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Intelligent Management System For Electric Power Microgrids Aiming At A Minimum Overall Operation Cost

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Abstract:
This article presents a new proposal for an energy management system (EMS) that addresses the conditions imposed on a microgrid operated with diesel moto-generators (DMG) sets, such as inserting non-dispatchable renewable sources like photovoltaic systems (PV), battery energy storage systems (BESS), a contracted demand with the utility, and hourly prices and fines. In this context, this work proposes a real-time EMS capable of minimizing the cost of microgrid operation, including energy consumption, subject to constraints of ideal power factors and voltage levels. Thus, an algorithm is proposed to solve the mixed integer nonlinear problem of the DMG sets and BESS dispatch based in relaxing technical restrictions and operating restrictions with all the necessary information acquired from loads and PV with a 15-min ahead forecast, and load flow simulations with the OpenDSS software in Python interface. The results obtained show a 16% reduction in energy consumption, 60% in relation to the cost of diesel used to meet the objective function compared to the DMG-only microgrid with the use of BESS and PV. In addition, a fine of R$ 61,175.38 for exceeding demand is eliminated.
Keyword: *Energy management; Energy storage; Generation dispatch; Microgrids; Moto-Generator sets; OpenDSS; Optimization; Photovoltaics; Python.*

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I. Introduction

New changes and guidelines in the policy of electricity production and supply are perceived in the current scenario of the electric power system, involving two distinct fronts. The first is related to the environmental impacts generated by electricity production. The second addresses the impacts of the increase in energy consumption caused by centralized generation sources and the expansion of the electricity grid. It can be said that the increase in energy consumption suggests a new decentralized generation format, such as microgrids, which decrease the size of energy-generating sources and make it possible to implement renewable sources.

The integration of distributed energy resources is evolving globally, contributing to the enhancement of electric power generation, transmission, and distribution infrastructure, which increasingly require reliability and quality. This development is driven by deregulation of utility industries and public awareness of the environmental impact of traditional electric power generation. The concept of power generation has undergone a significant transformation worldwide, leading to new energy supply proposals in the generation and distribution markets. The small generation and storage are distributed energy resources (DER) and already are a reality in the current electric power system since it produces less environmental impact, is easy to install, and is highly efficient with greater reliability, as predicted by [1] and as shown by [2].

However, microgrids urgently require an energy management system since the generation sources implemented are mostly renewable, making it impossible to control the generated dispatch. It is necessary to think about this control of the microgrid in an intelligent and coordinated way to adapt to this concept. In other words, the use of an advanced Micro Grid Supervisor Controller (MGSC) and Energy Management System (EMS) is necessary to make the microgrid intelligent or a smart grid [3]. One of the primary advantages of an intelligent microgrid is to provide electricity to rural areas with poor access to electricity, with lower cost and minimal energy losses, or help support the primary grid by offering alternatives for voltage and frequency control, enabling greater flexibility, control, and reliability when a microgrid is connected to the primary grid.

Bringing up the issue of the energy market, the biggest challenge facing the electrical system today is to promote a cleaner and more sustainable energy matrix that is less aggressive to the environment, as is the case with generations whose production base is the burning of fuels. large-scale fossils. However, as seen previously, the behavior of a resource classified as renewable is completely different than that of non-renewable resources. This ultimately affects the purchasing and selling capacity, as well as the import and export, of a microgrid that utilizes renewable resources as its energy source.

Parallel to this, strategies that involve optimizing DER into microgrids differ significantly from the conventional energy system and therefore require consideration of different factors. To function effectively, optimal solutions for the design and programming of DER need to be considered, along with energy market volatility [4].

The first works presented since the possibility of inserting distributed generation into the electrical grid was introduced in mid-2012 focused on the relationship between the construction payback cost and the generation capacity, as well as the amount of savings that the plant could provide. Being centered on economic issues, it was not the main focus of the analysis to understand the influence of distributed generation (DG) connections on electrical parameters applied to the network such as electrical voltage and energy losses, for example. With the current characteristics and demands of the electrical grid, it has been realized that expanding the view on technical and operational variables means making the solution more complete in managing microgrids. In this context, considering both technical and economic analyses, becomes crucial so that we do not only seek savings, but prioritize the operability of the microgrid involved with the insertion of distributed generation and energy storage.

Some researchers in the area have already proposed related discussions. In [5] a predictive control with pre-defined rules is proposed to optimize the energy management of a microgrid connected to the upper grid. The microgrid studied includes load and local generation with renewable energy sources, in addition to different types of storage such as batteries and ultracapacitors. In its methodology, two different models for describing the microgrid are shown, where the first aims for a smaller, shorter time interval and the second a larger simulation time interval. The authors justify that the smaller time interval applies to faster network dynamics, while the longer interval is a permanent analysis regime. Furthermore, they mention a new method of assigning binary values to variables being related to the on and off states of generators and storages with conditional rules that depend on the energy value. The problem is defined as Mixed Integer Linear Programming and aims to minimize economic costs and choose the best power flow to exchange energy with the upper grid. Generators with and without dispatch control were inserted.

In [6], the author begins by pointing out older techniques such as demand-side management, displacement and load operations and criticizes the discomfort this causes to the end consumer. He highlights that the intention of managing energy generation with non-dispatchable renewable sources versus the dynamism of the load currently becomes an extremely challenging movement. The author proposes an EMS that intelligently chooses energy sources at any time of the day using the energy cost and the state of charge of the batteries. In the analysis in question, a table is implemented that characterizes the loads (household appliances) by power quantity and basic and heavy loads. It is believed that the programming method used in [6], called Fuzzy, ends up oversimplifying the problem studied since for each important situation in the period of analysis, the modeling is summarized in two steps, such as: time of day is adjusted in the simulation as 1 or 2, with 1 representing day and 2 representing night or battery charge level classified as 1 being low charge (0 to 35%) and 2 being high charge (35 to 100%). Even so, over a period of 20 years, savings of 7.94% were obtained compared to the main scenario without implementing an EMS for the microgrid.

