Designing a Micro-grid to Optimize the Energy Storage Capacity using GridLab-D

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ABSTRACT: *We in this work have designed a micro-grid to optimize the energy storage capacity. For this exercise we have used an open source tool called GridLab-D for simulation of micro-grid elements. We have use the Matlab environment to run the optimization solver. We have also deployed the GridMat as the interface between Matlab and GridLab-D. To run the experiment, we have test eight different scenarios. Using optimization methods, we have used economic scheduling optimization problems on the micro-grid. The experimental results are analysed and presented in detail in this paper.*

Keywords: Microgrids, GridLab-D, GridMat, Matlab, Energy Scheduling Optimization

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1. Introduction

A microgrid is a low-voltage distribution system, integrating distributed energy resources (DERs) or renewable energy sources (RES) and controllable loads, which can be used/controlled in either islanded or grid-connected mode. In this paper an islanded microgrid is studied. DERs make the microgrid more secure and reliable in cases of disasters, such as earthquake, which might cause a long time power outage in electrical power grid. On the other hand the microgrid should be robust in controlling supply, demand, voltage, and frequency. The DERs production plan can be evaluated by using meteorological forecasts. In this case the use of energy storage (battery bank) can help in meeting the hourly production plan, providing the additional necessary energy to cover the peak load demand [2]. The capacity of the energy storage is limited and for the time when DERs cannot generate enough energy an independent from the main grid energy source, such like diesel generator is necessary.

Proper selection and optimal sizing of the energy storage is an important task in design of microgrids. The optimal battery bank capacity will allow a minimization of the fuel consumption by the diesel generator and reducing the harmful impact on the environment. At the same time the costs for the end user can be essentially reduced. To optimize the energy storage size eight scenarios with different battery bank capacity are considered. The corresponding optimization problems are based on an economic model for battery bank and diesel generator scheduling, similar to the model presented in [12,13]. The experimental microgrid setup includes a photovoltaic system, a wind turbine, a diesel generator and three houses. The considered microgrid operates in an island mode, i.e. its point of common coupling (PCC) is disconnected from the main grid. To formulate an optimization task the exact amount of power demand and power supply for the next 24 hours period should be known. This is a heavy requirement, especially in real world applications. For example, there could appear great fluctuations in the wind generators output. The solar radiation 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 [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 element.

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 solved by using the Matlab optimization toolbox.

2. The Experimental Microgrid

The microgrid studied in this work operates with a threephase medium voltage alternating current (AC) transmission system 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. The use of optimal battery bank schedule makes the microgrid under study a *smart* microgrid, since it ensures the balance between the loads and the energy produced by the RES, and allows the minimization of fuel consumption by the diesel generator. The system configuration of the microgrid is presented on Figure 1.

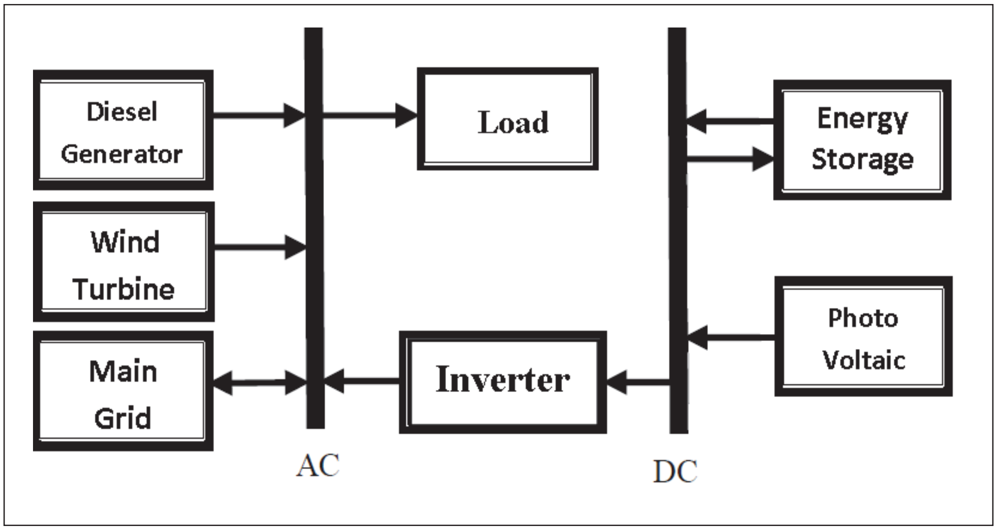

Figure 1. Microgrid system configuration

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

3. Economic Scheduling Optimization Model

It this study the behavior of the RES 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.

