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RESEARCH ARTICLE

A Novel Methodology for Reducing Excessive Reactive Power Consumption Penalties for Photovoltaic Prosumers

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ABSTRACT The present paper proposes a new methodology to solve a problem in the literature in which a consumer becomes eligible for reactive power excess charging (RPEC) after installing a photovoltaic (PV) system, even if its reactive demand has not changed. This problem mainly affects this kind of consumer, which is known as PV prosumers, in countries where the power factor at the point of common coupling (PCC) is used as the main parameter in calculating reactive power excess charges instead of directly pricing the surplus reactive energy delivered from the distribution network. The classical approaches to reducing or eliminating RPEC are based on providing reactive power within the consumer's installations from their PV inverters and their capacitor banks. However, the solutions presented require optimization studies since the costs of producing reactive energy can be even higher than the penalties involved. In this context, we developed a new hourly-based optimization model for the RPEC problem based on the variable neighborhood search meta-heuristic and the Fibonacci search method. In addition, we apply the proposed methodology to two medium voltage prosumers in Santo André, Brazil. The results showed the proposal's effectiveness, mitigating RPEC and minimizing the prosumers' electricity bills without installing new equipment to supply their reactive demand. The best results were found when reactive power was delivered by the capacitor bank and PV inverters simultaneously rather than applying these solutions separately. The proposed hourly-based correction method can help in day-ahead energy management, avoiding premature wear from switching the consumer's reactive power compensation equipment switches. Also, the methodology proposal improved the power factor at the utility substation, which benefits the power distribution systems.

INDEX TERMS Distribution systems, electricity bill, excessive reactive power consumption, Fibonacci search method, photovoltaic generation, power factor, variable neighborhood search.

I. INTRODUCTION

Photovoltaic (PV) generation is a renewable energy source that has experienced rapid growth among medium voltage (MV) consumers in recent years [1]. This growth is explained by many factors, including governmental incentives [2], reduced environmental impact [3], and low maintenance costs [4]. Thus, such growth has allowed the emergence of a new entity in distribution systems, namely PV prosumers, who can act as electricity consumers or

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producers based on the billing structure and its net power demand [5].

PV systems with smart inverters can provide active and reactive power to MV prosumers by adjusting their power factor. This feature reduces the prosumer's net power demand from the network, i.e., the difference between power demand and local power generation. Consequently, low net active power demand values represent reduced costs in the electricity bill. However, as the net active power demand is reduced, the prosumer's power factor measured by the utility at the point of common coupling (PCC) may reach low values [6]. In many countries, if the MV consumer's power factor reaches values below a reference threshold, economic penalties are charged due to the electricity bill as excessive reactive power consumption [7]. Likewise, these penalties apply to PV prosumers connected to MV distribution networks. The reference power factor threshold varies depending on each region's system operator's requirements. For instance, Brazil, Portugal, and Uruguay require MV consumers to maintain a power factor greater than 0.92, while in Canada, a power factor above 0.90 is expected [7], [8]. While the requirements for applying additional fees from excessive reactive power consumption may vary in each region, there is a consensus on imposing economic penalties for low power factor values at the PCC.

A. LITERATURE REVIEW

Transmission and distribution utilities meet reactive power needs by placing power factor requirements on distributed generators and large loads [9], [10]. Thus, the power factor thresholds allow distribution utilities to maintain an adequate substation power factor without investing in new reactive power compensation equipment [11].

The reactive power compensation capability of modern PV inverters is an alternative for improving the prosumer's power factor and avoiding reactive power excess charges. In the literature, several works have addressed the PV reactive power compensation for improving grid characteristics. In [12], the authors highlight the transition of PV inverters operation from unity power factor to new values for reactive power provisioning. The authors analyze the influence of reactive power injection by PV inverters on overall system technical losses. Reference [13] evaluates the effectiveness of distributed PV inverter systems' real and reactive power control to regulate network voltages, reduce energy losses, and increase the network hosting capacity. In [14], the authors provide insights into possible voltage rise problems due to high PV penetration in distribution networks. Reference [15] proposes a grid voltage support algorithm for smart PV inverters based on distributed optimization and peer-to-peer communication. In [16], a consensus-based algorithm is proposed considering PV systems as an intelligent agent for improving voltage profile and reducing voltage unbalances along a distribution feeder.

