RELIABLE PROSUMER: LOCAL ENERGY MANAGEMENT FOR INCREASED RELIABILITY IN INTERRUPTION-PRONE DISTRIBUTION GRIDS

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ABSTRACT: This paper presents a framework for the management of distributed energy resources (DER) in interruption-prone distribution grids, considering the formation of non-isolated microgrids in medium voltage feeders. A rule-based algorithm is developed to dispatch the microgrid-forming DER, given a set of power and reliability constraints, to ensure the continuity of supply for the customers within the microgrid. The proposed DER dispatch approach can be used as a reference for DER operators in networks where the distribution system operator (DSO) is responsible for a day ahead reliability assessment and where the DER has capacity contracts with the DSO under islanded operation. A real medium voltage feeder with low reliability is used to test the approach in a simulation environment, considering photovoltaic plants with battery storage as microgrid-forming DER.
Keywords: Microgrid, Non-Wires Alternatives, Distributed Energy Resources, Reliability, Islanding.

1 INTRODUCTION

Reliability in power distribution systems is a growing concern for utilities, regulators, and consumers worldwide, given the ever-increasing dependence on electricity for daily activities. Distribution systems are prone to fail due to several factors, such as insufficient maintenance, equipment aging, and severe storms, among others. Improving the system's reliability through investments in infrastructure assets (e.g., undergrounding of power lines) is often unfeasible because of financial restrictions. As an alternative, local energy storage can be used as a backup system to improve reliability in many cases, especially those battery-based. Furthermore, battery energy storage systems (BESS) are often deployed to improve self-consumption from distributed photovoltaic systems (PV), or in peak shaving and peak shifting applications.

An energy management framework with focus on reliability can find many applications in regions where frequent and long-lasting service interruptions may be present. Furthermore, with the expansion of distributed storage systems, energy scheduling approaches that consider the possibility of backup operation are becoming relevant and feasible in many cases. This paper presents a framework for the optimal management of DER in scenarios where power distribution reliability is a major concern. Such a framework could serve as a basis for the development of energy management strategies for microgrid-forming resources and as a reference for power delivery contracts. For example, the contract between a distribution system operator (DSO) and a microgrid-forming DER can consider reliability requirements on a time-dependent basis, to optimize the local energy resources and the microgrid operation.

The literature presents works that consider reliability in the optimization of distributed energy resources. However, the approach for signaling between the DSO and the DER is an innovative aspect of the present work. Khan *et al*. [1] present an optimization-based reliability enhancement scheme for active distribution systems, considering the energy storage availability of electric vehicles. Paudyal *et al*. [2] present an incentive-based optimization scheme for residential consumers; however, reliability is not considered. Liao and Parisio [3] present an optimization scheme for reliability in multi-energy systems that consider energy storage devices' effects under weather uncertainties, where a sequential Monte Carlo simulation is used for reliability evaluation.

The relevance of a reliability-oriented optimization framework that considers reliability from a time-dependent perspective is further corroborated by the works in [4] and [5], where the effects of weather conditions on power system reliability are investigated, and an operational risk assessment for transmission systems is made, considering weather impact.

In the present paper, a novel reliability-oriented energy management framework is considered for microgrid-forming DER (MFR) connected to failure-prone distribution grids. The framework is formulated as a rule-based optimization model to minimize energy costs for the MFR, while guaranteeing reliable operation, considering the interaction between the DSO and the MFR's energy management system (EMS): first, the DSO is responsible for evaluating the grid service failure probability on a day-ahead basis; then, the MFR's EMS uses this probabilistic assessment as a reference to dispatch its local energy resources (e.g., BESS, PV, and flexible loads).

The paper is organized as follows: Section 2 details the utility-led DER contracts that are considered the core business model for microgrid formation; in Section 3 the framework for DER energy management and the rule-based dispatch algorithm are presented; the framework explained in Section 3 is applied to a real distribution feeder, and the results are presented in Section 4, followed by the conclusions in Section 5.

