Optimal BESS Scheduling Strategy in Microgrids Based on Genetic Algorithms

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Abstract— Microgrids represent a promising concept able to solve problems specific to the traditional power systems, such as reliability and environmental issues, through a multi-sources coordination, including renewable energy integration and storage devices. In order to overcome the challenges of variation in load and generation, microgrids need efficiently operation and control. The paper proposes a scheduling framework for the microgrid operation considering renewable sources generation and battery energy storage system (BESS).

Index Terms— battery energy storage system, genetic algorithm, microgrid, renewable energy sources

I. INTRODUCTION

The accelerated development of the society and industrial sectors consisting in a substantial increase in energy consumption, has revealed many problems with the classical model of centralized generation, such as environmental impact and low reliability in case of extreme weather and other special events. Under these circumstances, power systems may find themselves incapable to respond to the new levels of energy demand, in terms of power quantity.

Defined as a cluster of loads, distributed generators and energy storage devices aggregated within the boundaries of a certain electrical area [1],[2], the microgrid concept represents a promising Smart Grid solution, able to improve the sustainability, reliability and efficiency of current power systems. Microgrids were initially introduced to facilitate the integration of distributed generation, as an efficient alternative to the centralized generation and bulk transmission [3],[4],[5]. In recent years, the microgrids deployment has seen an increased interest given their capacity to operate either in isolated or grid-connected mode [6]. A microgrid can function independently of the main grid, relying only on local resources, resulting in improved reliability and resilience against major outages [7],[8]. Additionally, this concept provides the flexibility needed to incorporate renewable sources, thus contributing to a reduction in the negative environmental impact of traditional power systems.

As the intermittent and stochastic nature of renewable energy sources brings with it many challenges in terms of control and operation of the microgrid, the energy storage devices represent an effective solution to cope with these variations [9],[10],[11],[12].

For an efficient microgrid operation, accurate load demand and renewable energy generation forecasting models are necessary to be implemented. In [13], a three stages approach based on Bender’s decomposition is proposed for sizing and scheduling the energy storage system and microturbine, considering also PV generation. A robust optimization model is presented in [14], where the generation scheduling at the Point of Common Coupling (PCC) is analyzed in a microgrid including both wind and PV generation. Despite their modeling accuracy, conventional optimization techniques show a slow convergence time when applied in multi scenario management studies. Therefore, numerous recent papers address heuristic optimization techniques to solve the optimal day-ahead scheduling problem, due to their low-computational complexity and algorithmic modeling flexibility [6],[15],[16],[17],[18].

In this paper, a genetic algorithm with a modified mutation function is developed in order to minimize the active power imbalance in a multi-source microgrid, including storage, wind and PV generation. The paper is organized as follows: Section II describes the analyzed microgrid and formulates the scheduling optimization problem. In Section III numerical simulations are performed for multiple daily scenarios and 1, while Section IV provides the conclusions of the study.

II. OPTIMIZATION PROBLEM FORMULATION

In this section, a general description of the analyzed microgrid is provided, followed by the optimal scheduling problem formulation.

A. Description of the Analyzed Microgrid

The microgrid topology considered in this paper consists of local generating units, including a wind power plant

(WPP) and a photovoltaic power plant (PVPP), electrical loads and a battery energy storage system (BESS), for the active power unbalance reduction. The general architecture of the analyzed microgrid is schematically depicted in Fig. 1.

Figure 1. Generic microgrid power exchanges.

B. Scheduling Optimization Model

The main purpose of the implemented model is to determine the optimal BESS scheduling for the day-ahead, based on the load demand curve and renewable sources (wind and solar) generation forecast, aiming at minimizing the active power unbalance. In this regard, an optimization problem is formulated, having as objective function the sum of the squared active power imbalance for each time interval k , within the day-ahead, that is

$$\min F(x) = \sum_{k=1}^n [P_{L,k} - P_{W,k} - P_{PV,k} + P_{B,k}(x_k)]^2 \quad (1)$$

where:

