

Optimal economic dispatch of hybrid microgrids integrating Energy Storage Systems with Grid-Forming Converters

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Abstract. New control strategies based on Grid-Forming converters make possible the operation of isolated microgrids without the support of synchronous generation. This paper proposes an Energy Management System algorithm that optimizes the operation of a microgrid, maximizing the integration of renewable energy and considering the possibility of disconnecting all synchronous generators. The algorithm is applied to a microgrid modelled with real data and two economic dispatch strategies are analysed: the first requires keeping at least one synchronous generator connected to provide frequency regulation following standard practice; and the second considers the disconnection of all conventional generation relying on the capabilities of Grid-Forming converters when sufficient reserve is available. The results show that the proposed strategy reduces the operational cost of the system, as well as solar PV curtailment and diesel consumption.

Key words. Microgrid, Grid-Forming Converter, Economic dispatch, VSC.

1. Introduction

Electrical grids are evolving towards a carbon neutral future. In this changing period Renewable Energy Sources (RES) play the leading roll. The concept of an electrical grid dominated by large, conventional power plants is disappearing while RES based distributed generation and Energy Storage Systems (ESS) are gaining more present in the modern electrical grid.

Linking distributed RES and ESS, microgrids are being proposed as a solution for various applications. According to the ENTO-E “Microgrids can be stand-alone or can be tied to the central grid” [1], so not only for islanded systems, but also for grid-tied solutions, microgrids are becoming more and more important for the energy transition.

To maximise the penetration of RES in microgrids, the load dispatch and the control of the ESS must be optimized. Many authors have worked with Unit Commitment optimization methods for microgrids [2]–[4].

Isolated microgrids with no connection to a larger grid are special cases, where there is no synchronous backup from

an interconnection. For isolated microgrids, a cost optimizing UC, or economical dispatch strategy with spinning reserve constraints must be implemented to control the microgrid in real time. Authors in [5]–[8] approach to this problem taking into consideration different aspects such as the integration of distributed RES, the optimal usage of a ESS, the technical limitations of the synchronous generators or different contingency constraints. In [9], [10] new constraints are introduced to integrate the frequency control into the Unit Commitment, adjusting the power reserve of the generators to regulate the frequency of the microgrid.

But all these previous studies have one constraint in common, they all assume that at least one conventional generator is operating all the time, so they rely on the dispatchable, conventional units to regulate the frequency and to control the microgrid.

The usage of power converters as uninterruptible voltage sources was introduced in [11], [12]. Further studies have introduced the concept of Voltage Source Converters (VSC) or Virtual Synchronous Machine (VSM) [13], [14]. Those kind of converters can operate not only in low-inertia grids, but also isolated, integrating frequency and voltage controls [15], [16].

The new concept of Grid-Forming Converters (GFC) also introduces the paradigm of a grid with no synchronous generators, dominated by VSCs [17]–[19].

This paper proposes an optimization algorithm to minimize the operation cost of an isolated microgrid where all conventional generation could be disconnected relying on a GFC. The final objective is the implementation of the proposed algorithm for an EMS in real time operation together with the grid forming controls.

2. Description of the study case and implementation

This study is carried out in a microgrid composed of 3 diesel generation units, 1 solar PV power plant and 1 battery energy storage system (BESS). Fig. 1 shows the

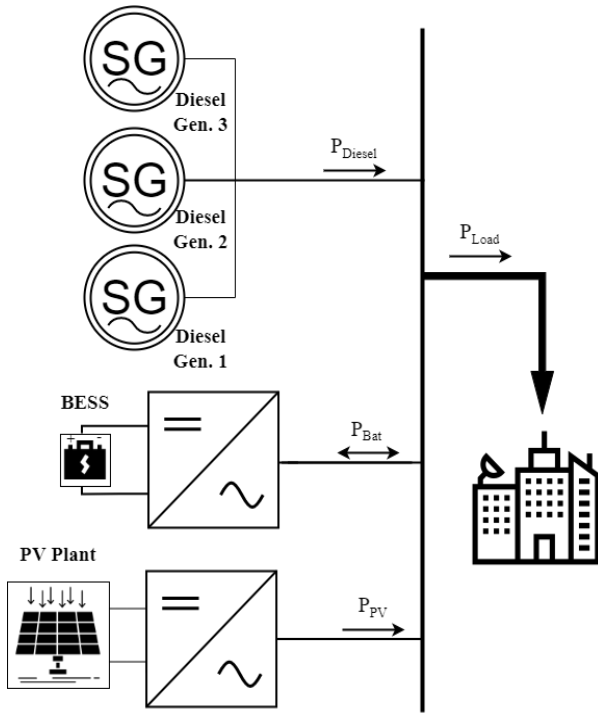


Fig. 1. Configuration of the microgrid

topology of the microgrid where all generation units, BESS, and load are connected to a single bus bar; consequently, the line losses are not taken into consideration.

