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Multiperiod Optimum Power Flow for Optimization of an Active Distribution Network with Battery Energy Storage Systems

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HIGHLIGHTS

- Optimization of distribution grid operation with distributed energy resources.
- Modeling and simulation of an Optimum Power Flow solved with Interior Points Method implemented in Python language.
- Robustness even with the implementation in a 90 bus test distribution feeder with multiple distributed energy resources simultaneously.

Abstract: Distribution power grids are continuously changing, mainly due to the insertion of distributed energy resources. Since the late 90's the distribution generation insertion has been growing, changing the planning and operation of the conventional grid. More recently, storage systems are also being placed on the distribution power system, aiming to improve system power quality and reliability. In this context of active grids, an Optimum Power Flow (OPF) was proposed, integrating generation from distributed generation with photovoltaic systems as well as a battery energy storage, which could be located at different feeder busses, including the substation bus. The OPF was modeled in a multiperiod structure, allowing simultaneous evaluation of all steps within the time horizon, being solved with the interior points method implemented in python. Different scenarios were evaluated considering different distributed generation levels, as well as battery placement at the substation bus and in the middle of the grid. From the multiperiod OPF results, it is obtained the minimization of losses and operational costs of the system, besides the minimum battery cost and the optimum behavior of charge and discharge of the battery.

Keywords: Active Distribution Network; Distributed Energy Resource; Optimum Power Flow; Battery Energy Storage Systems.

INTRODUCTION

Distribution networks are constantly changing since the increasing of the distributed energy resources, being transformed into active systems. In their conception, the distribution networks were planned to be passive systems, only delivering power to the loads installed along with the distribution system. However, since the late 1990s, with the initial generation systems installations at the distribution grid it becomes no longer passive, but an active system, in which the power flow goes not only in a one-directional but in multiple directions inside the feeder. With this change, the challenges to operating the power distribution grid start to increase.

Over the years more resources had been placed and enabled at the distribution networks, such as energy storage systems, which can contribute improving the power grid operation; electrical vehicles, that are growing mainly due to the concert with the greenhouse gas emissions; flexible loads and demand-side management, which are becoming possible due to the advanced metering infrastructure, and more recently the microgrids, that correspond to the possibility of part of the grid operate connected or disconnected from the main grid according to the necessity of energy transition between the microgrid and the main grid.

With all these distributed energy resources it is important to evaluate the operation of the distribution grid to ensure reliable operation and power quality levels. Thus, different techniques are possible to be applied to carry out these studies, being one of then the optimum power flow (OPF).

Considering the connection of photovoltaic systems (PV) with storage, the work developed by [1] presented an optimum power flow solved with multi-period programming. The main objective was to reduce the energy costs for the consumer, manage the power flow of its system to the power grid, and, additionally, reduce the aging cost of the batteries. From the optimum power flow solution, the resulting battery behavior presented the charge of the system during the solar generation and discharging during the peak load time.

In [2] a multi-period OPF including a battery energy storage system is proposed to predict the behavior of the system looking for a forecasted 24 hours ahead. The main objective of the optimization problem is to reduce the cost of the generation and the prices of battery operation, applying the constraints of active and reactive power flow balance, voltage limits, generators limits, and the battery system constraints. In this case, the optimization process is performed with GAMS software and the results show the best operation for the generators and the battery system considering different price scenarios.

The work developed by [3] evaluated the integration of battery energy storage systems in distribution systems that also present renewable energy systems connected, as photovoltaic and wind systems. To evaluate the integration of the systems, a multi-objective problem was proposed, in which the battery modeling is defined by the state-of-charge (SOC) and state-of-health (SOH), which considers the cycle aging and the temperature effects. In this case, the objective function of the optimization problem consisted in minimizing the distribution system costs, including the cost of power losses, the peak demand, and the voltage regulation. Battery and distribution system constraints were considered, resulting in a nonlinear optimization problem solved using the interior-point method.

Other papers, like [4], [5], also present the integration of a battery energy storage system (BESS) to distribution grids, evaluating their behavior and impacts on power system operation. In [6] authors propose the usage of a multiperiod optimum power flow that includes the BESS modeling. In a multi-period approach, an entire period can be optimized simultaneously, considering the dependency from one to another. For the battery modeling, the authors of [6] considered the power and energy limits of the BESS, as well as different costs for charging and discharging. The OPF is modeled for an IEEE-30 bus circuit and the objective function aims to minimize the costs of generation and battery operation.

Following a similar approach, this paper presents a Multi-Period Optimum Power Flow (MOPF) for an active distribution grid which presents distributed generation and energy storage system. For the modeling, the entire grid characteristics are considered instead of an equivalent grid model, allowing for optimization of the operation of the voltage regulators placed on the feeder. The horizon of study is 24 hours ahead. The developed MOPF is solved using the Interior Points Method considering Primal-Dual formulation since it presents a good approach for nonlinear systems. All the representations, including all the equations of the proposed MOPF, were implemented using Python language, being not used any solver. For the simulations, a 90-bus test circuit was considered.

The structure of the present paper consists in: Section 2 the MFOP concepts and formulation proposed are described, Section 3 presents the case of study and simulation scenarios, and in Section 4 the results from simulations are illustrated and discussed, as well the computational improvements.