In [7], it proposes a management system for an islanded microgrid, whose energy generation is assisted by: fuel cell, hydrogen tank, electrolyzer, wind and gas turbine, photovoltaic system (PV) models, in addition to also having a battery energy storage systems (BESS). With this, it aims to analyze the useful life of the batteries in the energy optimization process, as well as the operational cost of the different elements mentioned in the microgrid, which make the production of hybrid energy. In terms of operationality of the proposed management system, unlike this paper - in which batteries are the first dispatchable controlled resource to be used under the proposed conditions, in [7] batteries only come into play when the total generation does not sustain the load in question and is only charged when there is excess generation from wind turbines or PV. This is due to the fact that the energy sources used in the microgrid in question have zero operating costs and the objective involves looking at the durability of the batteries in the optimization process.

When it comes to energy management in a microgrid, it requires several different optimizations that are independent of each other. They range from forecasting the availability of energy from renewable sources, to forecasting demand from the microgrid, as well as energy storage as an auxiliary strategy for generating renewable sources. To resolve these problem situations, there is still the possibility of controlling the generation and demand dispatch.

The production and management of energy from non-controllable renewable sources, that is, those that have climate interference, without the possibility of stating with certainty what the amount of energy produced will be, cannot be determined accurately by deterministic methods. In this problem format, approaches must be stochastic. [8]. This is a type of programming with a great capacity for assertive results that fits into the attempt to model the uncertainties associated with forecasting energy from these sources. To achieve this, probabilistic methods are used to estimate as closely as possible how much energy renewable sources will be able to deliver.

In the work of [8], a planning model for microgrids is presented with economic and physical information with several uncertainties, evaluating the financial viability and the ideal combination of generation of distributed energy resources. The stochastic approach is used to model uncertainties in proposed generation systems, market energy prices, and energy demands in conjunction with a metaheuristic algorithm. Specifically in this topic, the author models, through characteristic equations, photovoltaic and wind generation. Afterwards, it uses Monte Carlo simulation with a scenario-based method to deal with uncertainties, and after that the decision variables are resolved in the PSO algorithm considering the constraints of the problem. This approach is interesting for defining photovoltaic and wind generation capacity, predicting different scenarios in the iteration by applying Monte Carlo simulation and making final energy management decisions using a PSO algorithm. However, the computational effort and processing speed are too much when there are shorter simulation intervals (for example 15 minutes, as is the case in this work).

In the work of [9], a stochastic energy management system is studied, indicating the participation of microgrids in the energy market to minimize the total cost based on operation and reliability restrictions that must be satisfied. The work proposes an algorithm to address the interactions between microgrids, the energy market, and the supply network. Furthermore, the author models the market by clearing price using the Game Theory model. Next, a comparison of microgrid in the energy market is presented, sizing the DER before and after their participation, in addition to capital, replacement, and maintenance costs. The author begins by proposing a distribution network operator whose function is to manage the relationship between the supply network and the microgrids observed by him. A two-way communication is formed where the microgrids inform their energy offer to the operator who organizes and calculates the energy price for negotiation in the market. In addition, it receives the expected energy price charged from the supply network. Then, the operator, with the market negotiation price of microgrids defined, makes a comparison with the price predicted by the supply network. If the price calculated by him is lower than that of the supply network, the energy will come from microgrids, otherwise, the supply network must supply the energy. The form of energy negotiation between microgrid and the utility network in [9] has no similarity with the form treated in this work, given that the rules practiced in Brazil do not allow buying and selling energy in real time. Furthermore, his work is a guide for planning new microgrids to be implemented, unlike this work which aims to manage and operate DER with the lowest overall cost.

In [10] the author cites the use of diesel generators, which are always widely used in remote microgrids. He also cites the high cost when diesel generators need to operate 24 hours a day. So, the author proposes an energy management system that minimizes the use of diesel generators using photovoltaic generation and energy storage. It causes diesel generators to be dispatched on an emergency basis with unity power factor, which can harm the power factor of the connected microgrid.

In [11] the author presents a cost optimization model, focused on the performance of diesel/PV/battery generators in microgrids, to minimize operational costs and environmental impact. The model considers fuel consumption as well as this work. The optimization was implemented for high, medium and low electricity demand scenarios, with eight possible system configurations. An economic assessment was made to compare what the author calls: Levelized Cost of Energy (LCOE). The impact of fuel prices was investigated using sensitivity analysis. The results confirmed that for a specific electricity demand, each scenario requires a unique set of diesel generators, and the selection is affected by the PV quota and battery energy storage (BES) units included.

In [12] there is another work about Diesel Generators focused on reduced costs. A new model is proposed for the optimal dispatch of diesel generator sets in real time with the aim of reducing fuel consumption. The various restrictions rely on maintenance considerations and prime power ratings specific to generator sets. The model described in this work is deterministic in nature and is a mixed integer linear programming optimization problem just like this article. The results showed that the model adequately reproduces the intended behavior, and that it could have reduced fuel consumption by 4.3% when compared to the actual dispatch during these 2 days.

In [13] a management system is proposed to support and plan the operation of a microgrid by the new agent in the electricity market, the microgrid aggregator. The aggregator manages microturbines, wind and photovoltaic systems, energy storage, electric vehicles and energy use to have the best market share. The developed microgrid support management system has a formulation based on a stochastic mixed integer linear programming problem that depends on the knowledge of the stochastic processes that describe the uncertain parameters. A set of plausible reduced scenarios calculated by Kernel Density Estimation defines the characterization of the random variables. The scenario reduction performed is a two-level procedure, following a K-means clustering technique and a fast backward reduction method. The case studies reveal microgrid performance and validate the methodological basis designed for the microgrid support management system.