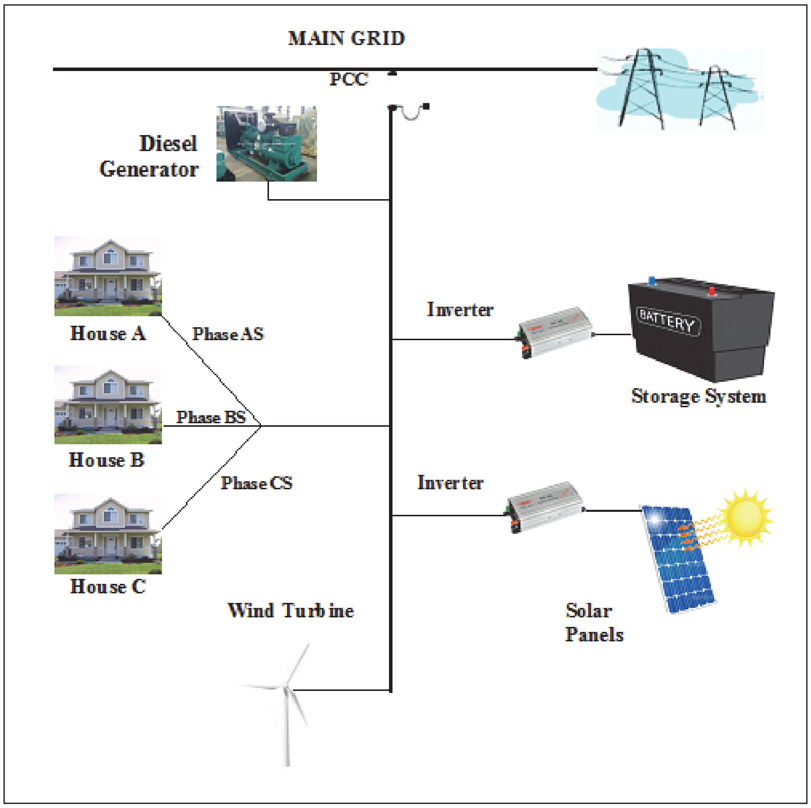

Figure 2. The experimental microgrid

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%) ; 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]):

$$P_{RES} + P_B = P_L \tag{1}$$

$$P_B = P_{Bat\_d} + P_{DG}\,, \tag{2}$$

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.

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:

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

Parameter	Description
CC	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

Table 1. Parameters

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 ***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:

$$CC_{DG} = \frac{Ccap_{DG}.\mathrm{CRF}(i, \mathrm{y})}{5475}, \tag{4}$$

Assuming, that the diesel generator is used average 15 hours in a 24 h period, the denominator is: 5475 = 15 × 365;

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

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

$$i = \frac{i' - f}{1 + f} \tag{6}$$

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

The one hour operation maintenance cost is:

$$OM = \frac{Ccap_{DG}.(1-\lambda)}{5475.\mathrm{y}} \tag{7}$$

for the diesel generator, and

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

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 x 18 = 6570 hours annually), the one hour battery bank replacement cost is:

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

where: *Crep* is the replacement cost of battery bank, and SFF is the sinking fund factor, which is calculated as follows [11]:

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

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:

$$G(t) = (0{,}246P_{DG}(t) + 0{,}08415.P_R) \qquad (11)$$

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:

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

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:

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

Table 2. The Economic Data

Detailed data about the microgrid components are given in [13]. The data in Table 2 are taken from [9], only the fuel cost value is taken from [10]. Other parameters to be defined are the energy amount for charging and discharging: *Pbt_max*, and the maximal battery bank capacity E_{bt_max}. Since $PR = 38$, hence $Ccap_{DG} = 19000$ \$. In [6] is stated, that the high speed (3600 r/min), air-cooled diesel can be used for about 20000 h. Hence the project life time *y* in formulas (5), (7) and (8) is: $y = 3{,}653$

years. The annual interest rate i = 0,53846154. Hence CRF(i, y) = 0,67926. CC_{DG} = 2,3573 \$/h. OM_{DG} = 0,095 \$/h. SFF = 0,141. $Ccap_{Inv}$ = 10000 \$. The inverter one hour capital cost is: CC_{Inv} = 0.0761 \$/h.

To evaluate the optimal energy storage eight scenarios with different battery bank capacity and the same other parameters are tested. The battery bank capacity data are presented in Table 3.

	Ebt_max [kWh]	**Pbt_max [kW]**	**$Crep_{Bat}$ [\$]**	**OM_{Bat} [\$/h]**	**RC_{Bat} [\$/h]**
1	10	1	2000	0,00167	0,0429
2	25	2,5	5000	0,00417	0,1072
3	50	5	10000	0,00833	0,2143
4	100	10	20000	0,01667	0,4286
5	150	15	30000	0,02501	0,6429
6	200	20	40000	0,03334	0,8572
7	250	25	50000	0,04168	1,0716
8	500	50	100000	0,08335	2,1431

Table 3. The Battery Bank Data

The constraints concerning the diesel generator are:

$$0,3.P_R \le P_{DG}(t) \le P_R \tag{13}$$

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

$$P_{DG}(t) = \begin{cases} 1,2.(1,25.P_L - 0,63.P_{PV} - 0,7.P_{WT} - P_{Bat\_d}) \\ \quad if \;\; 0,63.P_{PV} + 0,7.P_{WT} + P_{Bat\_d} < 1,25.P_L \\ 0. \qquad\qquad\qquad\qquad \text{otherwise} \end{cases} \tag{14}$$