Multiperiod Optimum Power Flow

Concepts of the MOPF and Solution Techniques

An OPF corresponds to an optimization problem that is defined by an objective function and some constraints. In this case, the objective function describes some characteristics that must be optimized, such as power losses, operational costs, and others. The constraints, however, represent the operational limits of the power grid and equipment, being defined by equality and inequality expressions. When a MOPF is considered, the optimization is realized considering a given number of periods for a selected horizon, simultaneously.

The sizing of the objective function is related to the sizing of the variables and its complexity is related to the objectives that are modeled. On the other hand, the constraints are dependent on the complexity of the variable modeling as well the sizing of the system. In a multiperiod approach, both structures are dependent on the number of periods.

As it consists of an optimization problem, different techniques can be used to solve it, being found examples that implement classical techniques as Interior Points, Linear, Non-Linear or Mixed Programming, Quadratic Programming, and Newton's Method; solvers as GAMS, CPLEX, Matlab Interior Points Methods; or that implement artificial intelligence techniques as genetic algorithms, fuzzy, ant colony, or particle swarm optimization to solve the OPF [7].

The classical approaches for solving the OPF usually apply sensitive analysis and gradient-based optimization. Most of the computational time is related to the Karush-Kuhn-Tucker (KKT) conditions, which size is dependent on the size of the system (number of buses) and the size of the period simulated (number of periods) [8], [9].

For the present work, the Interior Points Primal-Dual version was implemented, since it presents a good convergence for non-linear systems, getting the optimum solution in a shot-time calculation.

Distributed Generation Representation at MOPF

The distributed generation systems considered correspond to photovoltaic systems, representing non-dispatchable sources, since it depends only on solar radiance. In this way the PV generation profile is provided, being characterized as an input variable.

In the developed formulation, the PV power factor is considered constant during the entire period. Therefore, for the MOPF the PVs placed along the distribution grid correspond to an active and reactive power source since the power factor previously defined can be different from one.

Energy Storage System Model at MOPF

For the energy storage representation, it was considered a battery system (BESS), due to a large number of real-case applications at the distribution grid [10]. The battery formulation proposed is based on [7] and [11], is considered the power, energy, efficiency, and degradation cost of the BESS operation.

Active power of a BESS which is connected at bus i at the period t ($Pbat_i^t$) is limited according to the sizing of the system and how much power it can absorb (charge, positive value) or provide (discharge, negative value) to the power grid (1) along 24 hours:

$$Pbat_i^{min} \leq Pbat_i^t \leq Pbat_i^{max} \quad i=1,.., nbat \text{ and } t=1,..,24 \tag{1}$$

where $nbat$ is the number of BESS connected at the system, $Pbat_i^{min}$ and $Pbat_i^{max}$ are minimum and maximum limits of the active power of BESS at bus *i,* respectively

The stored energy in the BESS which is connected at bus i at the period t ($Ebat_i^t$) represents its storage energy (given in kWh), which is associated with the battery capacity. It can be represented by a range of values, being the inferior boundary dependent of the DoD (Depth-of-Discharge). If a battery realizes a DoD of 70%, the minimum value of the energy in the BESS is 30% of its nominal capacity:

$$Ebat_{acum}{}^{\mathbf{min}} \leq Ebat_i^t \leq Ebat_{acum}{}^{\mathbf{max}} \quad i=1,.., nbat \text{ and } t=1,..,24 \tag{2}$$

where $Ebat_{acum}{}^{\mathbf{min}}$ and $Ebat_{acum}{}^{\mathbf{max}}$ are the minimum and maximum limits of energy stored capacity of BESS*;* respectively*.*

$Ebat$ can be calculated using equation (3), which is calculated as a sum of the power that is stored or provided from the system at each time interval (Δt) regarding the energy storage at the beginning of the simulation time ($Ebat\_arrival_i^{t0}$). In this calculation, the energy efficiency (eta) of the charging and discharging process is considered, since it affects the amount of energy that is being delivered through the system. This efficiency value is dependent on the storage technology, being for example for lithium-ion batteries above 90% [12].

$$Ebat_i^t = \sum_{t=1}^{24}[Pbat_i^t - (1-eta).|Pbat_i^t|].\Delta t + Ebat\_arrival_i^{t0} \quad i=1,..,nbat \text{ and } t=1,..,24 \tag{3}$$

The cost of operating BESS is associated with the cost of the degradation due to the battery usage since with each operation the system reduces its lifetime, and therefore, it should be depreciated from its cost of acquisition. To estimate the degradation cost, equation (4) was defined, based on [13], in which $cost_{BB}$ is the cost of the battery bank acquisition [$], $cycles$ is the number of cycles that BESS perform with the DoD defined until failure, and $Ebess$ is the battery energy capacity [MWh]:

$$cost_{degradation} = \frac{cost_{BB}}{DoD.cycles.Ebess} \quad \left[\frac{\$}{MWh}\right] \tag{4}$$

