Sustainable and Optimized Black Start in Microgrids

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Abstract – The modern energy transition has resulted in the development of sustainable Microgrids (MGs) that utilize Renewable Energy Sources (RES) in order to cover the demand in an environmental-friendly way. One of the main benefits of a MG is the ability to operate independently and provide flexibility services to the main grid's operator. Perhaps one of the most desirable services that a MG can provide is the black start, which is required when the overall system faces a blackout. Up until recently, the main idea of the black start was to restart the operation of the MG utilizing fuel-based Distributed Energy Resources (DER) such as diesel generators. However, there are other controllable units that can be utilized for this purpose, such as Battery Energy Storage Systems (BESS). Therefore, provided that the BESS are charged with renewable energy, it is possible to have a totally sustainable black start. The purpose of this paper is to present an optimization algorithm that assists the MG's operator in making key-decisions related to black start in MGs equipped with RES and BESS. The developed Mixed-Integer Linear Programming (MILP) optimizer is developed in Python with the use of Pyomo and the decision variables are the energy that needs to be discharged from (or charged to) each BESS and the curtailment of RES production, if required. The algorithm is tested on a MG that contains two BESS (one main and one secondary) and two sorts of RES, i.e., Photovoltaics (PV) and a Wind Generator (WG). The results highlight the sustainability and practicability of the proposed solution, even under extreme conditions.

Keywords: black start; microgrids; optimization; sustainability; batteries; renewables

1. Introduction

Microgrids (MGs) constitute self-sufficient intelligent grids that can incorporate a variety of Distributed Energy Resources (DER), such as Renewable Energy Sources (RES) and diesel generators, as well as storage units such as Battery Energy Storage Systems (BESS) [1]. Their self-sufficiency stems from their ability to operate either connected to the main grid, in grid-following mode, or independently, in grid-forming mode (also known as islanded operation) [2]. Of course, since they are active networks, they require energy management algorithms and decision support systems in order to operate efficiently [3].

One of the main services that a MG can provide is the black start which is the autonomous reactivation in case a blackout occurs [4]. This means that while the overall system is disconnected, the MG does not wait for the main grid to be reactivated. Instead, the controllable units are activated (usually with one of them in grid-forming mode) and then the non-controllable units are gradually reconnected until the MG operates fully, still islanded. Once the power of the main grid is restored, the MG can be reconnected in grid-following mode [5]. This is considered to be a valuable ancillary service to the main grid operator and also reduces significantly the overall duration that the loads of the MG are not served.

In literature there is a variety of approaches related to black start algorithms. For example, the authors of [6] propose a rule-based strategy for the black start of a MG including PV and BESS. Furthermore, the authors of [7] explore the challenges that may be encountered when energizing a windfarm, as part of a MG. The authors of [8] propose a restoration strategy for MGs that rely heavily on diesel generators, with special focus on system stability. The authors of [9] have developed a rule-based algorithm for the restoration of grids including nuclear power plants but also RES and storage. Yet, the ongoing energy transition and the advanced capabilities of MGs require a solution that focuses on handling automatically and optimally a plethora of RES and BESS with the minimum possible environmental impact. Therefore, an optimization-based approach that emphasizes on sustainability is considered to be a necessity and an update to the conventional case-specific or rule-based strategies as well as to the strategies that may include an optimizer but do not prioritize sustainability.

The purpose of this paper is to present an algorithm for black start in MGs including a variety of RES and BESS. The core of the algorithm comprises an optimizer that prioritizes sustainable energy utilization. The purpose is to provide an

optimal and flexible solution for MGs that are environmental-friendly, in the sense that they do not rely on fuel-based resources. The proposed algorithm is developed in Python [10] and validated with the use of PowerFactory, DIgSILENT [11]. Its performance is tested on a MG including PV panels, a WG, two BESS and load, showcasing the potential of sustainable architectures in electrical grids.