- P_L is the active power demand [kW];
- P_W – the active power generated by the WPP [kW];
- P_{PV} – the active power generated by the PVPP [kW];
- P_B – the active power exchanged by the BESS [kW]; positive values stand for consumption, and negative values stand for generation;
- n – the number of time intervals considered in the study;

The BESS power at every time interval is expressed as a function of the BESS energy capacity, $W_{\max}$ [kWh], as

$$P_{B,k} = x_k \cdot W_{\max} \quad (2)$$

Before applying the optimization algorithm for BESS behavior, the power unbalance for each time interval is calculated based on the forecasted generation and load curves, by:

$$\Delta P_k = P_{L,k} - P_{W,k} - P_{PV,k} \quad (4)$$

Since the BESS exchanged power can be either positive or negative, in order to avoid opposite operating state, the following restrictions as defined:

- when there is power generation excess ($\Delta P_k < 0$), the BESS can only be charged; therefore, the BESS generation limit, at the time interval k , is formulated as

$$x_k^{\min} = \begin{cases} 0 & \text{if } \Delta P_k < 0 \\ x_{\min} & \text{otherwise} \end{cases}$$

- when there is power generation deficit ($\Delta P_k > 0$), the BESS can only be discharged; therefore, the BESS consumption limit, at the time interval k , is formulated as follows:

$$x_k^{\max} = \begin{cases} x_{\max} & \text{if } \Delta P_k > 0 \\ 0 & \text{otherwise} \end{cases}$$

where $x_{\min}$ and $x_{\max}$ are the actual active power limits, expressed as percentage of the BESS total energy capacity.

By combining the two conditions, the following constraints can be written:

$$\begin{aligned} x_k^{\min} &\leq x_k \leq 0 & \text{if } \Delta P_k > 0 \\ 0 &\leq x_k \leq x_k^{\max} & \text{if } \Delta P_k < 0 \end{aligned} \quad (5)$$

For every time interval, the BESS state of charge (SOC) must be maintained within its minimum and maximum limits, $SOC_{\min}$ and $SOC_{\max}$, that is:

$$SOC_{\min} \leq SOC_k \leq SOC_{\max} \quad (6)$$

In order to determine the state of charge at the end of the k^{th} time interval (SOC_k), the state of charge variation during this time interval (ΔSOC_k) is added to the SOC at the end of the previous interval (SOC_{k-1}), that is:

$$SOC_k = SOC_{k-1} + \Delta SOC_k \quad (7)$$

The numerical simulations begin from a predefined (initial) value denoted by SOC_0 .

The SOC variation during a time interval, ΔSOC_k , is determined as follows:

$$\Delta SOC_k = \frac{\Delta W_k}{W_{\max}} = \frac{P_k \cdot \Delta t}{W_{\max}} = \frac{x_k \cdot W_{\max} \cdot \Delta t}{W_{\max}} \quad (8)$$

Furthermore, considering that the time interval Δt is 15 minutes, then $\Delta t = 15 / 60 = 0.25$, (7) becomes:

$$SOC_k = SOC_{k-1} + 0.25 \cdot x_k \quad (9)$$

In order to ensure that the state of charge limits are not violated, a penalty function P_1 is introduced:

$$P_1 = \prod_{k=1}^n p_k$$

where p_k is the penalty coefficient for the time interval k :

$$p_k = \begin{cases} 1 + SOC_{\min} - SOC_k & \text{if } SOC_k < SOC_{\min} \\ 1 & \text{if } SOC_{\min} \leq SOC_k \leq SOC_{\max} \\ 1 + SOC_k - SOC_{\max} & \text{if } SOC_k > SOC_{\max} \end{cases}$$

The active power is considered constant during each time interval. Therefore, the energy unbalance is directly proportional with the power unbalance (by a factor of 0.25),

so that the objective function can also be written for energy, instead of power unbalance.

III. NUMERICAL SIMULATIONS

A. Simulation algorithm

The simulations presented in this study are performed under the Matlab 2018 programming environment. The genetic algorithm used for solving the optimization problem presented in section II is based on the default “ga” function from the Matlab Global Optimization Toolbox. A custom mutation function is the most notable customization performed by the authors. Describing the genetic algorithm is out of the scope of this paper, as the purpose is to develop the optimization mathematical model and to study in detail the requirements in terms of BESS capacity in a small grid.

