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Optimization of energy flow in a microgrid application with a photovoltaic electricity supply

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Abstract. Microgrids can be powered using wind turbines, generators, batteries, or solar panels. In case of emergency, a microgrid provides backup from the main grid in times of crisis like storms or power outages, also it can be used to reduce the energy consumption from the main grid. This paper presents optimization of a battery schedule in a microgrid application when it is used in a grid-connected mode (connected to the main grid) with a photovoltaic electricity supply, battery and inverter. The data used for the problem formulation include the photovoltaic energy production in 24 hours for 3000 houses of California state with solar panel power output 27 MW, and 32,4 MW, battery capacity with 100MWh, 150MWh, and 200MWh. One objective function with six different scenarios is used to test the problem for minimization of the consumed energy from the main grid in a summer day. The same simulations are performed for a winter day also. The MATLAB solver ***fmincon*** from Optimization Toolbox is used for the calculations. The data about the consumption of the houses is taken from nanoHUB platform, and the production results of the solar panels are from GridLab-D tool. The obtained results show that a reduction of energy costs for the end user can be achieved by means of optimal battery schedules, as well as that the energy consumption from the main grid can be minimized. The presented approach is promising and it can be applied successfully to real microgrids.

Keywords: Microgrids, Energy Scheduling Optimization, Models & Simulation, MATLAB, GridLab-D, nanoHUB.

1 Introduction

A microgrid is a local energy grid that generates electricity through a combination of renewable energy sources (RES). Microgrid integrates various distributed generators, energy storage equipment, control devices and energy consumers. It can operate in both grid-connected mode and island mode (disconnected from the main grid). Microgrids are expected to become part of the next evolution level of electric power system [2]. The microgrids are especially important for the robust energy infrastructure capable to withstand the weather anomalies [3]. They are designed to achieve a low-polluting economy and a better adaptation to the global climate changes [4]. The microgrid should be robust in controlling demand, supply, voltage and frequency [1]. There is a lot of research devoted to optimize the configuration of the microgrid [5]. The life time of the energy storage system must be taken into account. The energy consumers would like to have high quality electricity on a low (reasonable) price. Optimization of consumption energy is a very good way to impact energy costs.

This article builds a mathematical model of a microgrid in a grid-connected mode and analyzes the effect of increasing the capacity of the battery system on electricity consumption, respectively on the price of electricity consumed. In addition, the effect of increasing the area of the photovoltaic system by 20% was studied. The formulated optimization tasks are solved by means of the ***fmincon*** solver of MATLAB, which allows any kind of constraints.

2 The experimental microgrid setup

The microgrid considered here operates in a grid-connected mode (connected to the main grid) through a Point of common coupling (PCC). In case it should operate in an island mode, an additional generator (for example a diesel generator) should be connected with the microgrid in order to produce the necessary electricity covering the lack of energy in some time periods. The experimental microgrid uses a photovoltaic system as RES. The photovoltaic system includes a group of solar panels and an inverter. The area of solar panels for 3 houses is set to 1500 ft^2, value which corresponds to a produced power with peak around 25-30 kW. Additionally an energy storage (group of batteries) is also interconnected to the microgrid through a DC/AC bi-directional inverter (see Fig. 1).

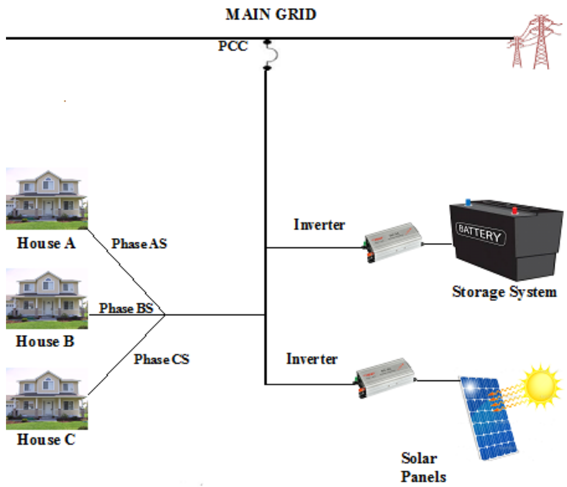

Fig. 1. The experimental microgrid setup

The schedule of charge/discharge of the batteries can be optimized based on an objective function connected to the microgrid. This optimization makes the studied microgrid a *smart* microgrid. The constraints in the optimization task should take into account the behavior of the loads and the energy production by the RES. The microgrid on Fig. 1 is composed by a group of three houses, but for the formulated optimization tasks in this study an application including 3000 houses is considered. The data about the consumption of the houses are taken from nanoHUB platform [6]. The data used for the photovoltaic energy production in 24 hours for the considered 3000 houses are for California state with solar panel power output 27 MW, and 32,4 MW (for area of solar panels enlarged by 20%). The battery system capacity can vary with values 100MW, 150MW, and 200MW. Hence there are six possible scenarios for a summer day data. The same simulations are performed for a winter day also.

The production of solar panels is obtained from the site of GridLab-D - tool (see http://www.gridlabd.org/). For the optimization the solver "*fmincon*" from "Optimization Toolbox" of the software environment MATLAB is used.