It is possible to observe how important the predictability of energy available from sources is, especially those sources with energy generation characterized by significant variations. Identifying the expected output of DER assists EMS in making informed decisions to manage very short-term energy fluctuations. This approach is crucial for ensuring appropriate decision-making and effective management.

The main contributions of this work are listed below:

1) A management model was proposed, integrating various energy sources and storage to achieve lower overall operational costs, including managing contracted demand with the utility and avoiding penalties for exceeding it.

2) Solutions are categorized based on operational and technical constraints.

3) Monthly simulations with 15-minute intervals were conducted to examine various load and renewable generation scenarios, a practice that is uncommon in the current literature.

The remainder of this article is organized as follows: Section II presents the system modeling and problem formulation. Section III describes the proposed management system. Section IV presents the simulation studies and results, and Section V concludes the article.

II. Formulation Of The Proposed Problem

This paper proposes an EMS based on measures and forecasts with a 15-minute interval. The microgrid comprises controllable diesel motor-generators (DMGs) sets and BESS, along with PVs and loads connected at low voltage through power transformers. The microgrid is connected to the utility distribution network through a contractual agreement that specifies separate values for peak and off-peak demand. The contracted demand is charged monthly with a tolerance of 5% under the contract limit, regardless of whether the use has been reached. If the microgrid exceeds its contractual demand, it will be subject to a fine.

The main algorithm consists of other internal algorithms responsible for demand forecasting, operation management of the DMG sets, and creating and verifying the dispatch list available for testing the best solution. The BESS discharges when needed and will be loaded during off-peak hours at dawn, where there is a sufficient margin for the contracted demand.

The power produced by the generators available in the microgrid are P_{DMG} and P_{PV}, representing the nominal power of the DMG sets and the PV power, respectively. The power available by the BESS is defined by P_{BESS}, and the load consumed by the microgrid is given by P_{LOAD}. The total power of the microgrid is determined by:

$$P_{total}(t) = P_{LOAD}(t) - (P_{DMG}(t) + P_{BESS}(t) + P_{PV}(t)) \quad (1)$$

P_{PV} is obtained by measurements; there is no need to investigate uncertainties or unpredictability since the simulation time between iterations is short in real-time. P_{DMG} is defined by the sum of the powers of the generators available at the time of iteration t:

$$P_{DMG} = \sum_{1}^{n} s(t) \cdot P_{Gn} \quad (2)$$

Where n is the number of generators available, P_{Gn} is the rated power of each generator, and s is the availability state at instant t, with 0 unavailable and 1 available. DMG sets are modeled as a constant power source, with a power factor set to 0.9 to maintain reactive power injection into the microgrid. On the other hand, PV generation will have a unitary power factor. This behavior reduces the active power consumed, but not the reactive power, which worsens the power factor seen by the utility and is penalized if it is below 0.92.

The BESS are at the same connection point as the PV plants, so that they can charge and discharge whenever possible. If this is impossible, the recharge will be done by the microgrid itself, but always outside peak hours, when the cost of kWh is higher, and without violating the contracted demand. As a result, the model presents the following technical characteristics:

$$0.2 \times P_{BESS} \le P_{BESS}(t) \le P_{BESSmax} \quad (3)$$

Where P_{BESS} is the nominal power of the involved storage, a capacity reserve of 20% was placed to meet any excess demand that may occur during rush hour without having a useful loading time until the entry of this scenario. When the consumed load of the microgrid exceeds the contracted demand (Dem_C), the excess demand is calculated (Dem_E) on a monthly basis for each period (peak and off-peak), like in (4):

$$Dem_E = \max \begin{cases} 0, & P_L(t) \le Dem_C \\ P_L(t), & P_L(t) > Dem_C \end{cases} \quad (4)$$

The objective function is the total cost (C_T) of operation:

$$C_T = C_{energy} + C_{diesel} + C_{PF} + C_V + C_{EDp} + C_{EDop} \quad (5)$$

Where C_{energy} is the amount of energy purchased from the utility (6), including the BESS charging and losses. C_{diesel} represents the total cost of diesel consumption by the DMG sets in the dispatched solution (7). C_{PF} is the cost for violating the power factor (8). C_V represents a virtual cost of the voltage violations in microgrid nodes, if the worst voltage level exceeds the restriction limits $Max_V \geq 1.05$ pu (9). Every alternative considered a possible solution is simulated in order to verify the voltage levels at the microgrid nodes. When the imposed restriction limits are violated, they will be measured with a fine, the smaller the violation, the better your classification in the ranking. Finally, the C_{ED} is the cost that is charged for exceeding the contracted demand with the utility company, at peak and off-peak periods, resulting in a threefold fine of the amount exceeding the contracted value (10).

$$C_{energy} = \sum P_{total}(t) \cdot \frac{\$}{\text{kWh}} \quad (6)$$

$$C_{diesel} = \sum P_{DMG} \cdot \frac{\text{l}}{\text{h}} \cdot \frac{\$}{\text{l}} \quad (7)$$

$$C_{PF} = cost_{PF} \cdot abs\left(\left(PF_{find} - 0{,}92\right)\right) \quad (8)$$

$$C_V = \begin{cases} Max_V \leq 1.05\,pu = C_V = 0 \\ Max_V > 1.05\,pu = C_V = cost_V \cdot Max_V \end{cases} \quad (9)$$

$$C_{ED} = \begin{cases} (Dem_E - Dem_C) \cdot \frac{\$}{\text{kW}}, & Dem_E \leq 1.05 Dem_C \\ (Dem_E - Dem_C) \cdot 3 \cdot \frac{\$}{\text{kW}}, & Dem_E > 1.05 Dem_C \end{cases} \quad (10)$$

III. Proposed Management System

The proposed Energy Management System (EMS) involves a mixed integer nonlinear problem in such a way that the state of the DMG $s(t)$ is defined by a binary vector. The generator power dispatch variable is modeled as binary because the objective of its use is to eliminate the fine for exceeding demand. The PV generation can vary from 0 to 100% of the nominal power. The BESS also varies its charge and discharge according to the needs of the system between 20% and 100%, and is idle if not needed. Figure 1 generally illustrates the EMS.