2 UTILITY-LED DER CONTRACTS

A recent business model to consider DER resources in distribution planning is the adoption of utility-led contracts with third-party DER providers. This approach was explored in [6], where a "contract for deferral scheme" was used to integrate DER as an alternative for demand-driven grid investment, where such contracts are procured in a three-step auction process. Another possibility for third-party DER procurement is to open public calls addressing specific planning objectives in the utility's areas of interest. One example is presented in [7], which procured DG with islanded operation capacity to form microgrids on a preselected set of substations and feeders with poor reliability.

The present paper considers an approach similar to the one in [7], where the utility procures third-party Microgrid-Forming Resources (MFR) via power and energy contracts as a planning alternative focused on improving reliability. During normal operation, an MFR operates as a regular distributed generator, selling energy to the utility, while in contingency, the MFR must be able to operate islanded, hence forming a microgrid to supply a predefined set of consumers. Therefore, the MFR contract must specify the contracted energy price, $\rho_{E,MFR}$, (*e.g.* in \$/MWh); the amount of contracted energy from the MFR over the planned horizon, $Q_{E,MFR}$; the rated power capacity during islanded operation, P_{MFR}; and the islanded autonomy time, T_I. From P_{MFR} and T_I, the energy capacity of the MFR, E_{MFR}, can be calculated. A methodology to determine P_{MFR} and E_{MFR} is developed in [8], where the planned demand profile, historic data of interruption levels, and solar resource forecast are used to size the DER.

3 DER MANAGEMENT FRAMEWORK

The framework for the optimal management of DER energy resources considers scenarios where power distribution reliability is a major concern. Such a framework could serve as a basis for the development of energy management strategies for microgrid-forming DER and as a reference for power delivery contracts. For example, the contract between a distribution system operator and a DER can consider reliability requirements on a dynamic basis to optimize local energy resources and microgrid operation. The two-stage workflow of the framework is depicted in Figure 1.

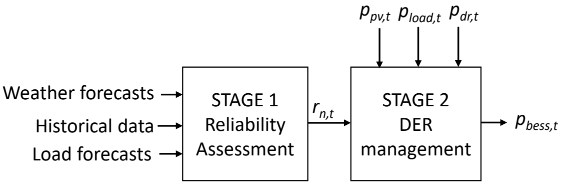

Figure 1: Framework for reliability-oriented MFR management.

The first stage relies on the DSO capacity to assess $r_{n,t}$, which is the probability of energy supply availability at a grid node *n* and time *t*. The node *n* corresponds to the point of connection (POC) of the microgrid (*i.e.*, where the islanding switch is located). $r_{n,t}$ quantifies the confidence level of the DSO with which the system will be servicing the loads and is calculated on a day-ahead basis for each timestep (*e.g.* hourly or quarter-hourly). $r_{n,t} = 1$ indicates to the MFR of the microgrid connected at the n^{th} node that the DSO is 100 % confident that there will be service available at a given time *t*. When a severe storm is forecast, for example, the DSO might reduce its confidence in service, thus adjusting $r_{n,t}$. To this extent, several factors may influence the quantitative assessment of $r_{n,t}$ by the DSO, such as weather forecasts, historical data, equipment failure rates, and load forecasts.

In the second stage, a rule-based energy management algorithm is used to dispatch the local DER on a real-time basis. In addition to $r_{n,t}$, the dispatch algorithm has the following inputs: $p_{pv,t}$ which is the forecasted PV production; $p_{load,t}$, and $p_{dr,t}$ which are the forecasted power demands of the full load and the demand-response capable loads, respectively. The algorithm used in this paper considers the BESS as a controllable DER, with $p_{bess,t}$ being the optimal dispatch of storage and $p_{dr,t}$ a fixed fraction of $p_{load,t}$.

The MFR can operate in three states, as indicated in Figure 2. In the Normal Connected Operation state, the MFR operates connected to the distribution grid and there is neither a islanding event scheduled nor any probable islanding forecast (as probable, it is being considered an $r_{n,t} < 0.7$ in a day-ahead horizon). If the DSO forecasts a probable islanding in the day-ahead horizon, the MFR enters the Pre-Islanding Operation state, where the microgrid resources prepare to island (*e.g.*, by maintaining the BESS in a high state of charge). Finally, when the islanding occurs, the MFR is responsible for supplying the local microgrid loads. In the event of islanded operation during long periods, the MFR may be unable to supply the loads, then a Full Stop state occurs as the MFR is disconnected. Note that the Full Stop state does not mean that all consumers within the microgrid are de-energized, since some may have backup systems.