Table I presents the technical data of the different components based on the dimensions of a real microgrid in operation. The solar PV generation data and the load demand profile are obtained from the real data of its operation. The maximum and minimum load demand over a year are 3418 kW and 1043 kW respectively, following a typical residential load profile as shown in Fig. 2.

Table I. – Characteristics of the microgrid

Diesel Generators (per unit)	Values
Rated Power	2000 kW
Technical Minimum Power	400 kW
Fuel Cost	197 (€/MWh)
Hourly wearing cost	100 (€/h)
PV Plant	Values
AC maximum output power	4000 kW
BESS	Values
Power	2000 kW
Capacity	2000 kWh
Roundtrip Efficiency	90%
Degradation Cost	20€/MWh

This work models, analyses and compares two different operation strategies:

- Demonstration I: A base case where at least one synchronous generation unit remains connected, to provide frequency regulation following the current implementation in the system.
- Demonstration II. In this case conventional generation units could be disconnected, and the frequency regulation would be provided by (GFC).

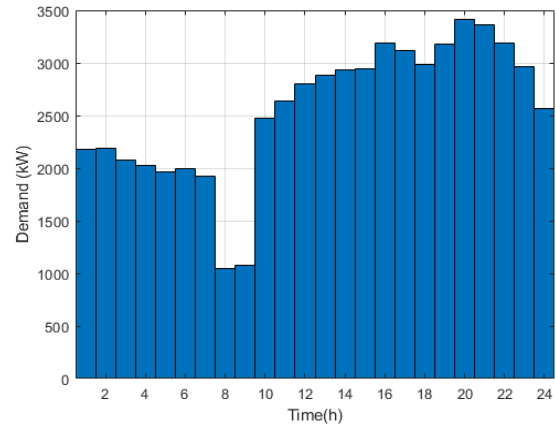


Fig. 2. Daily Load demand profile

The optimization algorithm is formulated as a Mixed-integer linear programming (MILP) problem and solved using the MATLAB optimization toolbox with the future purpose of integrating and testing it in a Real-Time Digital Simulator.

3. Optimization algorithm

To assure an optimal load dispatch of the microgrid, an Energy Management System is implemented to command the active power set-points for the generators. The EMS runs an optimization algorithm that minimizes the fuel consumption while following the reserve requirements. The EMS requires forecasting data (the load demand and the PV resource). The algorithm is formulated as a rolling horizon control scheme that runs every hour with a horizon time frame of 24 hours, receiving and updating the forecasting data for the next rolling horizon each hour.

A. Objective function

The objective function (1) minimizes the operation cost for a time horizon of K hours (24 in the case of this study):

$$\min \sum_{t=1}^K \left(((n_{1,t} + n_{2,t} + n_{3,t}) * H^{\text{COST}}) + \left(\frac{p_t^{\text{GEN}}}{p_t^{\text{GEN}}} * F^{\text{C}} \right) + \left(\frac{p_t^{\text{BAT}}}{p_t^{\text{BAT}}} * D^{\text{COST}} \right) \right) \quad (1)$$

Where H^{cost} is the hourly wearing cost of the diesel generators, F^{C} is the fuel cost, p_t^{GEN} is the total power output of the diesel generators and $n_{i,t}$ indicates the status, on or off, of the diesel generators ($i = 1,2,3$) at each hour t . p_t^{BAT} is the absolute value of the hourly power of the battery, charging or discharging, and D^{COST} is the degradation cost of the BESS.