Objective Function of the Proposed MOPF

The objective function (OF) proposed is a multi-criteria function, being composed of three parcels: the minimization of power losses (5), the operational cost (6), and the battery degradation cost (7):

$$flosses = wp.\mathrm{c}\left(\sum_{t=1}^{np}\sum_{i=1}^{nb} Pg_i^t + Psun_i^t - Pd_i^t - Pbat_i^t\right) \tag{5}$$

$$foper = wc.\mathrm{c}\left(\sum_{t=1}^{np}\sum_{i=1}^{nb} Pg_i^t\right) \tag{6}$$

$$fcost\_bat = wbat.\mathrm{c}\left(\sum_{t=1}^{np}\sum_{i=1}^{nb} Pbat_i^t\right) - wload.c\left(\sum_{t=1}^{np}\sum_{i=1}^{nb} Pbat_i^t\right) \tag{7}$$

where: *nb* is the number of buses, np is the number of periods; c( ) are the cost functions; Pg_i^t is the total generation power at each bus i and period t corresponding to the substation; $Psun_i^t$ is the solar generation at each bus i and period t; Pd_i^t is the power demand at bus i and period t; $Pbat_i^t$ is the power injection of the BESS connected bus i and period t, wp, wc, and $wbat$ are the weights of the OF objectives; and $wload$ is a weight to maximize the battery charging. At equation (7) the cost function of the BESS active power behavior is associated to the cost degradation, defined at equation (4).

Complete Formulation of the Proposed MOPF

The complete problem formulation is given by:

$$\min flosses + foper + fcost\_bat$$

s.t.

$$Pg_i^t + Psun_i^t - Pd_i^t - Pbat_i^t = P_i^t(\dot{V}, areg) \tag{8}$$

$$Qg_i^t + Psun_i^t \tan(\operatorname{acos}(pf)) - Pd_i^t.\tan(\operatorname{acos}(pf)) - Pbat_i^t.\tan(\operatorname{acos}(pf)) = Q_i^t(\dot{V}, areg) \tag{9}$$

$$Vmin_i^t \le \left|\dot{V}_i^t\right| \le Vmax_i^t \tag{10}$$

$$-flmax_j^t \le fl_j^t \le flmax_j^t \tag{11}$$

$$amin_j^t \leq areg_j^t \leq amax_j^t \tag{12}$$

$$Pbat_i^{min} \leq Pbat_i^t \leq Pbat_i^{max} \tag{13}$$

$$Ebat\_acum^{\mathbf{min}} \leq Ebat_i^t \leq Ebat\_acum^{\mathbf{max}} \tag{14}$$

i=1,.., nb, j=1,…, nl and t=1,..,24.

Equations (8) and (9) are the equality constraints that represent the active and reactive power balance, respectively. The inequality constraints represent the operational limits of the grid or the equipment. Equation (10) is related to voltage limits ($\dot{V}_i^t$ is the voltage magnitude of bus *i* and period t). Equation (11) is related to the limits of the power flow through the *nl* lines of the network (fl_j^t is the power flow through the line *j* and period t) and equation (12) represent the limits of the taps positions of voltage regulators ($areg_j^t$ is the tap position of voltage regulator installed at line *j* and period *t*). And Equations (13) and (14) are related to the limits of power and energy of the BESS (as described in equations 1 and 2). The sub-indices *i* represent the buses, *j* the lines, and *t* each time step.

The input data are the power demand, solar generation, voltage limits, taps positions limits of voltage regulators and power lines flow limits, in addition to the system parameters, reference bus, and location of the equipment. For the BESS model, the input parameters are power and energy limits, energy at the begging of the evaluation period, system efficiency, and the location of the BESS, as well as the degradation cost parameters.

The control variables are the voltage magnitudes of each bus and each period, the power provided by the substation bus at each time step, the taps positions of each voltage regulator, also at each time step, and the power and energy of the BESS at each time step.

RESULTS

Study Case

For the simulation, a system with 90 buses was chosen (Figure 1), being 69 Medium Voltage (MV) buses and 20 Low Voltage (LV) [6]. There are 16 PV systems installed at buses 7, 15, 20, 25, 30, 35, 38, 40, 45, 51, 53, 55, 60, 65, 68, totalizing 3.33 MW of installed power; and 69 buses with loads, that totalize 4.755 MW of installed power.