In contrast to previous works in the literature, in the present study, we consider the reactive power compensation capability of PV inverters to benefit the prosumer by avoiding penalties on their electricity bill. In addition, this compensation improves the power factor of the high-voltage substation of the distribution utilities. However, it is essential to note that the inverter's rating current limits the reactive power compensation. Therefore, due to the low power factor value, reactive power injection from the PV system could not be enough for prosumers to avoid charges. Thus, other alternatives are explored and included in the proposed solution strategy. Typically, the MV consumers' conventional power factor correction operation is carried out by capacitor banks. This reactive power compensation equipment could be used jointly with the inverter power factor adjustment to avoid additional fees due to low power factors in critical cases.

B. PAPER PROPOSAL

This paper presents a novel methodology aimed at mitigating excessive reactive power consumption penalties for PV prosumers connected to the MV network. Since these penalties are part of the electricity bill, the problem is formulated as minimizing the total electricity bill of MV prosumers. This formulation allows visualizing the impact that penalization has on the total electricity expenses, both before and after the application of the proposed approach. For solving this problem, the solution technique considers adjusting the PV inverter's power factor and operating switchable capacitor banks. Thus, this proposal assumes that switchable capacitor banks are installed in the PV prosumer facilities and can be used together for prosumer reactive power compensation. The proposed methodology is based on the Variable Neighborhood Search (VNS) meta-heuristic [17], a robust method that combines local search with organized changes in neighborhood structures to find optimal solutions. The Fibonacci Search Method (FSM) [18] is employed to efficiently explore the problem's search space in each neighborhood structure. Additionally, this paper shows the impacts on the power factor of the distribution companies' substations when prosumers adjust the photovoltaic inverters to a unity power factor. Therefore, the proposed methodology can help distribution operators in connection studies of new PV generators requested by consumers, determining the PV inverter power factor adjustment for the PV generators to be connected to the MV distribution network. Likewise, the proposal could assist the representative of each consumer within a day-ahead energy market.

C. PAPER CONTRIBUTIONS

This work proposes a novel methodology to reduce excessive reactive power consumption fees that manifest on the electricity bill of PV prosumers connected to MV distribution networks. The proposal is an offline tool that aims to reduce the prosumer's electricity bill. The main contributions of the paper are the following:

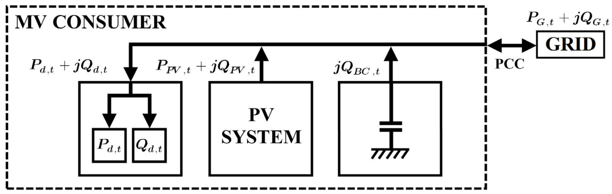

FIGURE 1. MV prosumer with PV system.

1) A new formulation is proposed to characterize the electricity bill reduction problem for MV prosumers with PV generation. This formulation includes the reactive power excess charges due to consumers' low power factor values, costs related to energy consumption, costs associated with the contract demand, and costs corresponding to the use of the distribution system. It should be noted that the proposed formulation is flexible and can, without loss of generality, include other charges considered in electricity billing systems;
2) A new coordinated approach is presented based on the VNS meta-heuristic and the FSM algorithm to solve the formulated problem. This approach includes adjusting the power factor of PV inverters and the operation of switchable capacitor banks to reduce the penalties for a low power factor of the prosumer and increase the economic benefits of installing PV generation;
3) An analysis is performed regarding the power factor variation at the substation that connects the distribution and transmission systems. This analysis encompasses the effects of PV generation operating with a unity power factor and the application of the proposed approach.

D. PAPER ORGANIZATION

The remainder of this paper is organized as follows: Section II presents the characterization of the problem. Section III details the proposed methodology. Section IV shows the performed tests and results, and Section V presents the conclusions of the work.

II. CHARACTERIZATION OF THE PROBLEM

A. THE EQUIPMENT INSTALLED IN EACH PROSUMER

In this work, the proposed methodology seeks to assist distribution operators in connection studies of new PV generators requested by prosumers, determining the PV inverter power factor adjustment for the PV generators to be connected to the MV distribution network. This way, the proposal is executed offline, considering generation and demand forecasts. Also, the methodology considers each MV prosumer has PV generation and switchable capacitor banks, as shown in Fig. 1.