2. Methodology

The flow chart of the proposed algorithm is presented in Fig. 1. In the beginning all components need to be disconnected. During the black start, the controllable power supply units, i.e., the BESS, are the first ones to be activated, followed by the load. Afterwards, the RES of the distribution network need to connect gradually. In the end, the distribution network is ready to be reconnected to the main grid, in grid following mode.
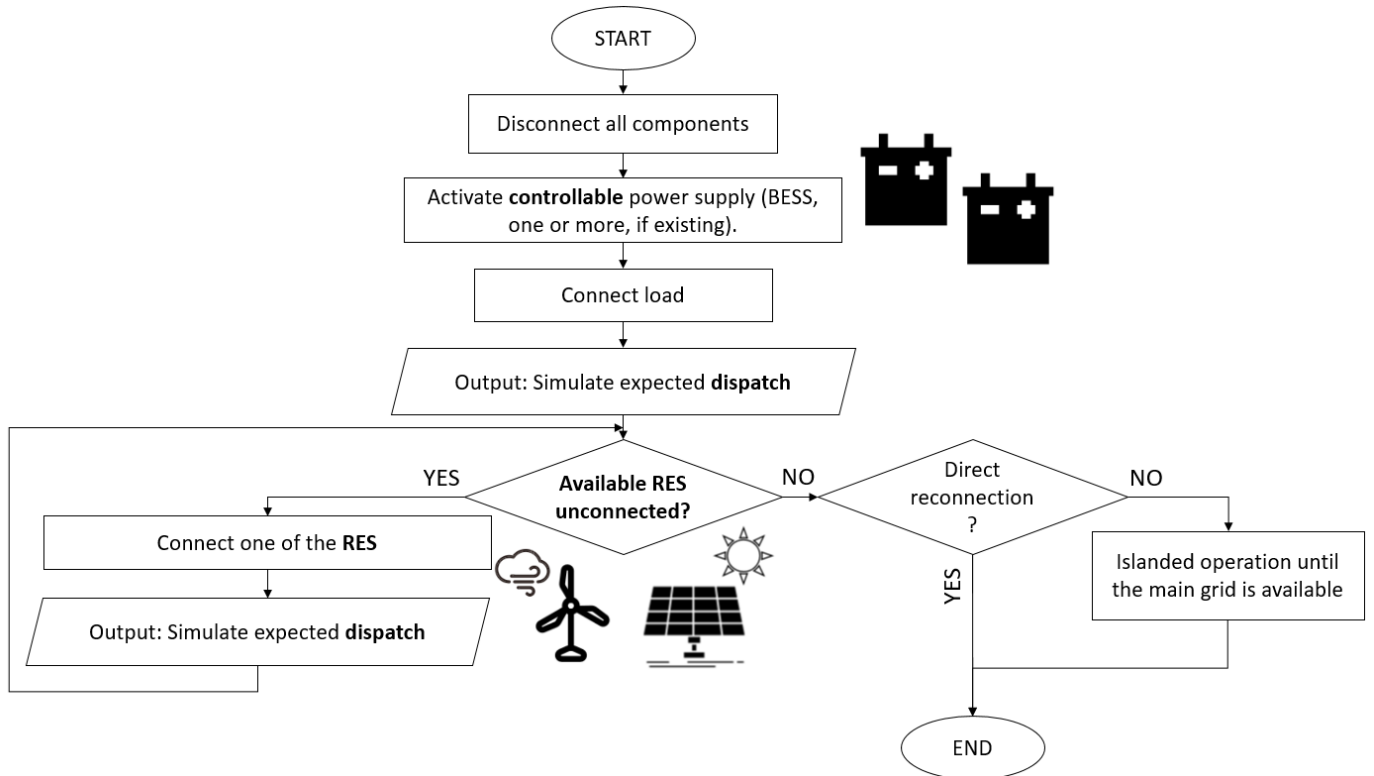

Fig. 1: Flow chart of the proposed algorithm.