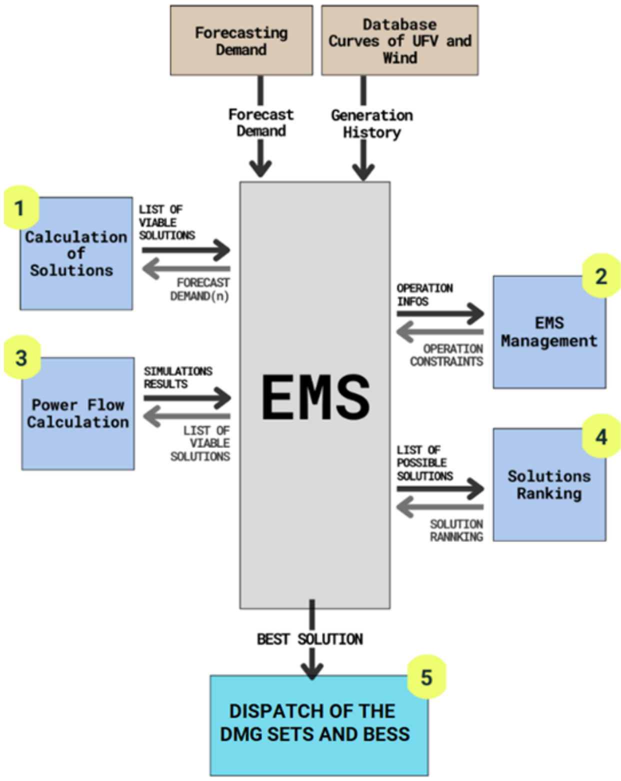

Figure 1. General representation of the proposed EMS.

The algorithm manages available DMG generation to prevent exceeding contracted demand based on technical and operational constraints. Figure 2 represents the flow of the algorithm created to define the dispatch list based on the information issued by the DMG sets of the previous iteration.

The dispatch list is initially created to obtain solutions that meet 100% of the exceeding demand. However, if there is some DMG not available from the constraints, a decrease of the solution by 5% is applied so that it is again possible to find dispatches that meet this new condition. The decrease occurs until the exceeding demand equals 5% of its value.

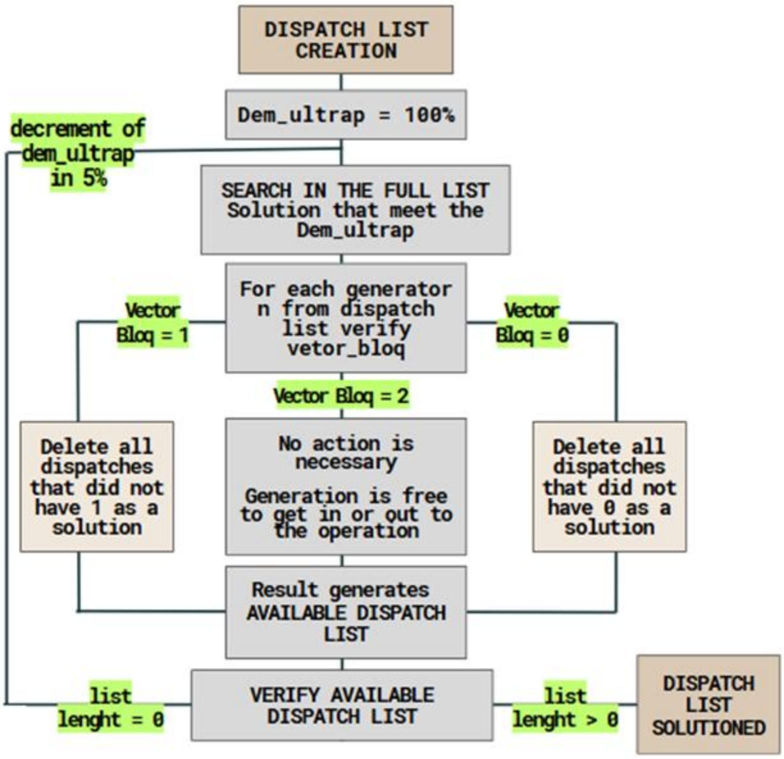

Figure 2. General representation of the proposed EMS.

Figure 3 shows the control and verification process for DMG operating limits, including minimum up and down time and fuel capacity. The algorithm identifies the DMG sets that are on or off or in free condition to enter operation and eliminate or maintain in the final list. The objective is to avoid situations of DMG intermittency, such as the generator being triggered at minute 15, deactivated at minute 30, and triggered again at minute 45. This will lead to premature mechanical wear and produce unwanted electromagnetic transients. This ensures that the intermittency of this type of generation is minimal.

Therefore, we have defined that a started DMG must stay on for at least an hour. If it is turned off, it should remain so for an hour. In this interval, the autonomy and supply are verified concerning the possibility of the chosen generator operating for another hour. Otherwise, it will be removed from the solution and refueled if necessary.

The proposed algorithm is part of the macro-EMS. It first verifies if there is a final solution to perform the proper management (top of the flowchart). In case there is no solution proposed with DMG, it is verified if there has previously been any shutdown or activation to define whether it remains off or on (bottom of the flowchart). Subsequently, it sends the solution of this verification to the proper management.