A smart meter at each PCC registers the instantaneous active and reactive power flows, integrating them over a measuring interval t [19]. The MV prosumer's apparent power demand at time interval t is denoted as $S_{d,t}$, where $P_{d,t}$ and $Q_{d,t}$ are the prosumer's active and reactive power demand at time interval t, respectively. The apparent power injected by the PV inverter at time interval t is $S_{PV,t}$, where $P_{PV,t}$ and $Q_{PV,t}$ are the active and reactive power supplied by the PV inverter at time interval t, respectively. The reactive power injected by the capacitor banks at time interval t is $Q_{BC,t}$.

It is possible to denote $P_{G,t} = P_{d,t} - P_{PV,t}$ as the total active power measured at the PCC at time interval t, and $Q_{G,t} = Q_{d,t} - Q_{PV,t} - Q_{BC,t}$ as the total reactive power measured at the PCC at time interval t. The power factor f_t^c measured by the utility at the PCC at time interval t is defined by equation (1).

$$f_t^c = \frac{P_{G,t}}{\sqrt{(P_{G,t})^2 + (Q_{G,t})^2}} \tag{1}$$

It is important to note that if the magnitude of $P_{PV,t}$ increases, the value of the power factor measured at the PCC, f_t^c, is degraded [19]. This degradation occurs even though the demand load curve of the MV prosumer does not change. Also, this degradation could lead to reactive power excess charging if the power factor at the PCC decreases below a threshold established by the distribution system regulator. Modern PV systems can control the reactive power injected into the network by adjusting the inverter's power factor. Therefore, adequate PV inverters and reactive power equipment settings contribute to correcting the power factor at the PCC.

B. PV GENERATION UNCERTAINTIES CHARACTERIZATION

The proposed methodology considers the uncertainties of the parameters that represent PV generation's behavior due to variations in solar irradiance and temperature. According to energy consumption calculation for each PV prosumer, these variations are characterized into an entire billing period. A non-elitist clustering algorithm k-means [20] is employed to generate a set of profiles that represent the behavior of PV generation, characterizing the variables' uncertainty [21]. The k-means algorithm establishes several centroids of data according to the information's similarities and proximity. Thus, historical metering data of PV prosumer is represented by a reduced group of tractable centroids, being the dimension of this group defined by the operator's requirement. The recorded measurements that estimate the behavior of PV generation are divided into N_p profiles depending on the area of study. The number of profiles for each billing period must possess a high internal homogeneity in the chosen grouping and high external heterogeneity of each group concerning its neighbors [22]. Thus, the output of the k-means application is a set of representative groups of PV solar generation curves and their frequency of occurrence within the historical base of the prosumer.

The used approach chooses a generation profile for each day using an evolutionary roulette operator [23], considering the frequency of occurrence as a probability. In this way, the roulette is divided according to the likelihood of each generation profile. This choice allows characterizing the stochasticity expected in the prosumer's billing period [24]. On the other hand, at the distribution operator's criterion, the roulette process can be repeated for each day of the billing period or for a higher amount to find a pattern representative of the electricity bill to be paid by the prosumer. This process results in scenarios for each billing period [24], [25]. Then, all the PV inverter power factor adjustments that correspond to this expected value of the prosumer's energy bill are determined from the average value of all the simulations the operator performs.

III. PROPOSED METHODOLOGY

This section presents the proposed methodology to solve the electricity bill reduction problem. The electricity bill reduction problem is formulated based on the net-metering schemes presented in [8]. The proposed model's main objective is to reduce the MV prosumer's expenses due to electricity consumption considering reactive power excess charges. As such, the problem is formulated as a minimization problem.

A. MATHEMATICAL FORMULATION

1) OBJECTIVE FUNCTION

The objective function of the problem, presented in (2), minimizes the total value of the prosumer's electricity bill, which includes the reactive power excess charges.

$$minimize\ \mathscr{F} = EC + CCD + UDS + REP + RPP \quad (2)$$

In equation (2), the objective function considers the cost of energy consumption (EC), the cost of contract demand (CCD), the cost of use of distribution system (UDS), and the reactive power excess charges due to low power factor values measured by the utility at the PCC. These reactive power excess charges are composed of the reactive energy penalization (REP) and the reactive power penalization (RPP).

There are two basic ways to penalize consumers for reactive excess energy [26], [27]. One of them would be to measure and price reactive energy directly. Another approach, which is practiced in Brazil, consists of pricing the value of the surplus of reactive power based on the power factor and not on the reactive energy directly. In this case, whenever the measured power factor is lower than a reference value, the value of the surplus of reactive power is calculated based on the price of active energy consumed, using a multiplier that depends on the measured power factor and the reference power factor, according to equation (6). In this way, the authors ensure that, at least in their country, this is a valid and practiced methodology for pricing surplus reactive power.