It is noted that at each step of the algorithm the energy dispatch needs to be simulated. For this purpose the algorithm's abstract MILP optimizer is developed. The objective function is presented in (1). The aim is to maximize the autonomy of the distribution network, prioritizing RES-based energy. In order to achieve this goal, the direct use of RES production has zero weight, therefore it is not mentioned in the objective function. The second preferable supply unit is MG's main BESS, the discharged energy of which, D_1, has low weight, w_1. The least preferable supply units are the MG's secondary BESS (one or more, if existing), the discharged energy of which, D_n, has higher weight, w_2. It is noted that, while operating islanded, the MG's BESS can only be charged with RES production. Finally, in order to ensure the maximum utilization of RES production and the maximum possible autonomy, the curtailed energy from the RES, R_m^{curt}, has the highest weight in the objective function, w_3.

$$\min F = w_1 D_1 + w_2 \sum_{n=2}^{N} D_n + w_3 \sum_{m=1}^{M} R_m^{curt} \tag{1}$$

Of course, since the optimizer is abstract, the number of components can be modified and, if required, excluded from the energy dispatch. For example, at the first step of the black start, where the RES are not activated, the respective values are removed from the objective function and the constraints. Furthermore, if a MG does not have secondary BESS, they are also automatically removed from the optimizer. Yet, the strategy cannot function without the main BESS. Also, since the optimizer is abstract, the duration of each time-step of the black start can be modified as well.

The constraints of each BESS are presented in (2)-(6). More specifically, the energy balance of each BESS is represented by (2), where S_n is the stored energy of each BESS, $S_{n,initial}$ is their initial stored energy, C_n is the energy charged to each BESS and η_n is the efficiency. The limitations of stored energy, S_n^{min}, S_n^{max}, are taken into account by (3). The maximum energy to be discharged from (or charged to) each BESS is modeled with (4) and (5), where D_n^{max} and C_n^{max} refer to the maximum values and u_n^{dch}, u_n^{ch} are the binary variables that are activated if the BESS is discharged or charged, respectively. Constraint (6) indicates that a BESS cannot be charged and discharged at the same time. The use of each RES is modeled by (7), where R_m is the RES production of the m-th plant and can be either used in the distribution network, R_m^{use}, or curtailed, R_m^{curt}. Finally, the energy balance of the MG is modeled by (8), where L_i is the load of the i-th node.

$$S_n = S_{n,initial} + C_n\eta_n - D_n/\eta_n \tag{2}$$

$$S_n^{min} \le S_n \le S_n^{max} \tag{3}$$

$$D_n \le D_n^{max}u_n^{dch} \tag{4}$$

$$C_n \le C_n^{max}u_n^{ch} \tag{5}$$

$$u_n^{dch} + u_n^{ch} = 1 \tag{6}$$

$$R_m = R_m^{use} + R_m^{curt} \tag{7}$$

$$\sum_{i=1}^{I} L_i + \sum_{n=1}^{N} C_n = \sum_{n=1}^{N} D_n + \sum_{m=1}^{M} R_m^{use} \tag{8}$$

The algorithm is developed in Python and the optimizer particularly is developed in Pyomo, with the Bonmin solver [12], which is a commonly used solver in this sort of problems. Its performance is verified with the use of PowerFactory, DIgSILENT.

3. Results

The proposed algorithm is tested on the real MG of CIEMAT [13] at Spain, which contains one main BESS and one secondary BESS, with maximum energy equal to 60 kWh and 24 kWh, respectively, PV panels with rated power equal to 15 kW and a WG with rated power equal to 5 kW. The daily RES production and demand curves are presented in Fig. 2. The daily RES production refers to a representative day of the year in Spain, derived from [14] and the demand curve is derived from the benchmark systems of [15] and represents a mix of residential and industrial loads. Two cases are simulated. In the first case, i.e., Case 1, the blackout happens at 12:00, when the maximum difference between the RES production and demand occurs, in favour of the RES. On the other hand, in the second case, i.e., Case 2, the blackout happens at 18:00 when the difference is maximized in favour of the demand. The time-steps of the black start are considered to have duration equal to one minute each.

The results of Case 1 are presented in Fig. 3 – Fig. 4. In more detail, Fig. 3 presents the energy of each BESS during each time-step of the black start and Fig. 4 presents the contribution of each BESS (negative values mean that the BESS are charged) at each time step and the utilization of RES production. It is noted that due to the high RES production, the main BESS supplies the demand only during the first time-step of the black start. During the next two time-steps, the demand is

fed by the RES which are gradually activated. The exceeding production is used to charge the two BESS. In the end, the state of charge of the main BESS is reduced by 0.4 % and the state of charge of the second BESS is increased by 0.1 %. During the black start, the demand is covered 33.3 % by the main BESS and 66.7 % by RES.