B. Input data

As mentioned in the mathematical model, only wind and photovoltaic generation units are considered in the simulated microgrid. The following types of data were used for simulations: real values obtained by measurements of PV and WPP units located in distribution networks from Romania, and a generic load curve.

Figure 2. Daily generated curves active power PVPP (a) and WPP (b) [MW], for every day of April 2018.

The real generated active power data was available for month April 2018 (30 days), with 15-minute granularity. The

maximum capacity of both the PVPP and WPP is 2 MW. The PVPP generation curves are illustrated in Fig. 2(a), whereas the WPP generation curve is shown in Fig. 2(b). It is easy to see that the PVPP generation is more predictable than the WPP generation. However, summer months in Romania are characterized by higher solar predictability and very low wind speeds, which means that the capacity of the battery should be bigger.

The load curve simulated in this study is a typical load curve, as the one presented in [19]. The load peak-value is 3 MW, the lowest value is 1.2 MW, whereas the average is 1.8 MW, over a 24-hour time interval presented in Fig. 3. The peak to lower power ratio is 2.5.

Figure 3. The load profile.

C. Scenarios

Multiple scenarios are considered in terms of the power and energy capacity of the BESS in order to identify the best power/energy ratio. Two different power/energy ratios are considered, i.e.: (1) $P_{\max} = 80\%W_{\max}$ and (2) $P_{\max} = 25\%W_{\max}$.

For diversity, a wide range of values for the BESS energy capacity are considered, i.e.:

- when considering both WPP and PVPP, $W_{\max} = 2, 4, 6, 8, 10, \text{ and } 12 \text{ MWh}$
- when considering the PVPP only, $W_{\max} = 5, 10, 15, 20, 25, 35, \text{ and } 40 \text{ MWh}$

The initial charging/discharging operation mode of the BESS is decided by the genetic algorithm.

1) SCENARIO 1: Simulation of the 16th April 2018 curves

For better understanding of the requirements on the BESS, the first scenario assumes simulations using the generation curves recorded for one day only.

All simulations assume an initial state of charge $SOC_0 = 50\%$.

CASE A: The BESS capacity is set to $W_{\max} = 8 \text{ MWh}$ and $P_{\max} = 0.25 \times W_{\max} = 2 \text{ MW}$. Both WPP and PVPP units are considered.

Figure 4 illustrates the power exchanged by the BESS as bars (left axis), and the SOC as continuous line (right axis).

This particular case reveals that the BESS exchanged active power is limited to the maximum value for almost two

hours (between 12 and 14), which means that the BESS is not capable of supplying the necessary load within the microgrid.

Correspondingly, the state of charge is limited both at the maximum value for almost three hours (15-18) and at the minimum value for almost another three hours (7-10), showing that the BESS is saturated.

Figure 4. The active power exchanged by the BESS (left axis) and SOC (right axis) for 16-Apr-2018.

In order to overcome the above inconveniencies, multiple BESS energy capacities have been considered. The active power unbalance on every 15-minute time-interval is represented in Fig. 5 for seven energy storage capacity values.

Figure 5. The active power unbalance for various BESS energy capacities, with 25% power to energy ratio.

Fig. 5 shows that, in the case of a 10 MWh BESS the active power imbalance would be zero for all the 15-minute intervals. For a maximum energy capacity of 6 MWh, there is only one time period with a non-zero power imbalance, from 16 to 22.

The next simulations consider several values for the BESS energy capacity.

Case B: The BESS capacity is set to $W_{\max} = 8$ MWh and $P_{\max} = 0.80 \times W_{\max}$. Both WPP and PVPP units are considered.

Fig. 6 illustrates the active power unbalance resulted during 16-April-2018, also for seven BESS energy capacities. The purpose of increasing the power to energy ratio is to limit the BESS saturation.