3 Battery scheduling optimization tasks

3.1 Task 1: Energy optimization of battery schedule

The data in this study is used only as a demonstration of the potential of the optimization approach. In case that there are available correct forecasted data for the RES production and houses consumption, the behavior of the microgrid can be forecasted one day before, and the schedule of the battery system can be optimized. By solving this task day by day, it will be possible to optimize the microgrid energy for the whole year. The time interval for the optimization task formulation is one day and one night (24 hours). It will be divided in 24 time steps, each with 1 hour length. The corresponding optimization task is presented in the form:

$$\min F1 = \sqrt{\sum_{i=1}^{24} [(H(i) - PV(i) - x(i)) * \Delta t_i]^2} \quad (1)$$

subject to:

$$-P_{bt\_max} \leq x(i) \leq +P_{bt\_max} \quad (2)$$

$$SOC_{min} \leq SOC(i) \leq SOC_{max} \quad (3)$$

$$\sum_{i=1}^{24} x(i) = 0; \quad i = 1,\ldots,24; \quad (4)$$

where: *H(i)* is the power absorbed by the houses during the step "*i*" [MW]; *PV(i)* is the power delivered by photovoltaic panels during the step "*i*" [MW]; *x(i)* is the power delivered by the battery system during the step "*i*" [MW], and Δt_i is the time step [h]. *Pbt_max* is the maximum power that the battery system can deliver/absorb [MW]; *SOC(i)* is the State Of Charge of the battery during the hour "*i*" [%] SOC_{min} = lower limit for the State Of Charge of the battery [%] SOC_{max} = upper limit for the State Of Charge of the battery [%]. In this study SOC_{min} = 20%, and SOC_{max} =100% respectively.

The $x(i)$ is considered negative when the battery is charging, and positive when the battery is discharging. Therefore, the equation (2) represents the power limit during the step "i", which can be delivered or absorbed by the inverter connected to the battery system; the system cannot supply or absorb a power more than the amount *Pbt_max*.

The SOC *of* the battery represents the amount of energy stored in the battery system. Therefore, the equation (3) means that, for each time step "i", the SOC must be included between a minimum and a maximum value depending from the system used for energy storage and it should agree with the physical limit of maximum SOC of 100%. The SOC is depending of the value of x for each time step; the relation between these variables is as follows [7]:

$$SOC(i) = SOC(i-1) - \frac{x(i)}{E_{bt\_\max}}.\Delta t_i \quad (5)$$

*where: SOC(*0) = Initial charge of the battery (it is an input value for the task). In this optimization task, the initial value of the SOC is fixed to 50%. It means that the battery system is charged to the half of its full charge at the beginning of the optimization. The last constraint, shown in the equation (4), is used in order to get, at the end of the 24h period, the same value of SOC, as at the begin of the period. Therefore, this value can be used as an input for the optimization task of the next day. Other parameters to be defined are the *Pbt_max*, fixed to 10% of battery system capacity for charging and discharging, and the battery system capacity E_{bt_max}, fixed to 100 MWh, or to 150 MWh, or to 200 MWh.

3.2 Task 2: Economic optimization of battery schedule

The objective function of this optimization task corresponds to the cost value of the energy in a summer/winter day bought by the microgrid from the main grid minus the cost value of the energy in the same period sold by the microgrid to the main grid. It is submitted to the same constraints as in the Task 1, because the characteristics of the microgrid do not have changed. The objective function has he form:

$$\min F2 = \sum_{i=1}^{24}\left[\left(H(i) - PV(i) - x(i)\right).\Delta t_i\right].P(i) \quad (6)$$

where: $H(i)$ = power absorbed by the houses during the step "i" [MW]; $PV(i)$ = power delivered by photovoltaic panels during the step "i" [MW]; $x(i)$ = power delivered by battery system during the step "i" [MW]; Δt_i = time step [h], and $P(i)$ = buying/selling price during the step "i" [$/MWh]

The value of the price $P(i)$ is calculated in the same way as in [8].

4 Optimization results

The experiments on the formulated optimization tasks were performed for a summer day, as well for a winter day (see Fig. 2 and Fig. 3) for the 6 scenarios, mentioned in Section 2 by means of the ***fmincon*** solver of MATLAB.

In case the area of solar panels used is not enlarged (PV = 100%), the following data are used:

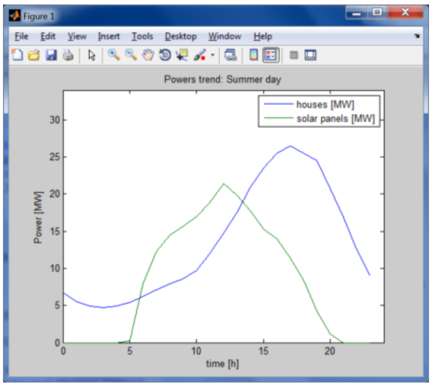

Fig. 2. Energies in a summer day

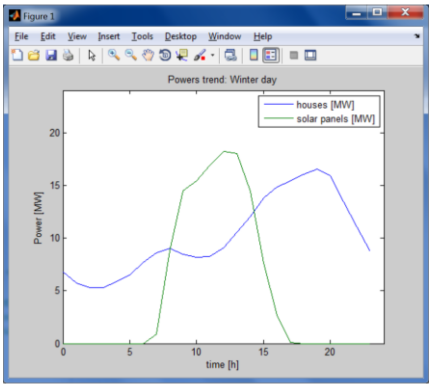

Fig. 3. Energies in a winter day

The experimental results for the summer day are summarized in Table 1.