On the other hand, when the black start is performed at 18:00, the optimal decisions are quite different from the previous ones, since at that time the demand exceeds the RES production the most. This is considered to be an extreme scenario, the results of which are presented in Fig. 5 – Fig. 6. The energy of each BESS is presented in Fig. 5. The energy of the second BESS remains the same throughout the black start. Also, Fig. 6 presents the contribution of each BESS at each time step and the utilization of RES production. During the first time-step, the two BESS are activated but only the main BESS feeds the load. During the second time-step, the first RES, i.e., the PV panels, are connected but their production is close to zero, as presented in Fig. 6, which is something expected at 18:00. Therefore, the main BESS continues to cover the demand. In the final time-step, the second RES, i.e., the WG is connected but since its production is not high enough to cover the demand, the main BESS still needs to be discharged. Yet, the black start is executed without challenging the limits of the system's components, which is mostly attributed to the successful sizing and management of its BESS and RES. In the end, the state of charge of the main BESS is reduced by 1.3 %. During the black start, the demand is covered 89.6 % by the main BESS and 10.4 % by RES.
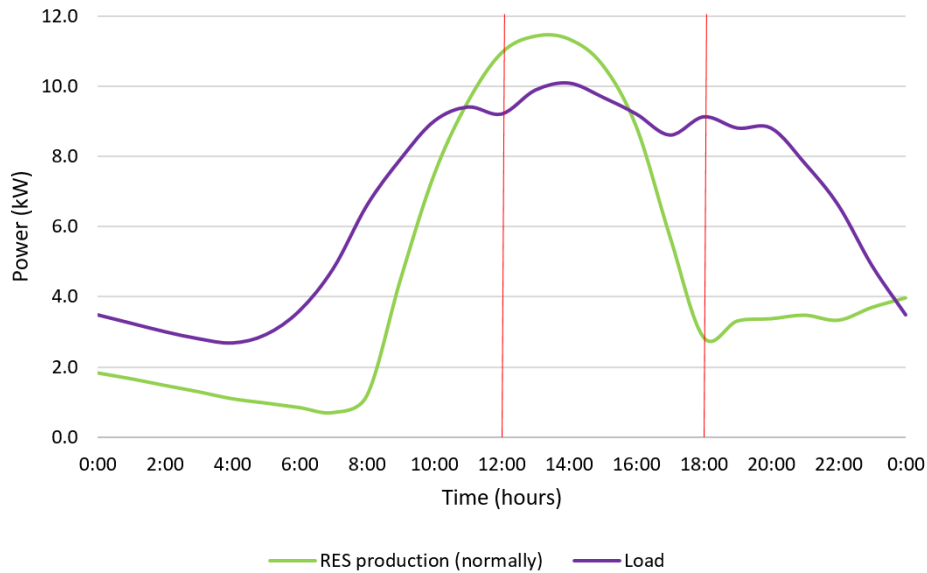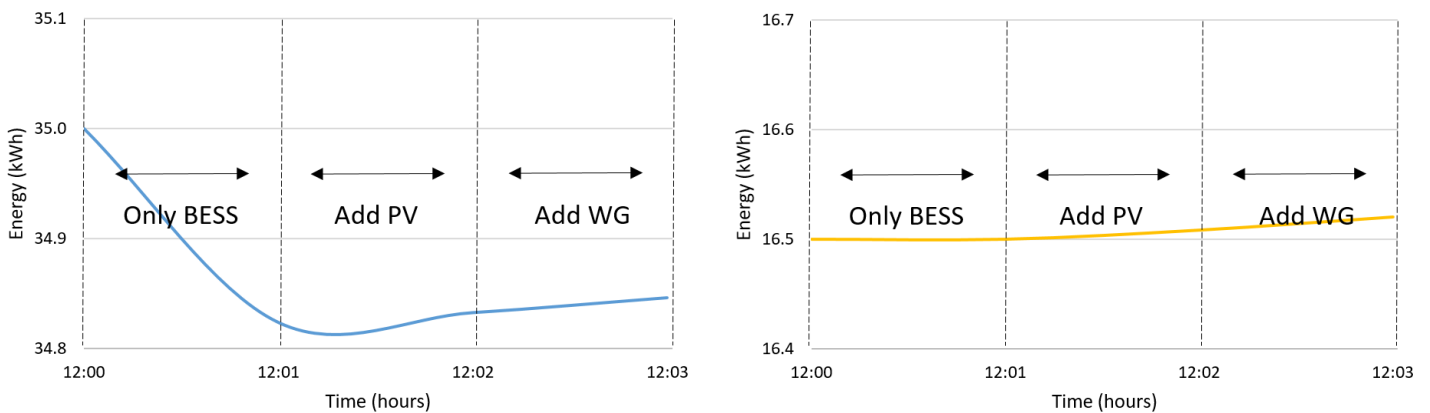