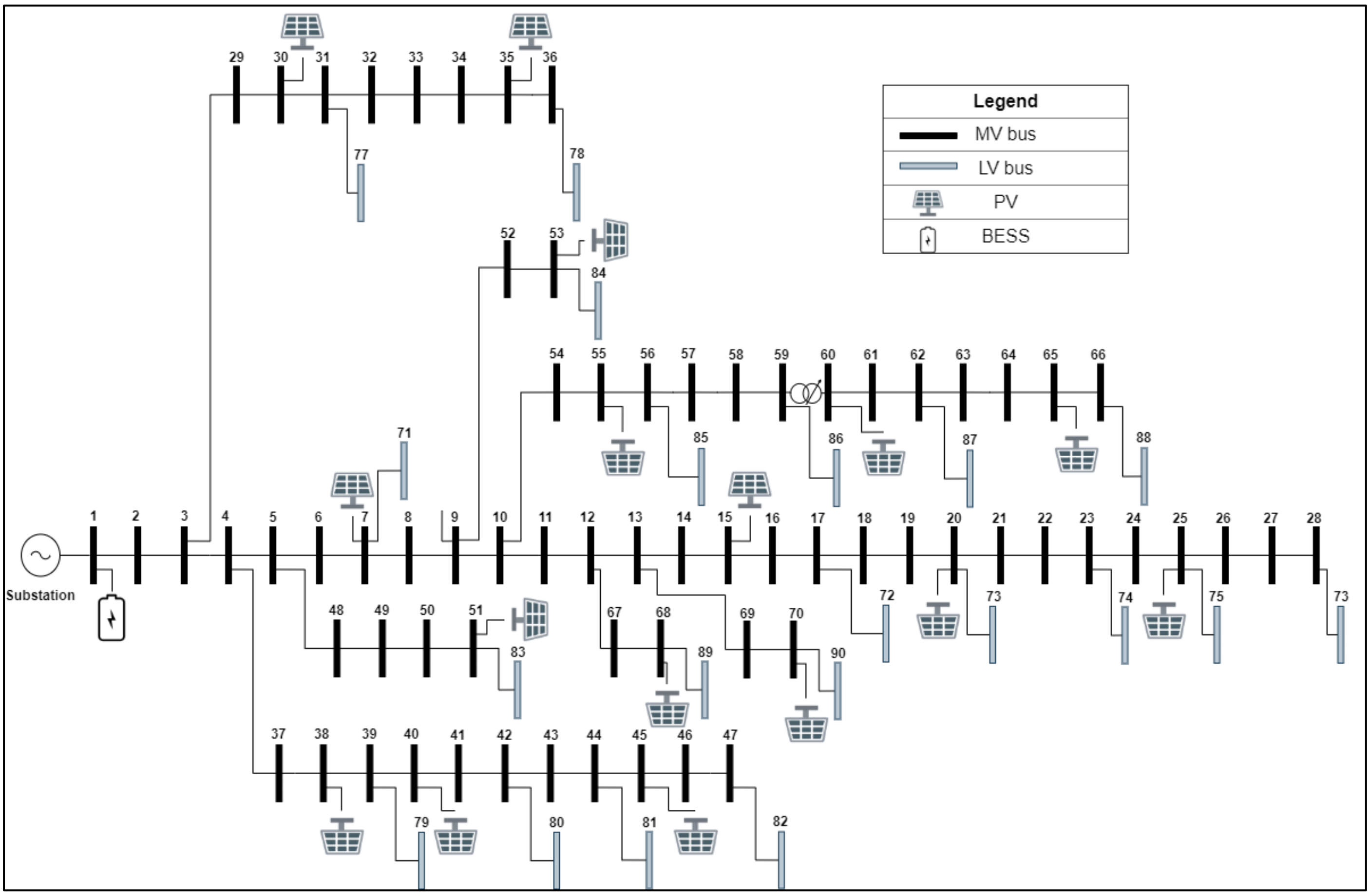

Figure 1. 90 Buses Test Circuit. Adapted from [6].

The total load and solar generation profile per unit are presented in Figure 2. For both curves, the reactive power is calculated considering a power factor of 0.92. The solar profile is based on a real data profile at Curitiba/Paraná/Brazil.

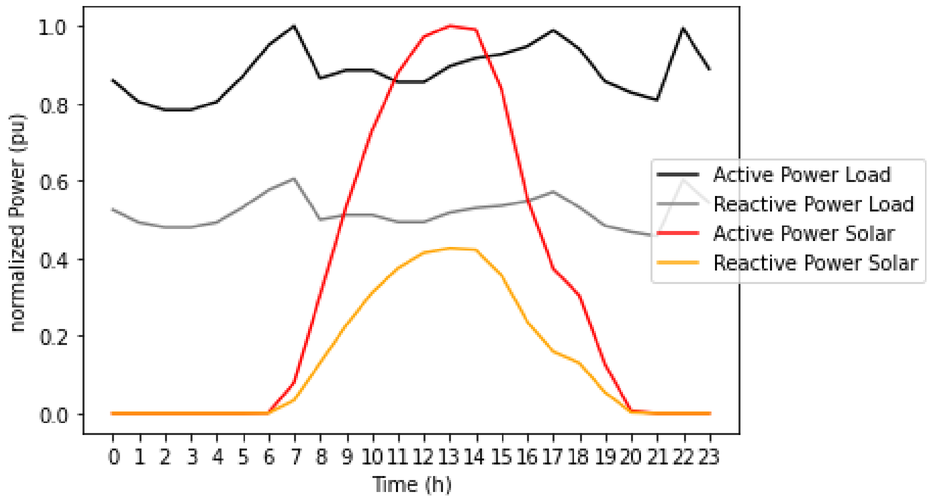

Figure 2. Load and Solar Profiles per unit.

For the BESS, it was chosen a lithium-ion battery with 2MWh/1MW, that will operate with a DoD of 70%. Considering the system technology and size, the cost would be around $ 12 million and the number of cycles until failure, considering the DoD specified is 4,000 cycles. These characteristics were chosen based on some pilot projects that are currently being implemented in Brazil. With these characteristics, it is possible to define the operation range limits as well as the degradation cost. The arrival energy of the battery was considered 30% of the nominal capacity of the system.

The BESS operation will be defined by the optimization problem, basically aiming to reduce the degradation cost of the system, but at the same time, reducing the operational costs and obeying the active and reactive power balance and the other restrictions.

The cost of energy is based on the Brazillian white tariff [14] which behavior is shown in Figure 3. The values used for the white tariff is considered without taxes since it will be used to calculate the operational costs of the power utility.