B. Technical constraints

The algorithm implements several constraints to ensure the correct operation of the microgrid. The first constraint is the power balance given by

$$p_t^{\text{GEN}} = p_t^{\text{LOAD}} - p_t^{\text{PV}} - p_t^{\text{BAT}} \quad (2)$$

$$\mathbf{0} \leq \mathbf{p}_t^{PV} \leq \mathbf{p}_t^{PV \text{ MAX}} \quad (3)$$

Because the EMS can curtail the PV power output at any time. Being $p^{PV \text{ MAX}}$ the available PV power at each hour, which depends on the predicted solar resource. The power supplied by the BESS is

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$$i_d - i_{dg} = \frac{C_f}{\omega_0} \frac{d v_d}{dt} - C_f v_q$$

$$i_q - i_{qg} = \frac{C_f}{\omega_0} \frac{d v_q}{dt} + C_f v_d$$
(15)

In the equation, it can be observed that voltage components v_d, v_q can be controlled through the current components i_d, i_q , respectively. Cross-coupling and feed forward elements are included to decouple each d and q control loops and reduce the order of each control loop to one single variable [19], [27]–[29].

A. Disconnection of Synchronous Generation

The safe disconnection of the synchronous generator has been proved through a simulation in PSCAD, implementing the system given in Fig. 1. In the simulation, the SG represents the last diesel generator connected to the system, which must be turned off in the following period. For that purpose, first the SG speed and voltage controllers are disabled, and then the power output is driven to 0 by ramping it down. The solar PV plant has been represented by a VSC without GFC controls, so the output power remains constant during all the simulation. The BESS uses a GFC, which takes control of the system voltage and frequency during and after the SG disconnection.

For a better understanding of the system behaviour during the SG disconnection transition, two simulation cases have been run. In the first case, the GFC power command, P^* in Fig. 3, is ramped up, as the SG power command is ramped down. Therefore, the system power balance is maintained without the adjustment of the power-frequency primary control, given by the power synchronization droop control of Fig. 3. Therefore, voltage and frequency are maintained nearly constant during the transition.

Fig. 4 shows the simulation results, where the SG is turned off from its minimum technical power output to 0. The PV plant is providing a constant power of 1000 kW and the load demand also remains constant at 1400 kW. The BESS with the GFC ramps up its power output to compensate the power loss of the SG. The voltage magnitude of the system remains stable.

In the second case, the GFC power command is maintained constant while the SG power command is ramped down. Therefore, during the transition, an adjustment is necessary to close the power balance in the system. This adjustment is performed automatically by the power-frequency control of the GFC, depicted in Fig. 3.

Fig. 5 shows the simulation results. As before, as SG power is ramped down, the BEES with GFC output is ramped up. But in this case, the BESS power increases due to the adjustment performed by power-frequency control, not because the power command is ramped up. Then, due to this adjustment, there is a frequency deviation, Δf in Fig. 3, proportional to the power deviation from commanded. Finally, at $t=15$ s, the frequency deviation is corrected by ramping up the GFC power command.

Obviously, the first case, ramping up the GFC power command as the SG power is ramped down, presents a better behaviour in terms of frequency response. However, the second case has been presented to illustrate the dynamic

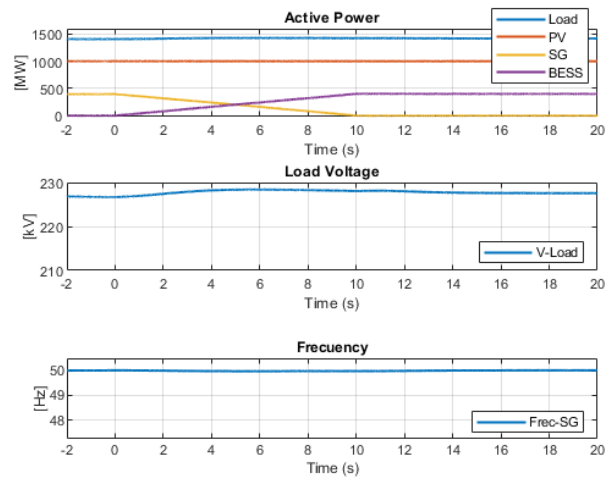


Fig. 4 Case I: System response to the SG turn-off.