Fig. 2: RES production and demand curves of the MG.

Fig. 3: Energy stored in the main (left) and secondary (right) BESS for black start at 12:00.
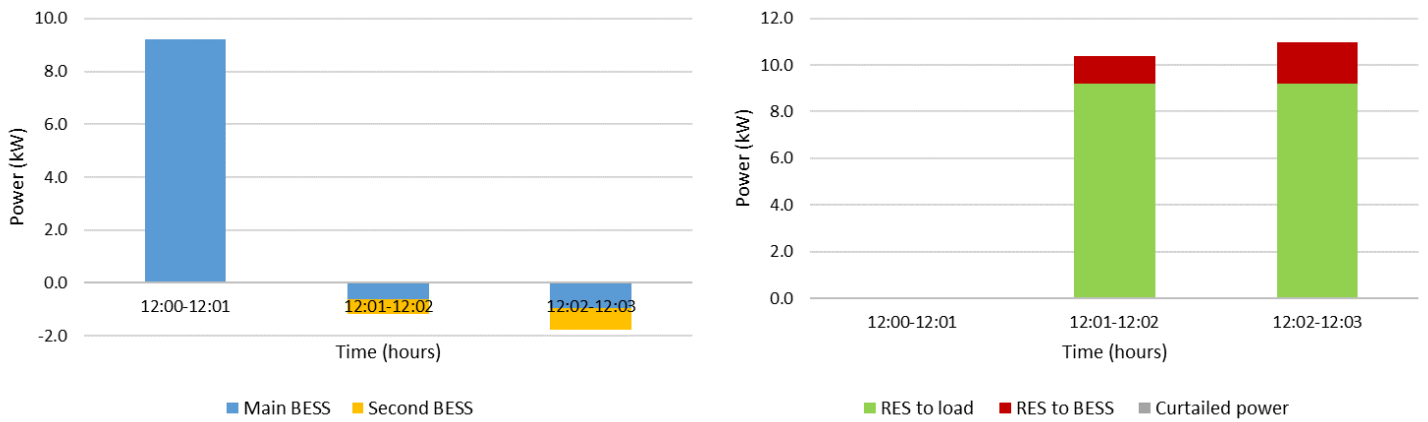
Fig. 4: Contribution of each BESS (left) and utilization of RES production (right) for black start at 12:00.
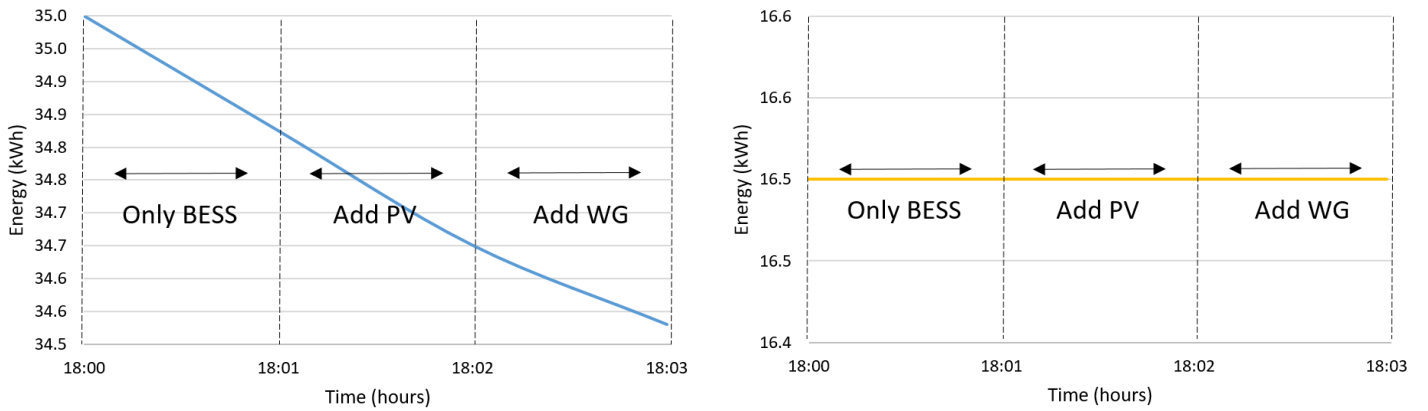