Taking the above into account, equations (6) and (7) consider the penalties that apply to users with high values of active demand, reactive demand, and low power factor (in most cases, factories), as shown in [28]. Although prosumers may have other billing forms, this class of consumers must meet the power factor restrictions, as shown in [29].

The revenue is calculated using equations 3-15 in intervals where the demand is greater than the generation. In intervals where the generation is greater than the demand, the revenue is zero. The cost related to energy consumption is determined by equation (3).

$$EC = \sum_{t\in\Omega_t} c^p_{EC,t}\ \Delta_t\ (P_{d,t} - P_{PV,t}) \quad (3)$$

In (3), a measuring time interval is denoted by t, the time duration of a measuring time interval is represented by Δ_t, and Ω_t is the set of all measuring time intervals along the analysis period. $P_{d,t}$ is the active power demand of the MV prosumer at t. $P_{PV,t}$ is the active power supplied by the PV inverter at t. The parameter $c^p_{EC,t}$ represents the cost of energy at t corresponding to period p. In this work, it is considered two periods with different prices, off-peak and on-peak periods.

The cost of contract demand is calculated by Equation (4).

$$CCD = c_D\ (max\{CD; MD\}) + c_{PD}\ (max\{0; MD - m_{max} CD\}) \quad (4)$$

In (4), the contract demand (CD) is the maximum amount of electric power that the MV prosumer will demand from the utility during the analysis period. The MV prosumer declares the value of CD to the utility. The maximum demand (MD) is the highest value of electrical demand measured during the analysis period. The parameters c_D and c_{PD} are the cost of demand and the penalty cost of demand, respectively. Finally, m_{max} is a tolerance preestablished by the utility. Note that, the first part of (4) multiplies c_D by the maximum value between MD and CD. The second part of (4) is a penalization applied to the electricity bill if MD exceeds the product of m_{max} and CD.

Equation (5) represents the cost for using the distribution system.

$$UDS = \sum_{t\in\Omega_t} c^p_{UDS,t}\ \Delta_t\ (P_{d,t} - P_{PV,t}) \quad (5)$$

In (5), $c^p_{UDS,t}$ is the energy cost related to the use of the distribution system at interval t corresponding to period p.

The reactive power excess charges are determined using Equation (6) and Equation (7).

$$REP = \sum_{t\in\Omega_t} c^p_{EC,t}\ \Delta_t\ (P_{d,t} - P_{PV,t})\ (\frac{f_R}{f^c_t} - 1) \quad (6)$$

$$RPP = c_D(max\{0; [\max_{t\in\Omega_t}(P_{d,t} \cdot \frac{f_R}{f^c_t}) - \max_{t\in\Omega_t}(CD; MD)]\}) \quad \forall f^c_t < f_R, t \in \Omega_t \quad (7)$$

Equation (6) calculates the reactive energy penalization. Equation (7) calculates the reactive power penalization. Both penalizations are only applied when the power factor at the PCC at t (f^c_t), is less than the power factor limit (f_R). Both equations were developed with the intent of penalizing users with high values of active demand, reactive demand, and low power factor (in most cases, factories) [28]. This means that these penalties were compensated to force users to reduce reactive power demand and were not developed considering the presence of distributed generation, although prosumers are currently penalized [30].

2) RESTRICTIONS

The restrictions of the problem are represented by equations (8)–(15).

$$Q_{PV,t} = \begin{cases} P_{PV,t} \cdot \tan(\cos^{-1}(f_t^{PV})) & \text{if } P_{PV,t} \geq \eta \cdot \overline{S}_{PV} \\ 0 & \text{if } P_{PV,t} < \eta \cdot \overline{S}_{PV} \end{cases} \tag{8}$$

$$(P_{PV,t})^2 + (Q_{PV,t})^2 \leq (\overline{S}_{PV})^2 \tag{9}$$

$$\underline{f}^{PV} \leq f_t^{PV} \leq \overline{f}^{PV} \tag{10}$$

$$Q_{cb,t}^{sw} = nsw_{cb,t}\Delta_t Q_{cb} \quad ; nsw_{bc} \in \{0, 1, 2 \ldots, nsw_{cb,max}\} \tag{11}$$