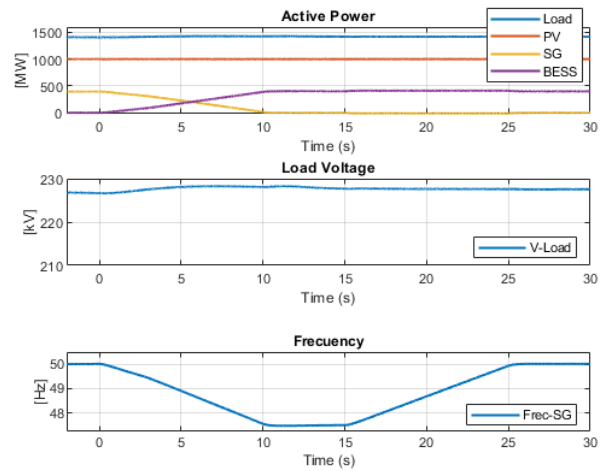


Fig. 5 Case II: System response to the SG turn-off.

of the GFC power-frequency control. Moreover, it must be noted, that power-frequency adjustment will be performed in the system any time there is a deviation from the forecast PV generation or load demand. Also, it is important to clarify that turning off a generator is only possible if the BESS has enough stored energy to maintain the commanded power during such period. This is considered by optimization algorithm of the EMS.

5. Simulation results and discussion

This section performs a four-day simulation for the case study comparing the two proposed strategies, running a UC every time frame for the next 24 hours with the provided forecasted data.

A. Demonstration I: Base Case

Fig. 7 shows the results for the base case where at least one SG remains connected according to (12). That leads to a high PV curtailment during high PV resource periods. Looking at the hours from 32 to 39 in Fig. 7, it can be seen how the SG remains at its minimum power (400 kW). Between the hours 35 and 37, the curtailed PV resource is sufficient to switch off the SG maintaining the reserve requirements with the BESS, but (12) prevents the system from doing it.

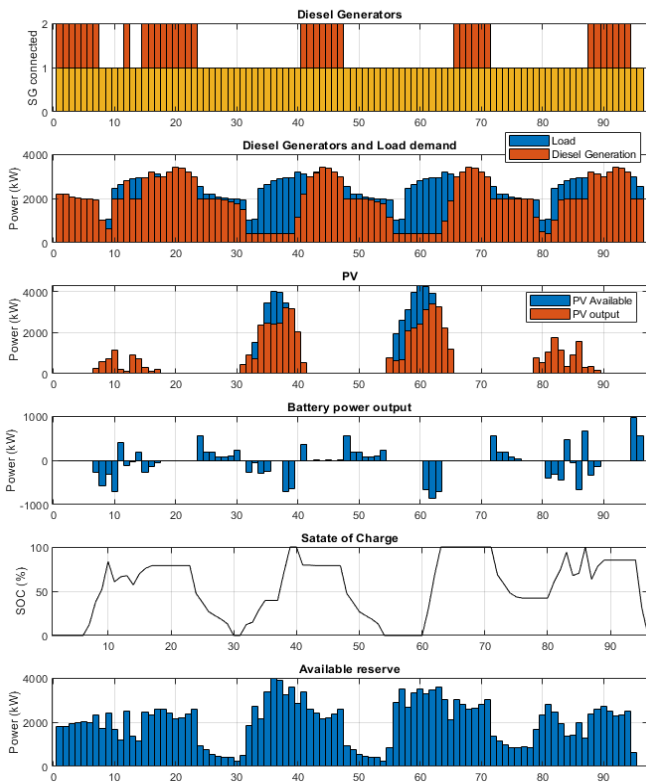


Fig. 7. Optimization results for the case with a GFC operating

B. Demonstration II: BESS with GFC

In this case, the BESS employs a GFC, allowing the system to operate without any SG. Note that without this restriction, there will be more room for the PV generation, reducing therefore the fuel consumption. The same optimization as the Base Case have been performed, without the constraint (16) included in the restrictions of the algorithm. Fig. 6 shows the results of the simulation. It can be seen how now the system is able to turn off all SGs. For instance, from the hour 56 to 63, the system runs without diesel generators connected, minimizing PV curtailment and diesel consumption.

C. Result Discussion

The BESS flexibility allows the system to optimize the resources. Comparing Fig. 7 and Fig. 6, it can be seen how the reserve provided by the BESS prevents the system from turning on another SG at some points. Looking at the hours from 72 to 89 at both simulations, the BESS provides the necessary energy and reserve requirements to avoid the connection of the second SG.