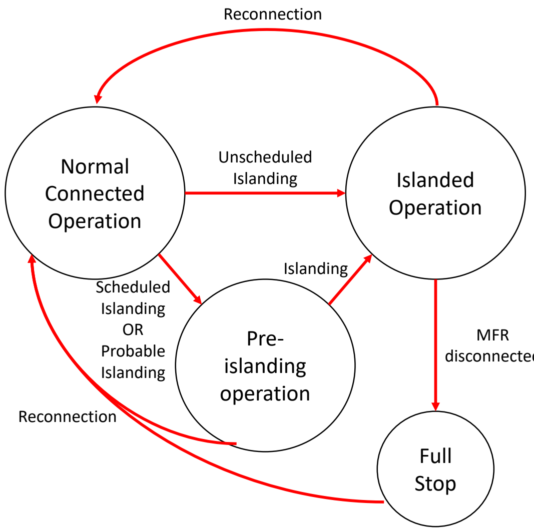

Figure 2: Possible operation states of the MFR and their transitions.

The energy management algorithm considers the following rules for each state:

3.1. Normal Connected Operation

- BESS is charged by the grid only from 0 to 6 am.
- BESS operates in peak-shaving mode at peak hours.
- BESS is used to increase self-consumption of PV, reducing energy exports.
- Exceeding generation is injected into the distribution grid.

3.2. Pre-Islanding Operation

- BESS must have a state of charge of at least SoC_P at the time that islanded operation is scheduled or expected.
- BESS can be charged by the grid during off-peak hours.
- BESS does not operate in peak-shaving mode.

3.3. Islanded Operation

- If the state of charge of the BESS is lower than SoC_{DR}, the microgrid operator may ask for a demand response from flexible loads.
- If the state of charge of the BESS is lower than SoC_{LS}, the microgrid operator sheds non-critical loads.
- If the state of charge of the BESS recovers and passes a SoC_{LR} threshold, demand response and load shedding are canceled and microgrid load is reestablished.

3.4. Full Stop

- If the state of charge of the BESS is lower than SoC_{FS}, the MFR is disconnected, de-energizing the microgrid until the grid connection is reestablished.

In the Normal Operation state, the BESS dispatch is calculated from the minimization problem defined in Equations (1-6), which minimizes the power demanded from the grid:

$$min \sum b_i(p_{bess,i} + p_{load,i} - p_{pv,i}) \ \forall i \in N_t \quad (1)$$

s.t.:

$$p_{bess,min} < p_{bess,i} < p_{bess,max} \ \forall i \in N_t \quad (2)$$

$$SoC_{min} < SoC_i < SoC_{max} \ \forall i \in N_t \quad (3)$$

$$SoC_0 = SoC_t \quad (4)$$

$$p_{bess,i} \leq p_{pv,i} \ \forall i \in N_{0\text{-}6} \quad (5)$$

$$p_{bess,i} + p_{load,i} - p_{pv,i} \leq p_{pksh} \ \forall i \in N_{peak} \quad (6)$$

where b_i is a binary variable that indicates when power is flowing from the grid to the microgrid ($b = 1$) or vice-versa ($b = 0$). Therefore, the minimization function only accounts for a reduction in power demanded from the grid, while power exported to the grid is ignored, since $b = 0$. N_t is the set of intervals considered in the day ahead simulation (*e.g.*, from 0 to 24 h), while $N_{0\text{-}6}$ and N_{peak} are subsets of N_t which correspond to the set of intervals between 0 and 6 h and the set of intervals during peak hours, respectively. SoC_{max} and SoC_{min} are the maximum and minimum operational SoC for the BESS, respectively, and $P_{bess,max,}$ and $P_{bess,min}$ are the maximum and minimum BESS charge and discharge power, respectively. Equation (4) is a constraint to ensure that the final SoC (SoC_t) is the same as in the beginning of the day (SoC_0), and the constraints in Equations (5) and (6) correspond to the rules of charging the BESS only during the first hours of the day and to the peak-shaving service, respectively. p_{pksh} is the maximum power demand during peak shaving service.