$$f_t^c = \frac{|P_{d,t} - P_{PV,t}|}{\sqrt{(P_{d,t} - P_{PV,t})^2 + (Q_{d,t} - Q_{PV,t} - Q_{cb,t}^{sw})^2}} \tag{12}$$

$$P_{PV_{dc,t}} = P_{mpp} Irradiance_t PTcurve(Temp_t) \tag{13}$$

$$P_{PV,t} = P_{PV_{ac,t}} = P_{PV_{dc,t}} EffCurve(P_{PV_{dc,t}}) \tag{14}$$

$$Q_{PV,t} = P_{PV,t}(tan(acos(\frac{P_{PV,t}}{\overline{S}_{PV}}))) \tag{15}$$

Equation (8) determines the reactive power injected $Q_{PV,t}$ by the PV system at t. Due to grid code and technical limitations, the PV system's possibility of reactive power injection is available if the PV active power generation is above a predefined percentage η of the PV inverter rating capacity $\overline{S}_{PV}$ [31]. Equation (9) represents the PV active and reactive generation limits. Equation (10) represents the limits of the PV inverter power factor f_t^{PV}. In (10), parameters $\underline{f}^{PV}$ and $\overline{f}^{PV}$ are the PV inverter's capacitive and inductive power factor limits, respectively. Equation (11) defines the reactive power injection of switchable capacitor banks $Q_{cb,t}^{sw}$ at t, as dependent on the individual capacity of each capacitor ΔQ_{cb} and the position of the tap $nsw_{cb,t}$ at t, considering a maximum number of tap positions $nsw_{cb,max}$. Equation (12) calculates the power factor of the consumer at the PCC at time interval t.

In many cases, the maximum capacity of distributed generators cannot match the consumer demand [32]. For example, in the case of urban areas where the consumer does not have enough area on their roof to place a photovoltaic system or even suffer from shading problems resulting from buildings or vegetation that can supply all the demand. This is the reason why we want to analyze the cases in which the net load is a positive value as they are the ones that most frequently and can impact the power factor of distribution substation.

For each time interval t, the PV modules output a DC power, $P_{PV_{dc,t}}$. Such power enters the PV inverter and is converted to AC power $P_{PV_{ac,t}}$. The DC power $P_{PV_{dc,t}}$ depends on the nominal value of the PV modules P_{mpp}, set of PV cells, the irradiance value $irradiance_t$ and the temperature efficiency curve $PTcurve(Temp_t)$, being calculated by (13). Considering a unitary power factor, the relationship between AC and DC power is a function of the inverter efficiency curve, being calculated by Equation (14).

For a non-unitary power factor, the amount of active power available will also depend on the amount of reactive power delivered, according to the inverter capability curve which can be represented by the Equation (15). In those equations, S_{PV} represents the maximum the apparent power, $P_{PV,t}$ is the active or real power at time t and $Q_{PV,t}$ represents the reactive power at time t. The equations above are available in various power flow software, such as OpenDSS [33], used in the case study presented in this work.

Initialization. Select the set of neighborhood structures NS_k, $k = 1, \ldots, k_{max}$ that will be used in the descent; find an initial solution x.
Repeat the following sequence until no improvement is obtained
(1) Set $k \leftarrow 1$;
(2) Until $k = k_{max}$, repeat the following steps:
(a) Exploration of neighborhood. Find the best neighbor x' of x ($x' \in NS_k(x)$);
(b) Move or not. If x' is better than x, set $x \leftarrow x'$ and $k \leftarrow 1$; otherwise, set $k \leftarrow k + 1$

FIGURE 2. Steps of the basic VND.

B. VARIABLE NEIGHBORHOOD SEARCH

The VNS algorithm is a metaheuristic that combines search strategies with systematic neighborhood changes to explore the search space of a problem efficiently, which has been used in specialized literature with the Fibonacci search method (FSM) to solve large-scale issues efficiently [34]. VNS is based on the principle that a local optimum within a given neighborhood is not necessarily one within another. The neighborhood change can be performed during the local search stage. VNS efficiency and robustness lie in the correct selection of neighborhood structures [35].

This work employs a coordinated approach based on Variable Neighborhood Descent (VND), a variation of the basic VNS algorithm, to determine the problem's optimal adjustment of the decision variables. In Fig. 2, the steps of the VND algorithm are presented [35].