The constraints concerning the battery system are:

$$-P_{bt\_max} \le P_{\mathrm{Bat}}(t) \le +P_{bt\_max} \tag{15}$$

$$SOC_{min} \le SOC(i) \le SOC_{max} \tag{16}$$

$$\sum_{t=1}^{24} P_{Bat}(t) = 0; \quad t = 1,\ldots,24; \tag{17}$$

where: $P_L(t)$ is the power absorbed by the houses during the hour "t" [kW]; $PPV(t)$ 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:

$$P_{Bat}(t) + P_{DG}(\mathrm{t}) \geq P_H(t) - P_{PV}(t) - P_{WT}(t)\ ,\ t = 1, ..., 24; \tag{18}$$

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 (15) 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 (16) 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 depends on the value of $P_{Bat}(t)$ for each time step; the relation between these variables is shown below:

$$SOC(t) = SOC(t{-}1) - \frac{P_{Bat}(t)}{E_{bt\_\max}}.\Delta t \tag{19}$$

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% from E_{bt_max}. At the begin of the optimization, the battery system is charged to the half of its full charge.

The constraint, shown in equation (17), 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.

4. Test Results

The simulations with GridLab-D give the results about the consumption of the houses, the production of the solar panels and wind turbine.

Ebt_max [kWh]	***F*(x0) [$]**	***F*(x*) [$]**	**Reduced costs [$]**	**Reduced costs [%]**	**Iterations (IP, AS, SQP)**
10	206,07	203,26	2,81	1,362	94, 9, 11
25	206,62	202,31	4,31	2,085	112,11,17
50	208,84	202,10	6.75	3,230	156,15,21
100	213,29	196,57	16,73	7,842	17, 16, 13
150	217,75	201,91	15,84	7,275	18, 27, 10
200	222,20	207,25	14,95	6,729	17, 26, 8
250	226,65	212,59	14,06	6,204	13, 24, 9
500	248,92	239,31	9,61	3,860	18, 27, 9

Table 4. Final Results

The minimization of (3) subject to (13)-(19) requires 48 variables: $P_{Bat}(t)$ and $P_{DG}(t)$, $t = 1, \ldots, 24$; To solve this optimization problem, the Matlab solver *fmincon* has been used. The optimization is performed by three methods: "Interior point (IP)", "Active set (AS)" and "Sequential quadratic programming (SQP)". The best solutions x^* in all cases are obtained by the SQP method. The calculations are started with one and the same initial solution $x0$. The final results are presented in Table 4.

The optimization results show, that the maximal value of reduced costs correspond to a battery bank with 100 kWh capacity. If the obtained reduced costs for a 24 h period in winter can be assumed as an average reduction, we could evaluate the total sum (*TS*) of reduced costs for the project life time (3, 653 years) as a result of optimization of the battery bank schedule and the diesel generator schedule. A comparison with the capital costs for the battery bank (CC_{Bat}) is presented in Table 5.

Scenario No	**E_{bt_max} [kWh]**	***TS* [$]**	**CC_{BAT} [$]**	**$Ts - Cc_{BAT}$ [$]**
1	10	3746,70	2000	+1746,70
2	25	5746,72	5000	+746,72
3	50	9000,08	10000	-999,92
4	100	22306,86	20000	+2306,86
5	150	21120,18	30000	-8879,82
6	200	19933,51	40000	-20066,49
7	250	18746,83	50000	-31253,17
8	500	12813,45	100000	-87186,55

Table 5. Comparison Between *TS* And CC_{BAT}

5. Conclusion

The optimization of battery storage capacity in a microgrid is considered in this paper. Eight scenarios with different battery bank capacity are tested. Real data for a winter day (the worst case) are used. Optimizing the battery schedule and the diesel generator schedule, the electricity costs are reduced in all cases. The greatest percent of cost reduction is obtained for 100 kWh battery capacity (see Table 4). Increasing the battery capacity over this value for the studied microgrid leads to decreasing the percent of costs reduction. The comparison presented in Table 5 shows that the total sum of cost reduction for the project life time is less than the capital costs for the battery bank in all cases with *Ebt_max* > 100 kWh. Hence, the increasing the battery capacity leads to increasing the daily costs for electricity for the end user. One possibility for improving this situation is to increase the project life time, saving at the same time the capital costs for the battery bank unchanged. It must be taken into account here, that the daily charging and discharging the batteries shortens their life time. Second possibility is to produce cheaper batteries. In [14] is noted, that for the real projects the "battery storage would need to cut costs by four-fold to compete in providing capacity". Another way to reduce the electricity costs is to use the microgrid in a mode, connected to the main grid. In this case the generated surplus energy (due to the safe margins in our model) could be sold to the main grid.

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