In the Pre-Islanding Operation state, the objective function is the same as in Equation (1), as well as constraints in Equations (2) and (3). A third constraint, described by Equation (7), is added to ensure that the BESS has a state of charge of at least SoC_P at the time that islanded operation is scheduled or expected, where SoC_f is the BESS state of charge in the moment of expected islanding.

$$SoC_p \leq SoC_f \quad (7)$$

In the Islanded Operation state, there is no optimization algorithm, and the entire operation is based on the rules defined in section 3.3.

4 SIMULATION RESULTS

The following study case illustrates the application of the presented framework for MFR dispatch. It is based on a remote system isolated from the Brazilian national grid and supplies over 4,400 consumers using a set of diesel-based generators. The MFR is composed of a 12 kW PV generator and a 53 kWh BESS, and, when islanded, must supply a set of loads with a forecasted aggregated demand profile (p_{load}) indicated in Figure 3. The forecasted PV generation profile for the MFR is indicated in Figure 3 as p_{pv}. Table I presents the parameters for the rule-based algorithm used in the simulations.

The database used to carry out this study is freely available from the Brazilian Electrical Energy Regulatory Agency (ANEEL) and contains georeferenced data for both medium and low-voltage circuits for each utility in Brazil. All data is given for the year 2020 unless otherwise noted. The daily power balance was performed for sequential quarter-hourly data available for the loads, and no distributed generation other than the MFR was considered.

Table I: Algorithm parameters.

Parameter	Value	Parameter	Value
$p_{bess,max}$	10 kW	SoC_{DR}	0.7
$p_{bess,min}$	-10 kW	SoC_{LS}	0.5
BESS Capacity	53 kWh	SoC_{LR}	0.8
PV rated power	12 kW	SoC_{FS}	0.3
p_{pksh}	3 kW	SoC_{max}	1.0
SoC_P	0.9	SoC_{min}	0.3

Figures 4 to 7 illustrate the BESS dispatch for both unprepared (normal operation) and prepared (pre-islanding operation) scenarios, with and without the occurrence of a fault. In the prepared scenarios, a fault is expected by 9 h, following the signaling from the DSO. Figures 4 and 6 illustrate the BESS dispatch for the unprepared and prepared scenarios, respectively, when no fault occurs. It is possible to note that in the prepared scenario, the BESS is charged from the beginning of the day, so a high SoC is obtained by the time a fault is probable to happen. In the normal operation scenario, shown in Figure 4, it is possible to note the peak-shaving service from the MFR, as the power at the POC of the microgrid to the distribution network is limited to 3 kW between the peak hours (from 18 h to 21 h), which is not observed in the pre-islanding scenario shown in Figure 6.

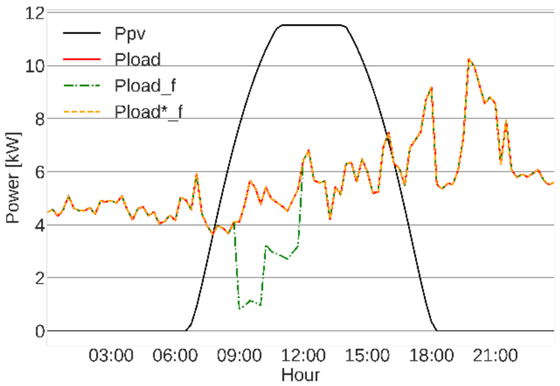

Figure 3: PV generation, reference load, load in the unprepared scenario under fault, and load in the prepared scenario under fault.

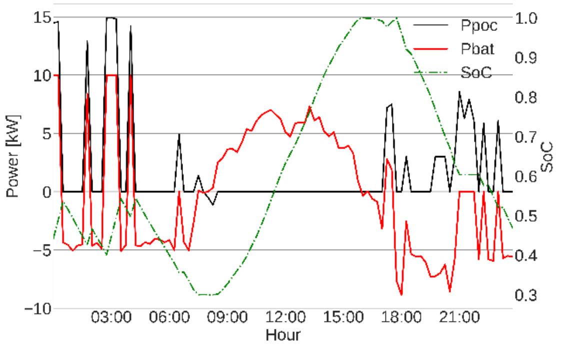

Figure 4: Battery dispatch, SoC, and power at the POC for the unprepared scenario, without fault.