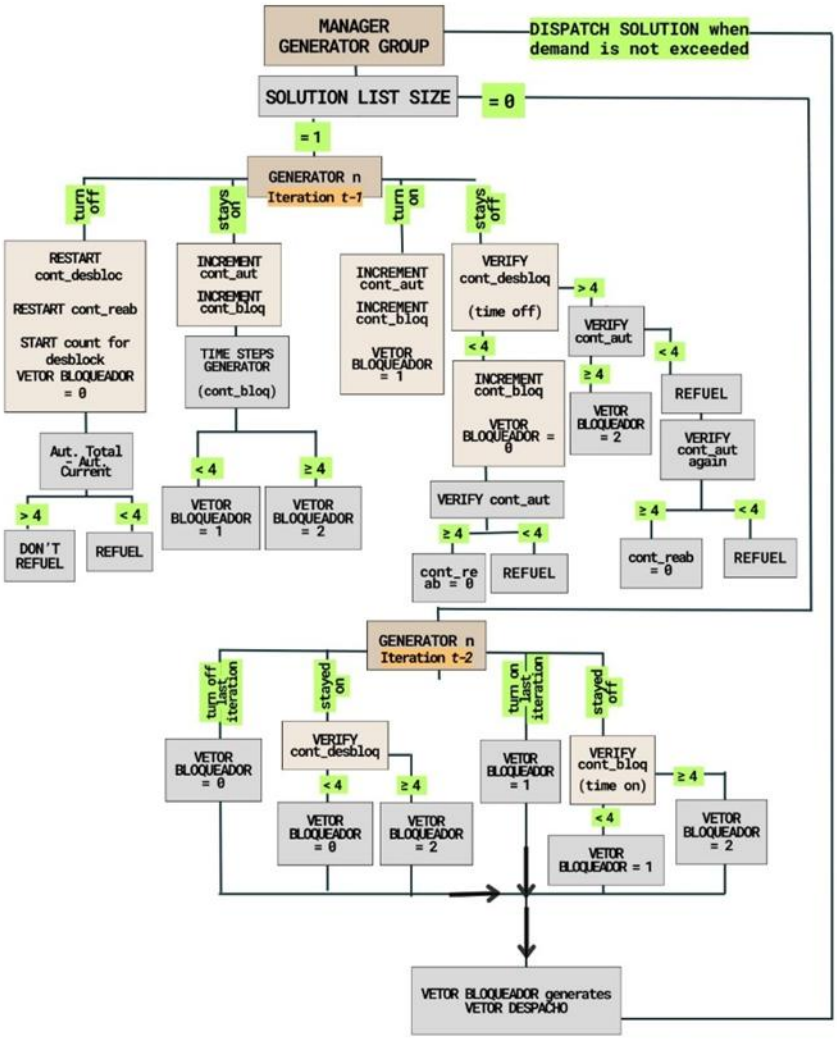

Figure 3. General representation of the DMG manager.

To simulate the EMS operation, each iteration follows these steps until its completion to find the best solution:
1) Receiving read demand information, generation curves, and disponibilities;
2) Calculation of excess demand based on the application schedule and identification of possible solutions;
3) Verification of operating constraints by eliminating generators that cannot be on the list or forcing those that must remain;
4) Calculation of diesel consumption cost for all remaining solution lists from item 3;
5) Application of technical constraints by resolving the power flow for each of the five solutions with lower diesel consumption, given time conditions and excess demand;
6) Evaluating the summation of all costs, assembling a ranking of solutions by identifying the lowest overall cost;
7) Dispatch of the first solution in the list to perform the necessary switches and send this solution to the DMG manager.

IV. Results

This section presents the results and comparisons between the microgrid with its original monthly demand and no support generation, and with distributed generation as DMG sets, with the addition of PV generation, and BESS support.

Microgrid Base Case with only DMG

The microgrid under study is part of the campus-wide power grid that serves the Federal University of Santa Maria. It comprises two feeders and 99 load points, totaling approximately 6.1 MW of maximum demand in April. However, the current demand contract is adjusted for 5.0 MW in off-peak hours and 3 MW in peak hours (according to Brazil's blue tariff) because this is the average of consumption. This microgrid has nine distributed DMG sets, which can be utilized for peak shaving purposes, as shown in Table 1.

Table 1. DMG Units

DMG unit	1	2	3	4	5	6	7	8	9
Rated Power (kW)	18	27	27	59.4	103.4	161.8	215.6	234	323.2
Consumption (l/15min)	1.25	2.5	2.5	3.6	6.75	9.25	13.75	14.75	20

The original network without the DMG sets in the month of analysis saw several demand exceedances, reaching 1,267 kW off-peak and 369 kW peak and has a 173,716.90 kWh energy consumption. The cost parameters are presented in Table 2. Overtaking resulted in a fine of R$61,175.38.

Table 2. Cost Parameters

Parameter	Value	Unit
Energy cost peak hours	0.61676197	R$/kWh
Energy cost off-peak hours	0.43569335	R$/kWh
Demand cost peak hours	50.02610031	R$/kW
Demand cost off-peak hours	33.71595391	R$/kW
Diesel cost	6.41	R$/l

Figure 4 shows the utility-measured demand resulting from the microgrid consumption without any DER for several weeks in April, when the largest contract overtook occurred.

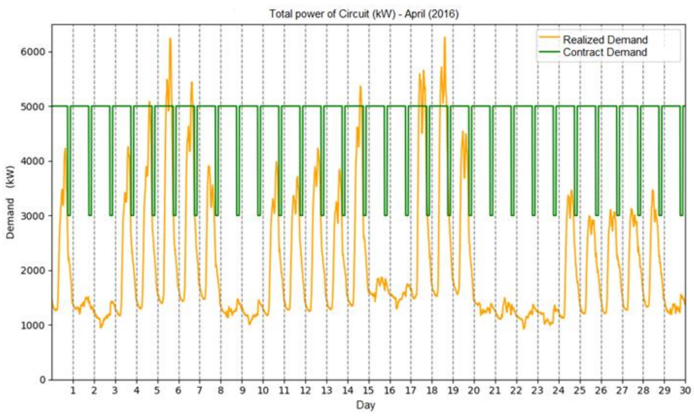

Figure 4. Demand measured in April.