Table 1. Optimization results for a summer day

PV [MW]	E_{bt_max} [MWh]	$F1$ [MW]	**Iterations**
100%	100	28.872151	57
100%	150	25.160954	28
100%	200	24.826380	21
120%	100	23.873894	40
120%	150	17.660724	31
120%	200	16.670429	15
PV [MW]	E_{bt_max} [MWh]	$F2$ [$]	**Iterations**
100%	100	15081.367316	17
100%	150	15081.367311	13
100%	200	15081.367308	8
120%	100	10633.481671	10
120%	150	10126.843151	13
120%	200	10126.843145	23

The optimization process for the last scenario *is presented in Fig. 4, and Fig.5.*

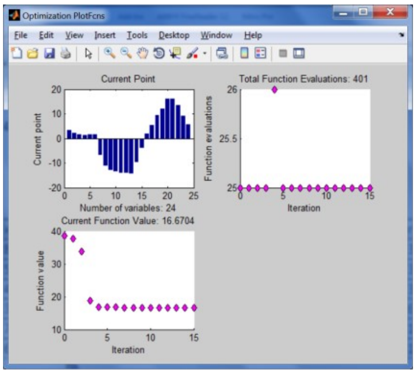

Fig. 4. Optimization of $F1$ (summer day)

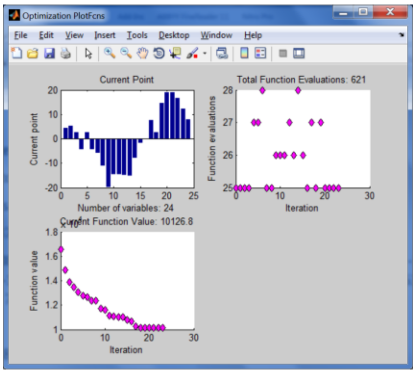

Fig. 5. Optimization of $F2$ (summer day)

The experimental results for the winter day are summarized in Table 2.

Table 2. Optimization results for a winter day

PV [MW]	E_{bt_max} **[MWh]**	$F1$ **[MW]**	**Iterations**
100%	100	27.276043	41
100%	150	25.606384	25
100%	200	25.606384	17
120%	100	25.616398	44
120%	150	20.963290	40
120%	200	20.809397	15
PV [MW]	E_{bt_max} **[MWh]**	$F2$ **[$]**	**Iterations**
100%	100	15555.198600	14
100%	150	15555.198591	10
100%	200	15555.198584	7
120%	100	13893.212055	13
120%	150	12641.156431	9
120%	200	12641.156424	12

The optimization process for the last scenario *is presented in Fig. 6, and Fig.7.*

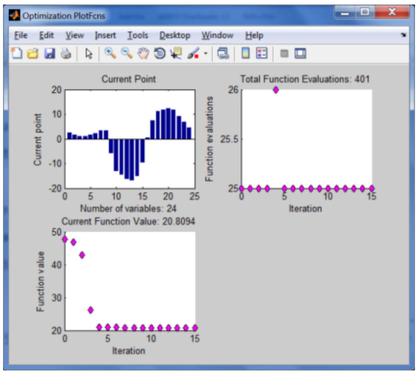

Fig. 6. Optimization of $F1$ (winter day)

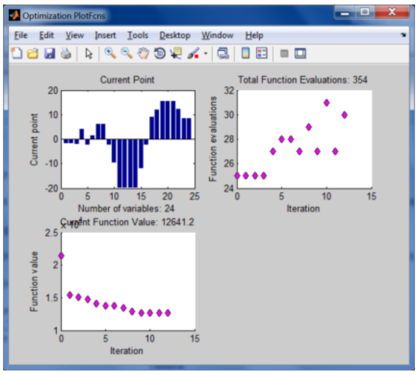

Fig. 7. Optimization of $F2$ (winter day)

5 Conclusions

The obtained results show that the presented optimization approach can be very useful. The best considered scenario with PV = 120% and E_{bt_max} = 200 MWh demonstrates compared to the worst scenario with PV = 100% and E_{bt_max} = 100 MWh that in a summer day the energy consumption can be reduced from 100% to 57,74%, and the price of the electricity purchased from the main grid can be reduced from 100% to 67,15%. In a winter day the energy consumption can be reduced from 100% to 76,29%, and the price of the electricity purchased from the main grid can be reduced from 100% to 81,27% correspondingly. These results are possible at the expense of increased investment for the battery system and for the photovoltaic system. In case the prices of the batteries and of the solar panels become low enough, the solutions obtained by this approach can be used in practice.

Acknowledgment

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