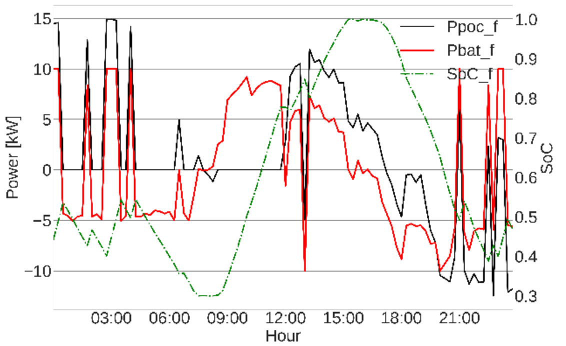

Figure 5: Battery dispatch, SoC, and power at the POC for the unprepared scenario, with fault.

Figures 5 and 7 illustrate the BESS dispatch when the fault occurs at the expected time (9 h), for both the unprepared and prepared scenarios, respectively. In Figure 5, it is noted that the BESS SoC at the time of the fault is under 40 %, making the microgrid operator request demand response from the loads, and perform load shedding on non-critical loads. Those actions from the microgrid operator can be seen in Figure 3, where p_{load_f} indicates the aggregated load in the unprepared scenario under fault, and it is possible to observe how it is reduced at the time of the fault when compared to the reference load. On the other hand, in the prepared scenario, illustrated in Figure 7, at the time of the fault, the SoC is 90 %, and no demand response nor load shedding is put in effect by the microgrid operator.

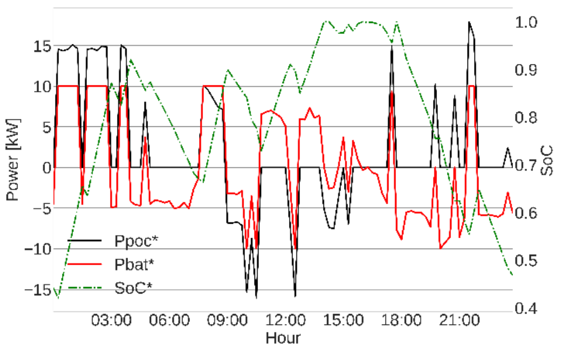

Figure 6: Battery dispatch, SoC, and power at the POC for the prepared scenario, without fault.

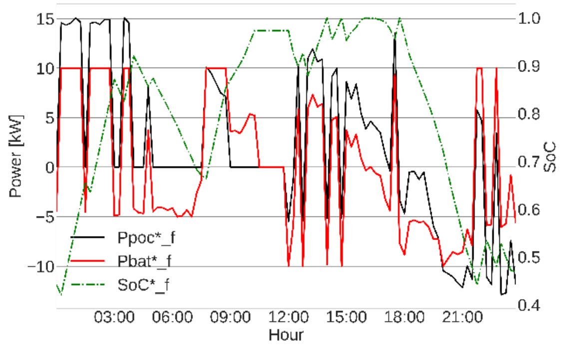

Figure 7: Battery dispatch, SoC, and power at the POC for the prepared scenario, with fault.

5 CONCLUSIONS

Using the proposed MFR dispatch framework it was possible to successfully adjust the BESS dispatch to prepare the microgrid for a probable islanding operation, while the rule-based algorithm also prevents the complete de-energization of the microgrid by performing demand-response and load-shedding operations in flexible and non-critical-loads. Such a framework is built upon the sizing and allocation methodology presented in [8] and serves as a reference for microgrid operation in grid-connected environments with high probabilities of interruptions.

The case study results showed that the MFR can improve the reliability of interruption-prone networks by operating islanded under fault conditions in the distribution grid. The energy management framework can be a feasible alternative to dispatch the MFR resources provided that there is signaling from the DSO to the microgrid operator.

In future works, an already available experimental set-up will be used to test the developed modeling using off-the-shelf devices that can emulate the operation of a small low-voltage feeder with PV-BESS and flexible loads.

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