It is possible to identify in Figure 4 that several demand exceedances occur both during peak and off-peak hours, the latter being more critical and costly. However, using DMG, the results are a consumption of x liters of diesel, and the Demand Graph results are shown below in Figure 5, and the DMG Power Injected results in Figure 6. Finally, Figure 7 shows the general single-line diagram of the microgrid base case.

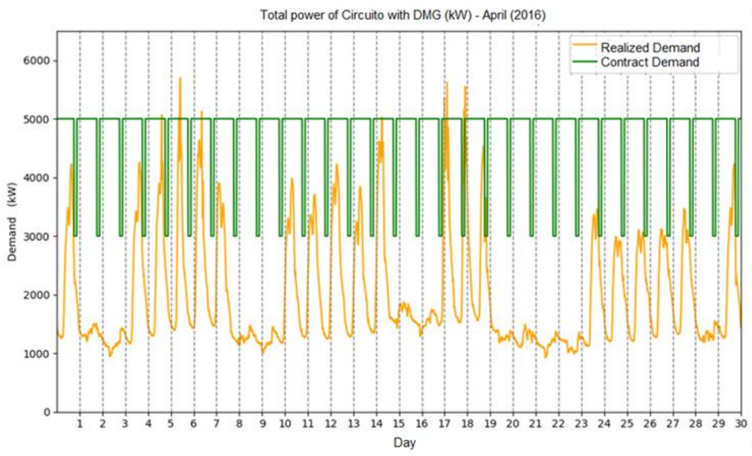

Figure 5. Demand resulted in April with DMG.

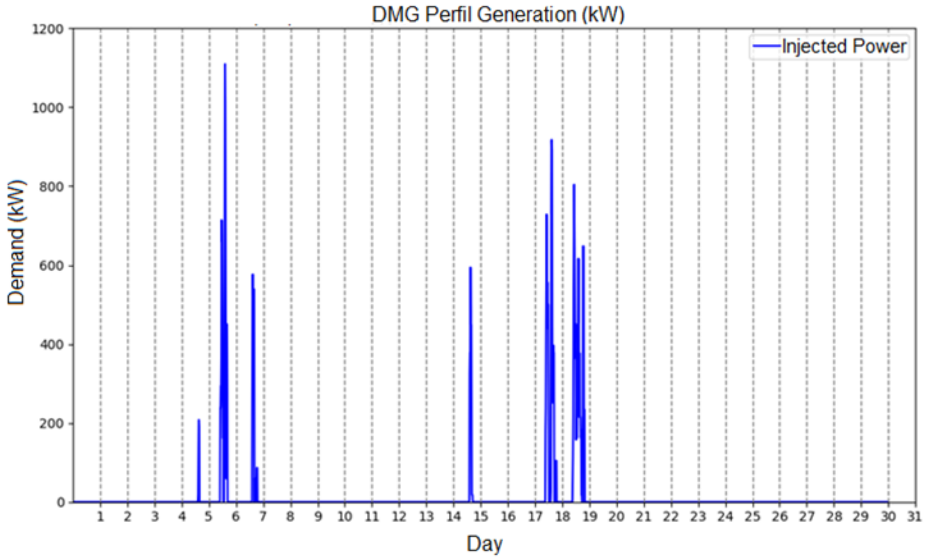

Figure 6. Power Injected by the DMG in April.