The VND algorithm begins with an initial solution established as the current solution. Then, the first neighborhood structure is selected and applied to the current solution, generating neighbors as candidate solutions. The quality of each candidate solution is determined by calculating the objective function value for each candidate. The best candidate solution is identified and compared with the current solution. Considering that the best candidate solution is superior to the current one, the best candidate solution is adopted as the new current solution, and the first search structure is selected once again.

On the other hand, if the best candidate solution is not better than the current solution, the second neighborhood structure is selected and applied to the current solution to produce a new set of candidate solutions. Then, the best candidate solution is selected and compared with the current solution. If the best candidate solution is better than the current one, the current solution is actualized, and the first neighborhood structure is selected. Otherwise, the third neighborhood structure is established, and so on until all neighborhood structures are visited.

C. FIBONACCI SEARCH METHOD

The Fibonacci search method [18] is the best approach for finding an optimal solution for single-valued functions [36]. The following characteristics must be considered when solving an optimization problem using the FSM algorithm: (i) the initial interval in which the optimal solution lies is known, (ii) the function to be optimized is unimodal, with one variable to be adjusted, (iii) the exact optimum solution cannot be identified, only a final interval is known. However, the last interval can be reduced as needed, (iv) the number of iterations, denoted as N_f, representing the times the objective function is evaluated, must be defined as an initial parameter. In the initial interval, the search procedure reduces the length of the uncertainty interval iteratively based on the Fibonacci sequence. The complete FSM algorithm can be found in [18].

D. VND-BASED COORDINATED APPROACH APPLIED TO THE PROBLEM

The VND-based coordinated approach identifies the best adjustments to minimize the electricity bill's value. For the problem, two neighborhood structures are defined corresponding to each one of the problem variables. For a correct search space exploration in each neighborhood structure, the FSM algorithm is employed to vary and adapt one decision variable's search process while fixing the remaining variables. The number and search process for each neighborhood structure were defined following the recommendations presented in [37]. The proposed VND-based coordinated approach is described as follows:

1) INITIALIZATION STAGE

The initial solution has the following characteristics: (i) the PV inverter operates with a unity power factor, and (ii) the tap position of the reactive power compensation equipment is set to zero.

2) MAIN STAGE

The proposed coordinated approach's main stage involves applying two neighborhood structures based on the FSM approach, selecting a different variable to be adjusted at each neighborhood structure. The first neighborhood structure performs inverter adjustment modifications, and the second neighborhood structure varies the tap position of reactive power compensation equipment.

It is important to clarify that the number of switchable capacitor banks is in accordance with the recommendations presented in [38].

- First neighborhood structure: This neighborhood structure modifies the inverter power factor using the FSM algorithm. For this purpose, the inverter power factor is the continuous variable that must be adjusted to optimize the objective function.
- Second neighborhood structure: The reactive power compensation equipment's tap position is determined in this neighborhood structure. Because the standard FSM solution is a non-integer value and the tap position must be a discrete number, the original FSM algorithm is modified based on the Branch and Bound Algorithm [39]. This modification checks the resulting FSM solution's upper and lower integer bound, selecting the position with a better objective function value.

E. DETERMINATION OF EQUIPMENT ADJUSTMENTS USING THE PROPOSED COORDINATED APPROACH

This section presents the steps of the proposed methodology to determine the equipment adjustments for the optimization problem. A flowchart is shown in Fig. 3 detailing the proposed approach.

The description of the flowchart is as follows:

Input data: Data of solar irradiance, temperature, active and reactive demand of the PV prosumer. The number of generation profiles (N_p). The number of neighborhood structures (NS). Establish NS_{max} as the maximum number of NS.

Step 1: Create the generation profiles using the k-means algorithm, considering the number of generation profiles, irradiance data, and temperature data.

Step 2: Define the initial solution. This initial solution consists of a unity power factor setting for the PV inverter, with no capacitor bank in operation.

Step 3: Set the first NS as the current NS, i.e., $NS = 1$.

Step 4: Perform the VNS-based approach until the last NS does not improve the incumbent solution.

Step 5: Gather the final set of equipment adjustments. Finalize the algorithm.

IV. TESTS AND RESULTS

The proposed methodology is applied using the electricity demand of two MV prosumers with different power demand load curves connected to the same distribution feeder. The first is an industrial customer with a contract demand of 1400 kW and an average load curve available in [40]. The distribution utility uses this curve for operation and planning analysis, representing an MV network's average active and reactive power consumption.