For this case, a BESS energy capacity of $W_{\max} = 8$ MWh is enough to reduce to zero the active power unbalance during the considered day. By comparison, in the previous case

(where the power to energy ratio was 25%) the necessary energy capacity was 10 MWh. Also, for $W_{\max} = 6$ MWh, in both cases only the time period from 16 to 22 is left with a non-zero power unbalance. However, in this case only the energy capacity is too low, while in the previous case both energy and power capacity were too low.

Figure 6. The active power unbalance for various BESS energy capacities, with 80% power to energy ratio.

Case C: The BESS capacity is set to $W_{\max} = 8$ MWh and $P_{\max} = 0.80 \times W_{\max}$. Only the PVPP unit is considered.

In this case, the PV power plant only is considered as generation source within the microgrid. PVPP generated power is scaled up so that the total active energy generated equals the total active energy demanded by the load. As a result, the maximum power generated by the PVPP increases from 2 MW to 7.35 MW, in order cover the 41.2 MWh of total energy demand during the entire day.

The numerical simulations are conducted for nine energy storage capacity values, as shown in Fig. 7.

Figure 7. The active power unbalance for various BESS energy capacities, with 80% power to energy ratio.

Fig 7 shows that a BESS having an energy capacity of 35 MWh is not enough to eliminate the active power unbalance, because its capacity is not sufficient to store the exceeding energy in the 9:00h-17:00h time interval.

The peak-load is reached at about 19:00h, when the PVPP generates at most 10% of its installed capacity. Moreover, when the PV generated active power is at its maximum, the

loads demand is about 1.5 MW ÷ 1.7 MW, which represents 50% ÷ 57% of the peak load value of 3 MW.

2) SCENARIO 2: Simulation of month April 2018 curves

In order cover a wider range of generation curves, with a wider diversity, the simulations were expanded for the 30 days of the month April 2018. The BESS characteristics assumed are $W_{\max} = 20$ MWh, and $P_{\max} = 80\% W_{\max}$.

The BESS initial state of charge (SOC_0) represents another important parameter that influences the BESS optimal scheduling. Therefore, three different initial SOC values were considered in this scenario, i.e. 30%, 50%, and 80%, respectively.

The daily total positive and negative active energy unbalances ΔW^+ and ΔW^- are calculated as sums of the positive and negative energy imbalances, i.e.:

$$\Delta W^+ = \sum_{k \in K_p} \Delta P_k \cdot \Delta t \text{ and } \Delta W^- = \sum_{k \in K_m} \Delta P_k \cdot \Delta t$$

where

$$K_p = \{k | \Delta P_k > 0\} \text{ and } K_m = \{k | \Delta P_k < 0\}$$

Then, four ΔW^+ and ΔW^- values are calculated: one for the case without BESS, and three for the considered initial SOC_0 values, for all the 30 days of month April 2018. The results are presented in Fig. 8.

Figure 8. The total positive and negative energy unbalance (ΔW^+ and ΔW^-) for the four cases determined for all days of the month April 2018.

Regarding the initial configuration of the microgrid under study, Fig. 8 shows that there are days when the positive energy imbalance is far greater than the negative imbalance (e.g. 6th, 14th, 17th or 24th of April) or the opposite (e.g. 20th of April). Also, for some days the values of the ΔW^+ and ΔW^- are balanced (e.g. 3rd, 4th, 6th or 27th of April).

For the cases when there is a significant higher positive energy unbalance, which means that there is an energy deficit within the microgrid, the best initial state of charge value is the highest of the three considered, namely 80%. In the opposite case, when ΔW^+ is significantly lower than ΔW^- , the microgrid operation is characterized by an energy surplus, thus the best SOC_0 value is the lowest of the considered values, namely 30%.

For the available microgrid data, the minimum BESS energy capacity for which the microgrid energy imbalance can be maintained at zero for the entire day ($W_{\min}$) is determined. As shown above, the initial SOC plays an important role in the battery optimal scheduling algorithm, therefore, $W_{\min}$ is determined for each of the three SOC_0 values considered: 30%, 50% and 80%, respectively. In this manner, for every day of April, three minimum energy capacities are determined, depending on the initial state of charge values: $\Delta W_{\min}^{30}$, $\Delta W_{\min}^{50}$ and $\Delta W_{\min}^{80}$.