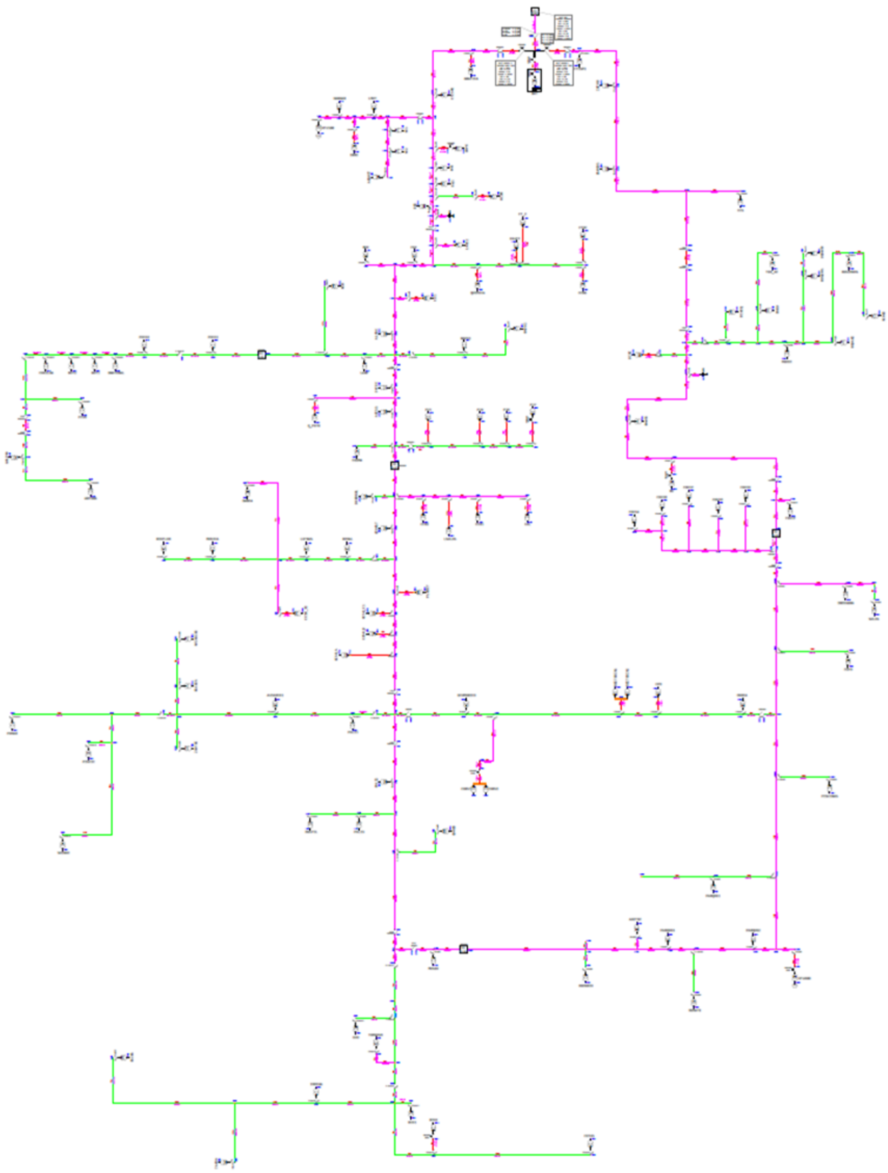

Figure 7. General single-line diagram.

Microgrid with DMG, PV, and BESS support

The proposal to use PV and DMG revealed that this type of curve behavior, where demand peaks occur outside of generation peaks, requires storage support. This allows for the utilization of energy and demand during specific times of predicted excesses, and PV plants can be used to charge the BESS for free. Therefore, four energy storage units, each the same size as the PVs, were installed to provide a secondary source of energy totaling 585 kW during 4 hours. The dispatch of BESS is preferred over DMG. Figure 8 shows the general single-line diagram with PV, BESS, and DMG.

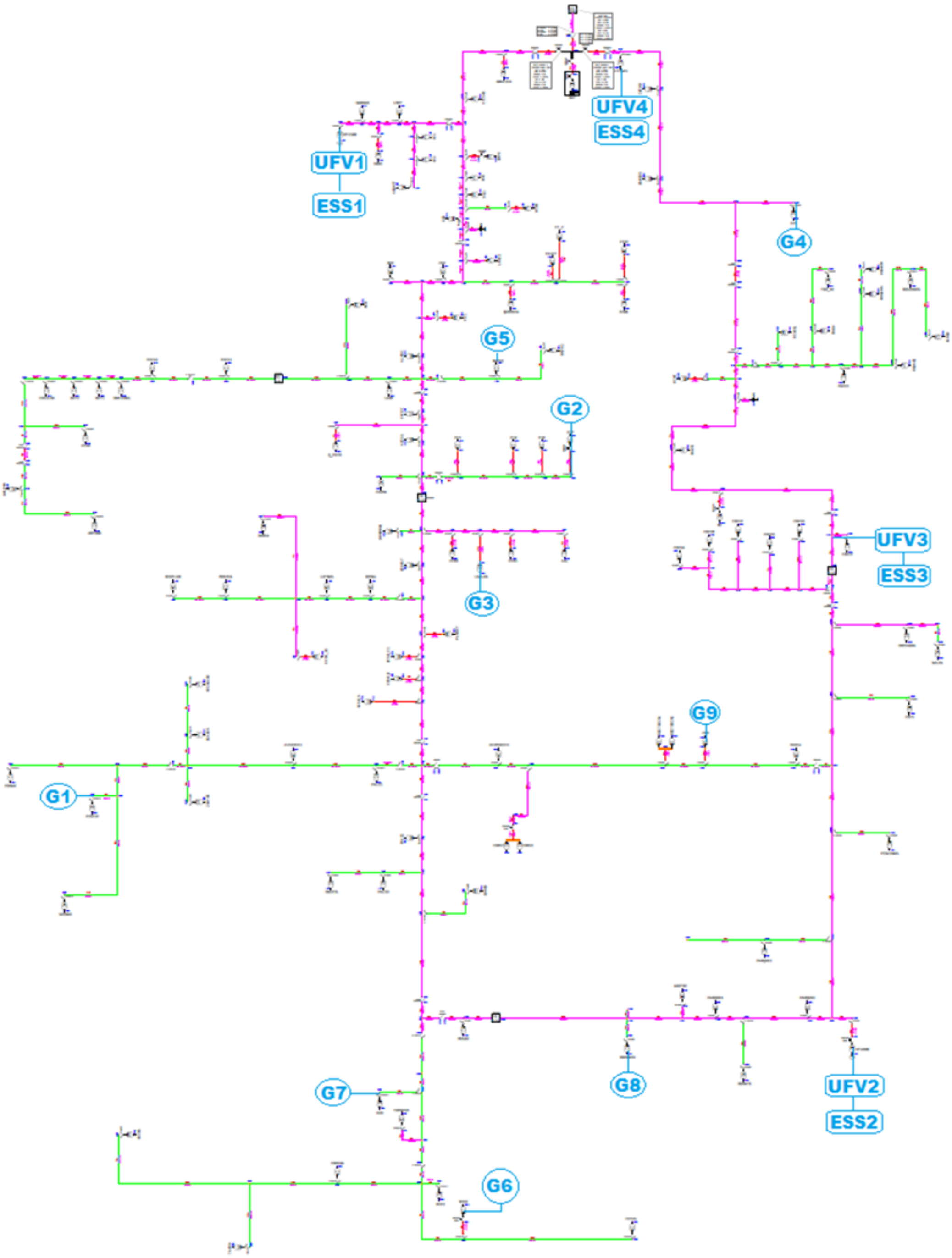

Figure 8. General single-line diagram with DGs.

Figure 9 shows the BESS dispatch with PV support. Negative values mean that the BESS is charging. Figure 10 shows the new DMG dispatch with the help of distributed generation sources. In addition, Figure 11 shows the result achieved in demand with the application of all possible generations managed by the EMS proposed by the author.