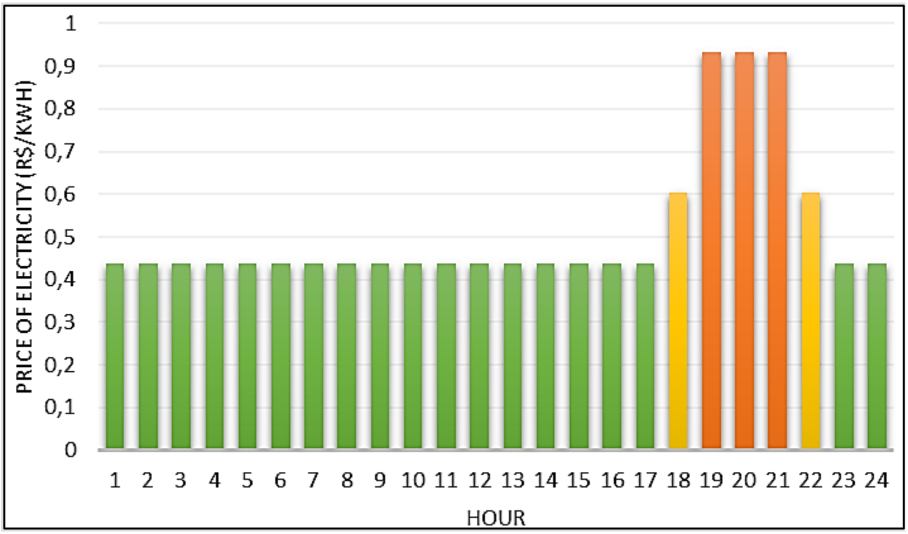

Figure 3. White Tariff prices and behavior. Adapted from [14].

Simulation Scenarios

Aiming to simulate different grid configurations, five scenarios are considered:

- Scenario 1: 90 buses circuit with PV generation;
- Scenario 2: 90 buses circuit with PV generation and BESS at substation bus;
- Scenario 3: 90 buses circuit with PV generation and BESS at bus 9;
- Scenario 4: 90 buses circuit and BESS at bus 9 and 100% of PV penetration (installed power on 4.755 MW);
- Scenario 5: 90 buses circuit with load increase of 20%, PV generation (same of scenarios 1,2, and 3), and BESS at bus 9.

The battery system is initially placed at the substation bus since its owner is the power utility, so this location contributes to the reduction of infrastructure and installation costs (CAPEX). However, when BESS is placed at the substation bus, its grid contribution is reduced in comparison with the cases when the system is placed along the feeder. To test this improvement in system operation, the battery is allocated at bus 9, since downstream of this point is placed 60% of the total load of the circuit.

Power System Results

Simulating all the scenarios, the main results are summarized in Table 1.

Analyzing the results, it is possible to visualize that the biggest difference happens when the solar generation is increased in scenario 4, resulting in the lowest global costs, however, regarding the highest number of iterations to solve the optimization problem. This scenario also presents the highest amount of reverse power flow in the circuit, with power flowing from the largest generation points with PVs to the load buses.

Looking at the total power losses results, it increases in the scenarios when the battery system is considered. It happens since there is the necessity to provide power to charge the BESS, hence, the amount of power flowing through the lines it is higher than in scenario 1. Meanwhile, in all scenarios the total power losses were lower to 5%, being conventionally considered lower. This happens even in the scenario with the increase of power system load.

Evaluating the operational cost, it is lower in the scenario with higher PV generation (scenario 4), because there is more power being provided by these systems and hence, less power needed to be supplied by the substation bus.

Regarding the BESS operation, the large amount of energy stored happens in scenario 4, due to the surplus of solar generation. Additionally, this scenario also presents the highest amount of power delivered from the BESS to the grid, reflecting higher degradation costs and lower operational costs.

The number of iterations is also higher for scenario 4 since in this case is more difficult for the grid to operate inside of the operational levels, defined by the MOPF constraints. In this way, the interactive method needs to do more calculations until finds the optimal solution that fits the boundaries.

Table 1. Results of MFOP simulation for all five scenarios.

Results	Simulation Scenario				
	1	2	3	4	5
Losses (MWh) (% of the total load)	2.520 (2,93%)	2.972 (3,45%)	3.119 (3,62%)	3.171 (3,68%)	4.669 (4,49%)
Total demand (MWh)	86	86	86	86	104
Operation Cost ($)	35,361.78	34,884.67	35,029.08	30,029.62	44,914.01
BESS Location (bus number)	NO	1	9	9	9
Energy Stored (MWh)	NO	1.545	1.414	1.610	1.531
Energy Supplied (MWh)	NO	1.316	1.205	1.371	1.305
Degradation Cost ($)	NO	6,121.24	5,603.90	6,379.16	6,069.20
Number of Iterations	18	25	22	40	27

Figure 4 is presented the power balance seen from the substation bus for scenario 4. In this figure it is visible the entrance of the solar generation during the radiation hours (positive values), as well as the battery charge happening during the same period (negative values), contributing to the reduction of costs since the solar generation is being free provided and contributing to the reduction of the reverse power flow that reaches the substation bus.