For the optimization problem defined in this paper, if the energy capacity and maximum active power of the BESS are large enough, the optimal solution is obvious. For every time interval the battery should charge/discharge if the active power unbalance is positive/negative, with an amount equal to the absolute value of the active power unbalance.

Therefore, the minimum energy capacity determined for every SOC_0 value as follows: for every W value starting from 1 MWh (and up to 50 MWh, increased by a step of 1 MWh) the scheduling solution mentioned above is implemented and then it is verified that all the P_B and SOC values are within their limits. When a $W_{\min}$ value that satisfied both criteria is found, the values is returned and the algorithm stops. Finally, for every day of April 2018, the minimum energy capacity $W_{\min}$ is determined as the lowest value of the three: $\Delta W_{\min}^{30}$, $\Delta W_{\min}^{50}$ and $\Delta W_{\min}^{80}$. The SOC_0 value that corresponds to $W_{\min}$ value is denoted as SOC_0^* , which is the best initial state of charge.

Fig. 9 shows the minimum energy capacity and the best initial state of charge resulted from the above described procedure. The SOC_0^* value, which is the initial state of charge that corresponds to the $W_{\min}$ value, it is indicated within Fig. 9 by the bar fill color as follows: orange – 30 %, red – 50% and blue – 80%.

Figure 9. The required BESS energy capacity in order to eliminate the unbalance for every day of April 2018 and the corresponding initial SOC represented by color (orange – 30%, red-50% and blue 80%).

Figure 10 shows the number of days within which the energy capacity value is able to balance.

From Figs. 9 and 10 it can be seen that a 45 MWh energy capacity BESS is necessary in order to eliminate the

microgrid active power unbalance for every 15-minute time interval of April 2018. Also, 35 MWh capacity BESS balances 29 days, 29 MWh are enough for 26 days, whereas an 18 MWh capacity can cover 15 days of April.

Figure 10. The total number of days from April 2018 that can be balanced by every considered BESS energy capacity value.

With an average power of 1.8 MW for the selected load shape, the daily energy is around 43 MWh, which is similar to the maximum BESS capacity required to cover each of the 30 days considered in the analysis. If the more economic 35 MWh capacity is chosen, there is a limited curtailment need of up to 7 MWh for only one day, which is only $7 / (43 \times 30) = 0.54\%$ of the monthly energy, quite acceptable for a reduction of 18% in installed capacity. The amount of 35 MWh provide $35/43 \times 24 = 19.5$ hours or required energy.

In a previous work [20], it is shown that a continuous week of operation of the total load in the Romanian power system, while having only renewables resources and the existing nuclear plant, requires a storage capacity capable of supplying energy up to 10 hours. A microgrid is however much more challenging, as it relies only on renewables (no baseline power such as with nuclear energy generation), and requires a much higher K factor (2.5 as compared to 1.2-1.3 valid at the national level).

IV. CONCLUSIONS

In conclusion, from the two different power/energy ratios studied, the 80% version represents a more appropriate solution than the 25% one, because in high power unbalance situations the latter is not able to provide enough active power, unless the energy capacity is further increased.

In order to ensure a perfect coverage of the daily energy unbalance, an oversizing of the BESS energy capacity is necessary. A cost-effective BESS solution of 35 MWh can be used for a limited curtailment of 0.6% from monthly energy.

The scenario with PVPP only is characterized by huge necessary BESS energy capacities, especially due to the time difference between the time when the energy is available from the sun (at noon) and when it is used by the loads (in the evening). The 35 MWh BESS solution is equivalent to keeping the microgrid 19.5 hours on storage, which can be expected for a 100% RES generation in a small microgrid with high load variation. The storage capacity suggests that a BESS solution needs to be combined on medium to long term with complementary solutions such as power to gas (P2G) storage, to address inter season energy resource contribution.

V. REFERENCES

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