The second and real consumer is the Federal University of ABC in Santo André, Brazil. In this consumer, the data used were from measurements taken of the structure that is already in operation. The PV systems are part of an energy efficiency project to encourage distributed renewable resources such as PV systems in public universities.

A modified version of the 14-node network [41] is employed for analyzing the power factor at the substation

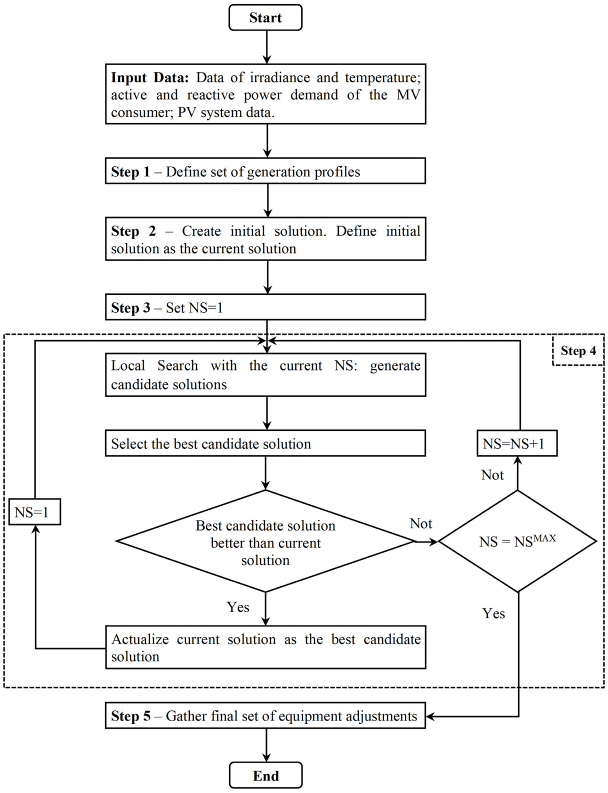

FIGURE 3. Flowchart of the proposed coordinated approach.

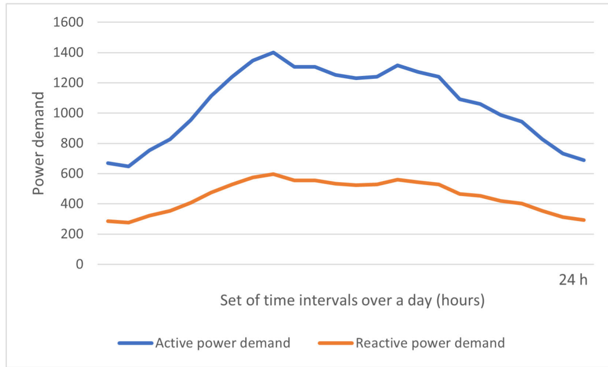

FIGURE 4. Load curve of the industrial consumer.

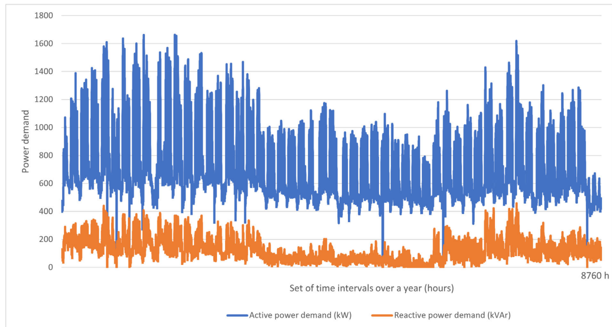

FIGURE 5. Load curve of the federal university of ABC.

that connects the distribution and transmission system. In this network, the load at bus 13 is replaced by the load of the industrial customer, while the load of the Federal University of ABC replaces the loads at buses 6 and 11.

For both MV prosumers, the total analysis period is defined as one year. The parameters of the proposed approach are as follows: $\underline{f}^{PV} = 0.90$ capacitive, $\overline{f}^{PV} = 0.90$ reactive, $\overline{S}_{PV} = 473$ kVA, $\eta = 50\%$, $NS^{max} = 2$, $N_f = 20$, $\Delta Q_{cb} = 30$, $nsw_{cb,max} = 3$. Following the recommendations in [8], the low power factor penalization values are analyzed hourly, as such $\Delta_t = 1$h, $f_R = 0.92$, on-peak hour price of energy is set as 0.0647 US$/kWh, off-peak hour price of energy is set as 0.0430 US$/kWh, on-peak hour price of use of distribution system is set as 0.0738 US$/kWh, off-peak hour price of use of distribution system is set as 0.0116 US$/kWh, $c_D = 1.6020$ US$/kW, $c_{PD} = 3.2040$ US$/kW, $m_{max} = 1.05$. The load curve of the industrial consumer during a day is illustrated in Fig. 4. This load curve is assumed to repeat every day throughout the year. The load curve of the Federal University of ABC over the course of a year is presented in Fig. 5.

