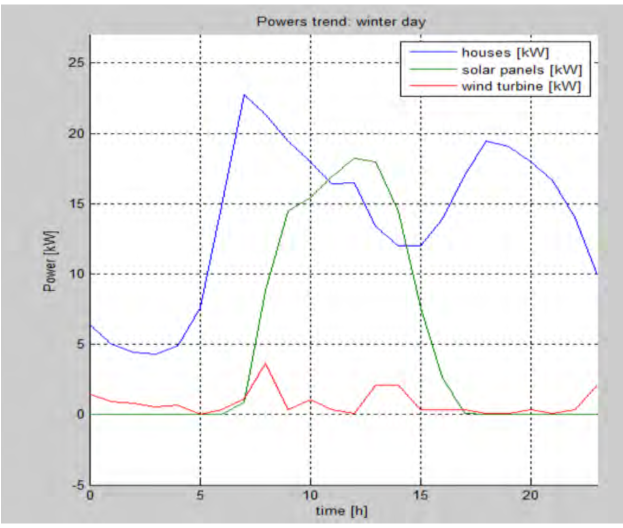

Fig 3. Houses consumption, solar panels and wind turbine energy generation for a winter day

The results of running "*fmincon*" for a winter day using the "*optimtool*" command in Matlab are shown on Fig. 4.

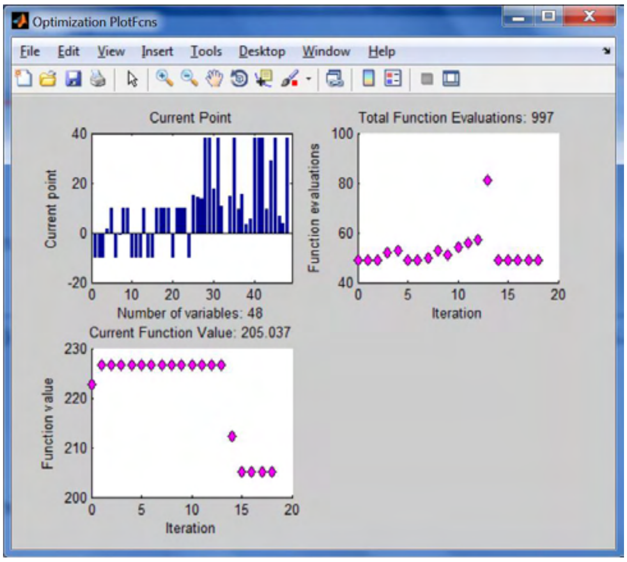

Fig. 4. Optimization result from "*fmincon*" solver

-0.8 -0.8 -0.8 -0.8 -0.8 -1 1 2 2] the objective function value is ***F*** = 226,717. Hence the optimization of battery schedule and diesel generator schedule simultaneously leads to about 10,574% reduction of necessary costs.

V. Conclusion

An optimization of a battery and diesel generator schedule in a microgrid is presented in this paper. Using the solution for the schedules two goals are achieved: 1) It is guaranteed that the load demand is covered by an enough high reserve. 2) The optimization leads to 10,574% reduction of the necessary costs. At the same time the costs for the end user are essentially reduced. Minimizing the objective function, the fuel consumption by the diesel generator is minimized, as well and the harmful impact on the environment is also reduced.

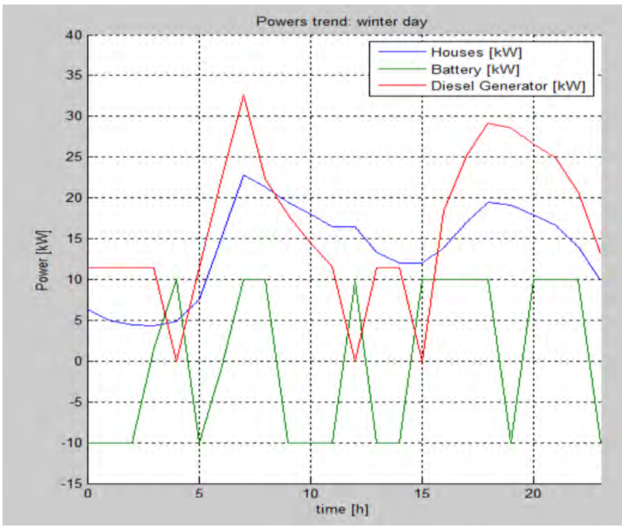

Fig. 5. Graphics of Houses consumption, optimized Battery schedule and optimized Diesel generator schedule

References

[1] Al Faruque M. A., F. Ahourai : "GridMat: Matlab Toolbox for GridLAB-D to Analyse Grid Impact and Validate Residential Microgrid Level Energy Management Algorithms", IEEE PES Conference on Innovative Smart Grid Technologies (ISGT'14), Washington DC, USA, February 2014. http://aicps.eng.uci.edu/papers/GridMat-ISGT-2014.pdf

[2] Marinelli M., "Testing of a Predictive Control Strategy for Balancing," *IEEE TRANSACTIONS ON SUSTAINABLE ENERGY*, 2014.

[3] Chassin, D. P., "GridLAB-D: An agent-based simulation framework for smart grids," 13 May 2014.

[4] Matlab, [Online]. http://www.mathworks.com/products/matlab/

[5] Chang G. W, H. J. Lu, H. J. Su, "Short-term Distributed Energy Resource Scheduling for a DC Microgrid," *Energy and Power Engineering*, 2013, vol. 5, pp. 15-21.

[6] Xiao J., L. Bai, F. Li, H. Liang, and C. Wang, "Sizing of Energy Storage and Diesel Generators in an Isolated Microgrid Using Discrete Fourier Transform (DFT)", *IEEE Transactions on Sustainable Energy*, Vol. 5, No. 3, July 2014

[7] Dufo-Lopez R. and J. L. Bernal-Agustin, "Multi-objective design of PV-Wind-Diesel-Hydrogen-Battery systems", accepted for publication in *Renewable Energy* (http://www.sciencedirect.com/science/journal/09601481)

[8] Skarstein O, Ulhen K., "Design Considerations with Respect to Long-Term Diesel Saving in Wind/Diesel Plants", *Wind Engineering* 1989; 13(2):72–87.

[9] Luu, N. A., "Control and management strategies for a microgrid", Ph.D. Thesis, Université de Grenoble, France, 18.12.2014, https://tel.archives-ouvertes.fr/tel-01144941/document

[10] Seryoatmojo H., A. A. Elbaset, Syafaruddin and T. Hiyama, Genetic Algorithm based optimal sizing of PV-Diesel-Battery System, Considering CO2 Emission and Reliability, *International Journal of Innovative Computing, Information and Control*, Vol. 6, No. 10, October 2010, 1-09-0844, ISSN: 1349-1198.

[11] Diaf S., M. Belhamelb, M. Haddadic, A. Louchea, Technical and economic assessment of hybrid photovoltaic wind system with battery storage in Corsica Island, *Energy Policy*, 36 (2) (2008), pp. 743-754