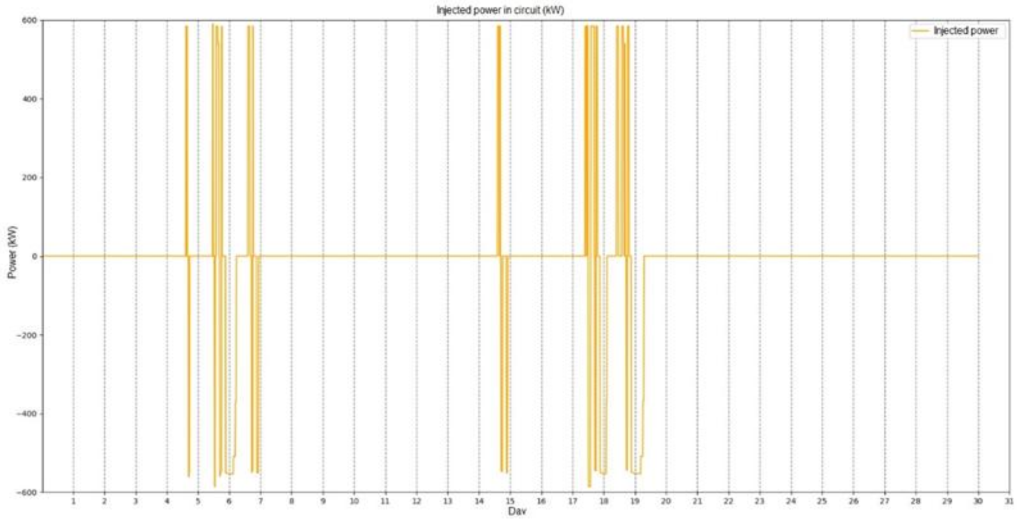

Figure 9. Dispatch of DMG and BESS with PV support in April.

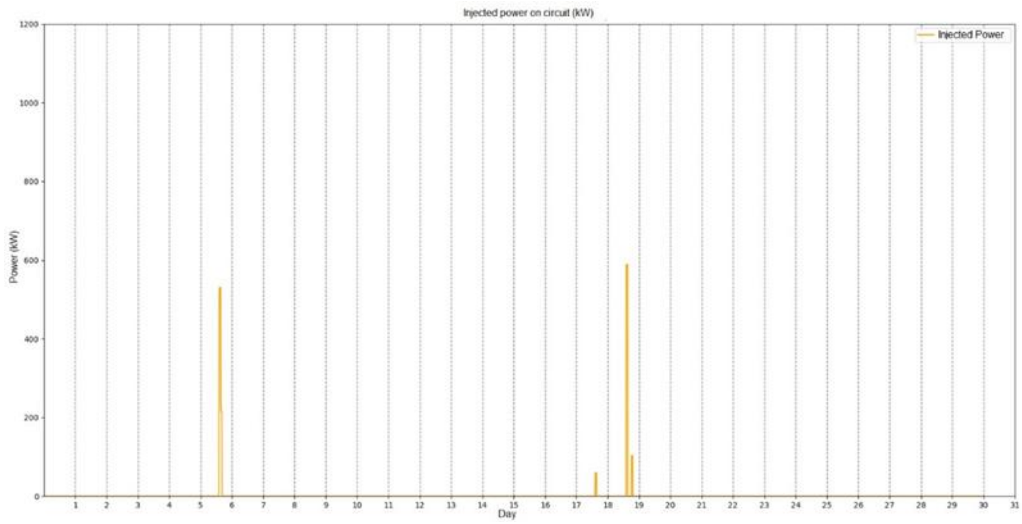

Figure 10. Power Injected by the DMG in April with all Distributed Sources.

Figure 11. Demand resulted in April with all Distributed Sources.

During the compared month, DMG sets showed a significant decrease in their entry into the microgrid operation. Upon analysis of the microgrid's demand, it was observed that the excess demand was eliminated, thereby avoiding any fines.

With PV and BESS support, the EMS was successful in eliminating R$166,447.37 in fines and excess demand by consuming 1342.70 liters of diesel, resulting in savings of R$201,717.47. Compared to the base case, the utility's consumption was reduced by 101,553.12 kWh through the use of PV and BESS. Table 3 presents a comparison of the results obtained, including energy consumption and demand in the two periods, as well as the operating cost of the microgrid.

Table 3. Results from case tests

Quantity	BASE CASE	BASE CASE + DMG	DMG + PV + BESS
Peak consumption [kWh]	173,716.90	169,556.97	170,757.78
Off-peak consumption [kWh]	1,333,889.15	1,288,333.44	1,230,295.15
Peak demand [kW]	3,369.20	3,000.00	3,000.00
Off-peak demand [kW]	6,267.20	5,715.50	5,135.60
Diesel consumption [l]	0.00	3,853.55	1,342.70
Spending on Diesel [R$]	0.00	24,701.45	8,606.39
Energy Cost [R$]	688,308.61	668,485.66	644,432.13
Demand Fine Cost [R$]	171,019.26	71,585.77	4,571.88
Total Cost [R$]	859,327.87	740,071.43	657,610.40

It is evident that the utilization of BESS results in a slight increase in energy consumption due to its loading and round-trip efficiency. However, it enables better control of demand and results in savings on diesel oil. Throughout the operation of the microgrid, there were no problems with bus voltage or feeder loading.

V. Conclusion

It is possible to obtain significant economic results with good energy management of controllable DER on the microgrid, especially when looking not to exceed a contracted demand with the utility and avoid fines. At first, it can be stated that the reduction in operating cost is quite significant when using dispatchable DMG sets. The decrease in maximum peak demand is not significant with the addition of PV generation. Still, the frequency of DMG use is reduced entirely, which was also sought throughout the work. Finally, the installation of BESS was a significant asset for utilizing clean energy from renewable sources, eliminating fines, and positioning DMG in reserve, functioning only as a backup outside of hours when there is no PV energy production or when the batteries are depleted.

VI. Acknowledgment

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