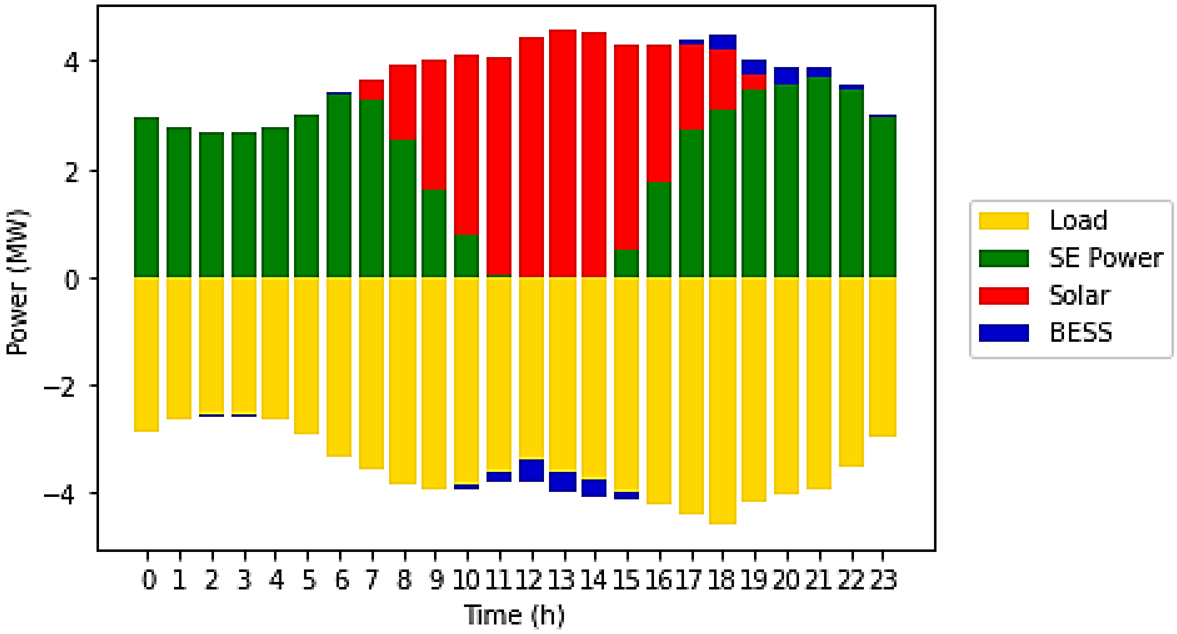

Figure 4. Active power balance at the substation bus at scenario 4.

This reduction of reverse power flow at the substation bus contributes to safety and reliable operation in case of PV increase (Figure 5). As the power grid is not built to have reverse power flow at the substation, and the protection systems are not prepared for this operational condition, the entire protection study must be redone.

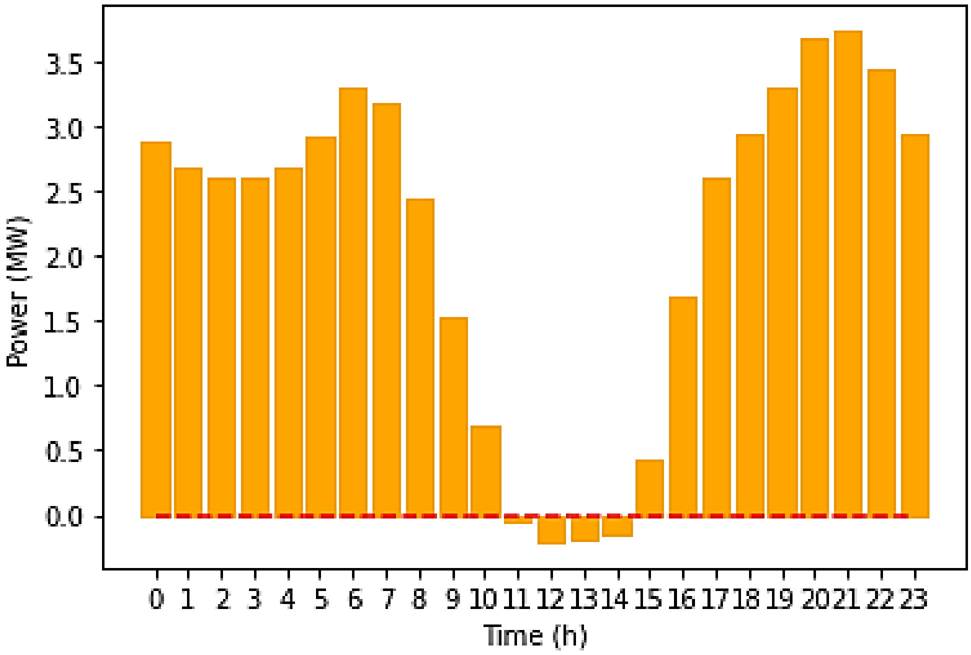

Figure 5. Power flow at the substation bus lines in scenario 4.

Also from scenario 4 results, the voltage regulation TAP needs to operate more than in other scenarios, to avoid the overvoltage caused by the insertion of active and reactive power by the PVs. Figure 6 it is presented the voltage profile of all 90 circuit buses, as well the voltage limits in dashed lines (0.93 pu and 1.05 pu, following the Brazilian regulation). The sinking seen at the entrance time of the solar generation happened by the substation voltage control associated with the TAP operation of the voltage regulator, as shown in Figure 7, being visible the reduction of the tap positions during the period with higher solar generation. For all the scenarios.