Comparing both results, the biggest difference is between the hours 56 and 63, where the base case is forced to have a SG connected, resulting in a high PV curtailment.

Another difference is that the base case shows higher available reserve, since it is necessary to keep a SG working at its technical minimum power.

However, to establish a fair comparison between cases, the full data must be analysed for a longer simulation. A full year have been simulated with the same data for both strategies.

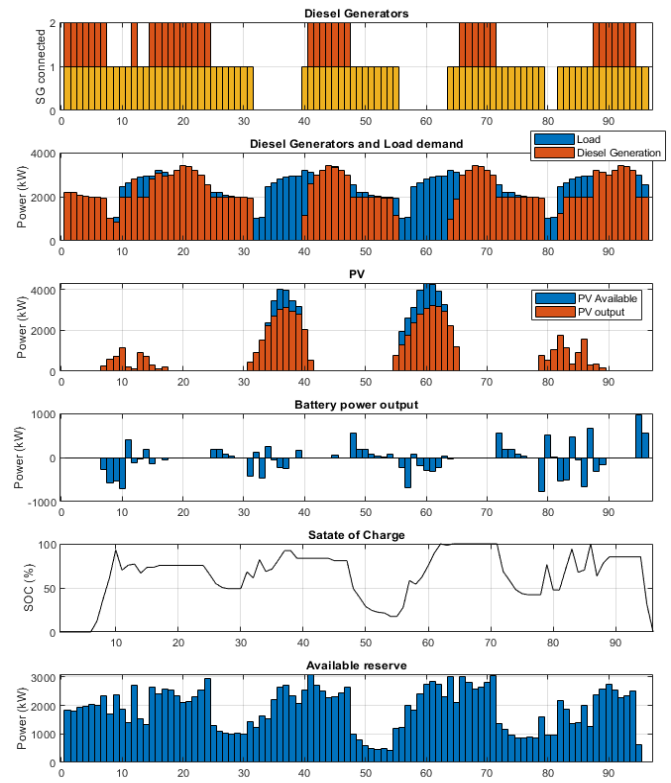


Fig. 6. Optimization results for the case with a GFC operating

Table II. – Results with accumulated values

1 Year Simulation	Base Case	With GFC
PV Plant		
Available Energy [kWh]	7,165,200	7,165,200
Final Energy [kWh]	6,231,800	6,532,800
Curtailment [kWh]	933,430	632,390
Curtailment [%]	13.03	8.83
Diesel Generators		
Total Energy [kWh]	16,164,000	15,865,000
Total Working hours [h]	11,245	9,467
BESS		
Discharged energy [kWh]	613,040	631,160
Charged energy [kWh]	758,110	779,210
Energy throughput [kWh]	1,371,150	1,410,370
Load		
Total Load [kWh]	22,250,228	22,250,228
Generation Cost [€]	4,336,231	4,100,300
Cost of Energy [€/kWh]	0.195	0.184

Table II shows the accumulated values for a 1-year simulation. As it was expected, the fuel consumption and the total working hours of the SGs is higher in the Base Case. With the proposed strategy including the GFC, the number of working hours of the SG is reduced by a 15%, and the curtailed PV by a 32.25% (from 13.03% to 8.83%). Compared to the base case, it is remarkable that the energy throughput of the BESS is only a 2.86% higher compared to the base case. Regarding to the total operational cost,

the proposed economic dispatch strategy achieves a cost reduction of the 5.4% compared to the base case.

6. Conclusion

This paper has analysed the operation of a microgrid, which includes conventional generation, RES and BESS. With the characteristics of Grid Forming Converters, it is possible to operate the microgrid without SGs, due to the voltage and frequency control capabilities of the GFC. These control capabilities have been demonstrated through a simulation showing the SG generation disconnection, while the GFC takes over the voltage and frequency control.

The proposed algorithm has been tested in a microgrid, comparing a base case where the SG cannot be disconnected with a case where the system can operate without any SG connected, regarding the characteristics of a GFC.

When comparing both cases, it has been demonstrated that not only diesel consumption and working hours of the diesel generators are higher, but also the PV curtailment is higher in the base case. A full year simulation has been performed, concluding that the case with a Grid-Forming Converter has a lower cost of energy than the base case.

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