Fig. 5: Energy stored in the main (left) and secondary (right) BESS for black start at 18:00.
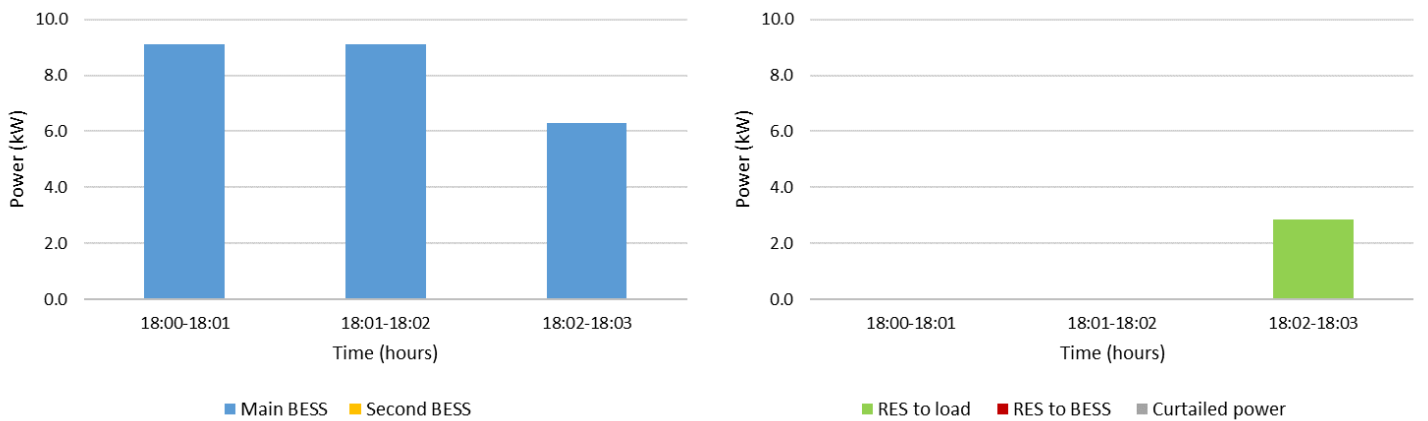

Fig. 6: Contribution of each BESS (left) and utilization of RES production (right) for black start at 18:00.

The results of each Case are summarized in Table 1 and showcase the importance of having diverse and adequate RES profiles, which can support the environmental-friendly operation of the MG throughout the day, as well as the paramount

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necessity of adequate storage systems that ensure the MG's autonomy and allow for the total use of RES production, without curtailments (which would be required if the storage systems were insufficient).

Table 1: Main results of Case 1 and Case 2.

	Case 1	Case 2
RES covering the load	66.7 %	10.4 %
Main RES	PV	WG
BESS covering the load	33.3 %	89.6 %
Reduction of state of charge of the main BESS	0.4 %	1.3 %
Reduction of state of charge of the second BESS	-0.1 %	0 %

4. Conclusion

This paper presents an optimization-based algorithm that provides the optimal decisions for MGs including RES and BESS when they face a blackout. The developed MILP optimizer derives decisions regarding the energy that needs to be discharged from (or charged to) each BESS at every step of the black start as well as potential RES curtailments, if required. The proposed black start algorithm is based totally on non-fuel based resources and is tested on a real MG that comprises PV panels, a WG and two BESS. The results showcase the feasibility of a totally sustainable black start, even under extreme conditions, provided that the MG is equipped with a versatile combination of RES and the BESS are adequately sized and charged.

Acknowledgements

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