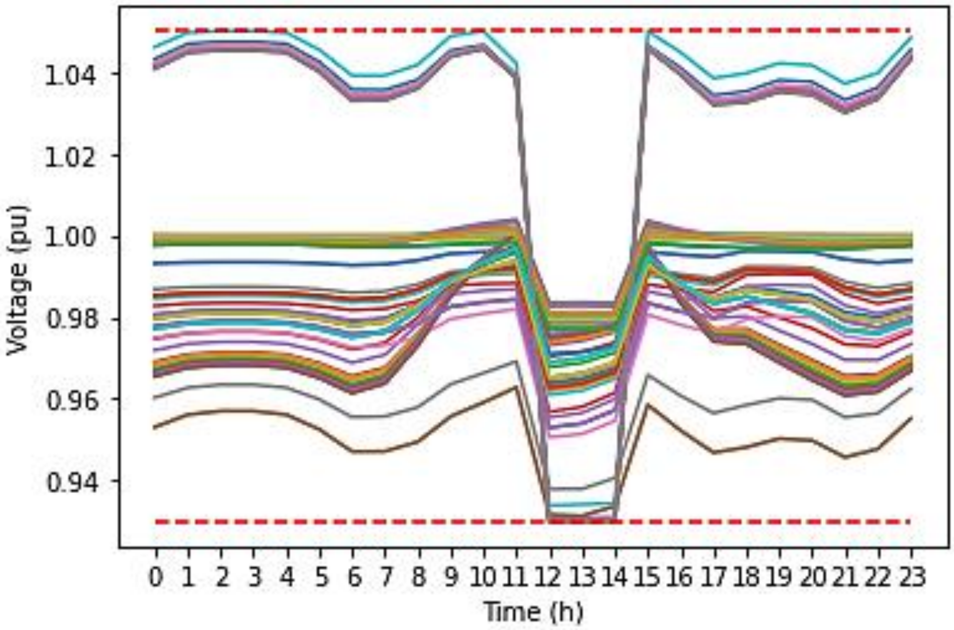

Figure 6. Voltage in all circuit buses when scenario 4 is considered.

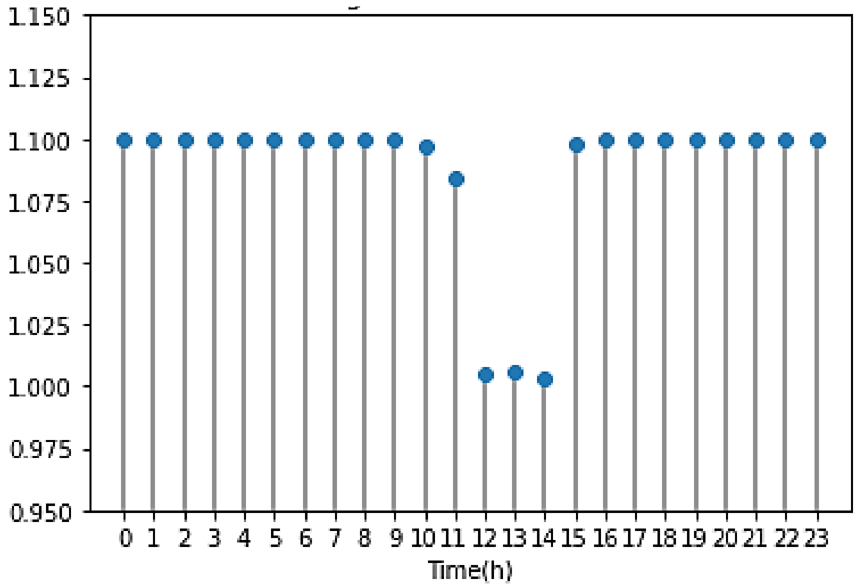

Figure 7. Voltage Regulator TAP positions when scenario 4 is considered.

From the BESS operation, the amount of power storage is not the same that is provided to the power system, since the efficiency of the energy conversion for the electrochemical storage is not 100% but it is considered 92%. The battery power and energy behavior are presented in Figure 8. It is visible that it performs a small charge during the first hours of the day due to the low load on the feeder and, the highest amount of change happens during the solar generation time. The provisioning of power to the grid happens at the peak time since a white tariff is being considered and the cost of the MWh is higher during 18 to 21h.

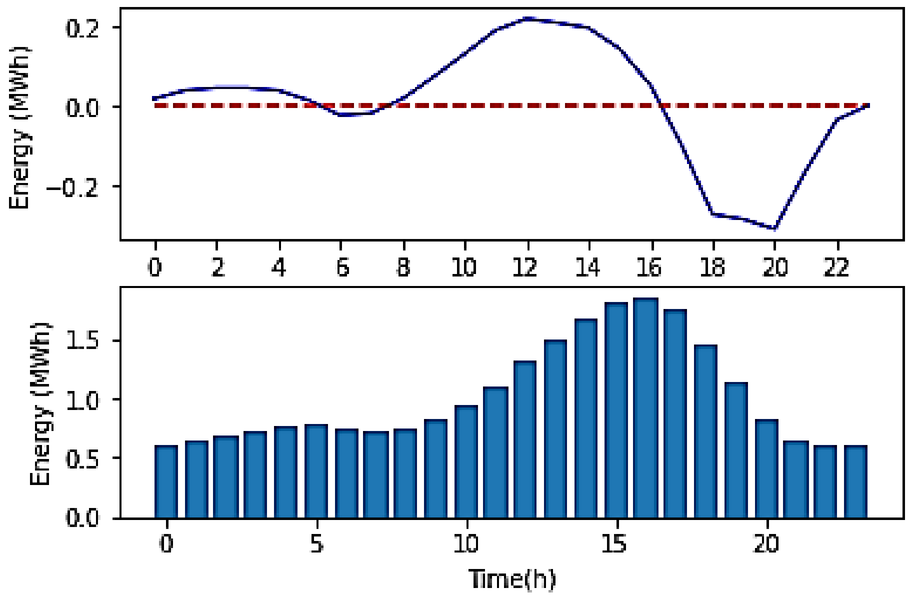

Figure 8. BESS power and energy behavior at bus 9 when scenario 4 is considered.

Computational time results

Throughout the implementation and development of the code, there was an effort to decrease the computational time of the program promoting a reduction from 2 h to approximately 90 seconds for a scenario with battery dispatch, for example. The gradual decreases obtained were obtained with the appropriate use of sparsity techniques and storage of matrices that remain constant throughout the iterative process.

The computational time is highly correlated to the structuring of the matrices. It is important to highlight that the scaling of the matrices depends on the number of buses of the modeled circuit and the number of periods that will be simulated. Therefore, the larger the system, the longer it will take to build the matrices and, consequently, it becomes more necessary to use techniques and models that allow the reduction of computational time, as is the case of matrix sparsity.

The computational program was developed in Python, using the Spyder IDE. All results were gotten considering a computer with 16 GB of RAM.

The process of calculating the solution through the FPO consists of an iterative method so that the solution starts to be found when the calculated infinite norm is smaller than the stipulated tolerance. Figure 9 shows the evolution of the norm values, for scenario 4, until the tolerance is reached and, therefore, the solution of the problem performing, for this scenario, 20 iterations.

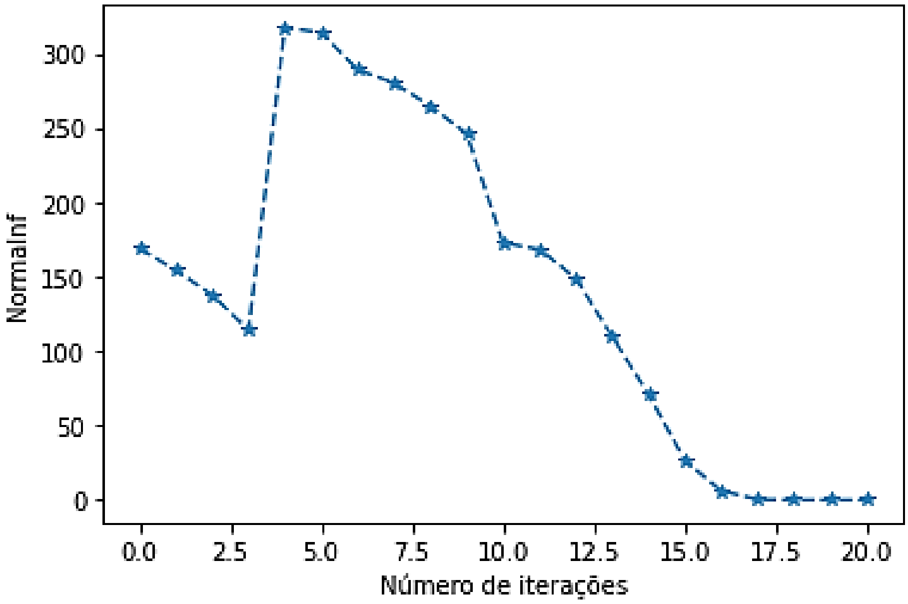

Figure 9. Convergence behavior of the optimization process for scenario 4.

CONCLUSION

With the changes in the distribution power grid, due to the insertion of distributed energy resources as generation and storage systems, it is particularly important to analyze and evaluate the grid operation in different scenarios. So, the article presents a multi-period optimum power flow formulation to make these studies.

With the representation of the battery energy storage and the PV generation, it was possible to evaluate and optimize the system operation considering the insertion of the BESS with different positions along the distribution grid and the insertion of PV with different levels of penetration.

When these different power grid scenarios are evaluated, the highest impact on grid operation is seen when there is the highest PV generation. However, the BESS system can operate aiming to contribute to keeping the grid operation at safety levels, contributing to absorbing reverse power flow that could reach the substation bus.

Evaluating the results obtained in the simulations, it can be seen that the peak shaving behavior by the battery is performed when the network operating costs are reduced, in the same way as seen in [1] and [3], contributing to the reduction of the feeder peak. In cases where there is the presence of distributed generation in conjunction with BESS, the same behavior as presented in [1] and [3] is verified, in which the charging of the BESS is performed during the period of higher solar generation, contributing to minimize the impacts on the grid.

Different power grid conditions can be proposed and evaluated using the formulation proposed, which always gets optimum results of costs (in terms of system operation), power losses, and battery cost degradation. Moreover, it is guaranteed that when the convergence of the optimization problem happens all the defined constraints are being respected in the proposed grid operation.

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