The proposed coordinated approach is implemented using MATLAB, on a computer with 2.20 GHz Intel® Core^{TM} i7-8750H CPU and 16 GB of RAM. Historical solar irradiance data and temperature are grouped using the k-means algorithm [20]. The proposed methodology considers that a set of photovoltaic solar generation scenarios were defined for consumers and utility executing the coordination proposal to define the power factor of the inverters and change the tap of the capacitor bank. These scenarios can be found by clustering techniques to find generation patterns in the study zone. When applying the proposal, was considered four scenarios using the k-means clustering technique. Such scenarios and methods have been employed by several authors in the specialized literature, as shown in [42], [43], and [44]. However, the necessary number of scenarios may differ for other study zones. It is important to highlight that the number of generation profiles and how they were obtained is a process that occurs before executing the coordination proposal and depends on the study zones. Figures 6a-6l present the generation profiles for each month throughout the year, respectively. In this figure, each color represents a generation profile for each analyzed month.

The maximum number of neighborhoods and their radius must be calibrated to execute the VNS algorithm. The parameters were calibrated following the recommendations presented in [35] and [45], verifying that after a series of executions, there is a high value of repetition frequency for the best solution.

On the other hand, in the Fibonacci method, the upper and lower limits of the interval where the decision variable is located must be defined, as shown in [46]. Regarding historical data, the algorithms and techniques used can reproduce the values that appear on the consumers'

TABLE 1. Summary of the results for an industrial consumer (US$).

Case	Minimum	Average	Maximum
I	564,403.35	568,518.69	573,057.38
II	561,212.90	566,033.25	571,280.96
III	559,750.43	564,287.41	569,320.81
IV	558,785.75	563,567.33	568,830.12

electricity bills under analysis. Additionally, the irradiance and temperature curves from metering systems in the study area were utilized. These curves enable the determination of the generation value of photovoltaic systems, using equations (13) - (15) available in the OpenDSS software. Many distribution companies worldwide run this software, and in Brazil, it is recommended by the regulatory agency in studies of distribution systems [47].

A. STUDY CASES

The following four cases are considered for analyzing the effectiveness of the proposed approach:

- Case I: PV inverter operates with a unity power factor. The operation of capacitor banks is disabled;
- Case II: PV inverter power factor is adjusted hourly. The operation of capacitor banks is disabled;
- Case III: PV inverter operates with a unity power factor. The operation of capacitor banks is allowed;
- Case IV: PV inverter power factor is adjusted hourly. The operation of capacitor banks is allowed.

B. DISCUSSION OF THE RESULTS FOR AN INDUSTRIAL PROSUMER

Table 1 presents the results for an MV industrial prosumer. This table provides the annual's minimum, average, and maximum electricity bill values across Cases I–IV.

By analyzing Table 1, it can be verified that the annual's highest electricity bill value corresponds to Case I, where the PV inverter is set to operate with unity power factor. Considering the PV inverter power factor adjustment, Case II in Table 1 shows that the MV prosumer's electricity bill value can be reduced compared to the case where PV inverters only inject active power. The average electricity bill value can be decreased by up to US$ 2,485.44 when compared with the results in Case I. However, the capacity of the PV inverter to inject reactive power is insufficient to avoid all excessive reactive power consumption fees entirely. According to (9), the inverter's rating capacity limits the PV system's reactive power injection.

The operation of capacitor banks (see Case III), can decrease the average electricity bill value by up to US$ 4,231.28 compared to Case I. This reduction results from the reactive power compensation capability of the capacitor banks. Moreover, it can be verified that the operation of capacitor banks offers better results than adjusting the PV inverter's power factor.

Finally, by analyzing Case IV, it is possible to verify that the total average annual electricity bill amount is reduced by up to a US$ 4,951.36 concerning the case with the PV inverter operating with unity power factor.

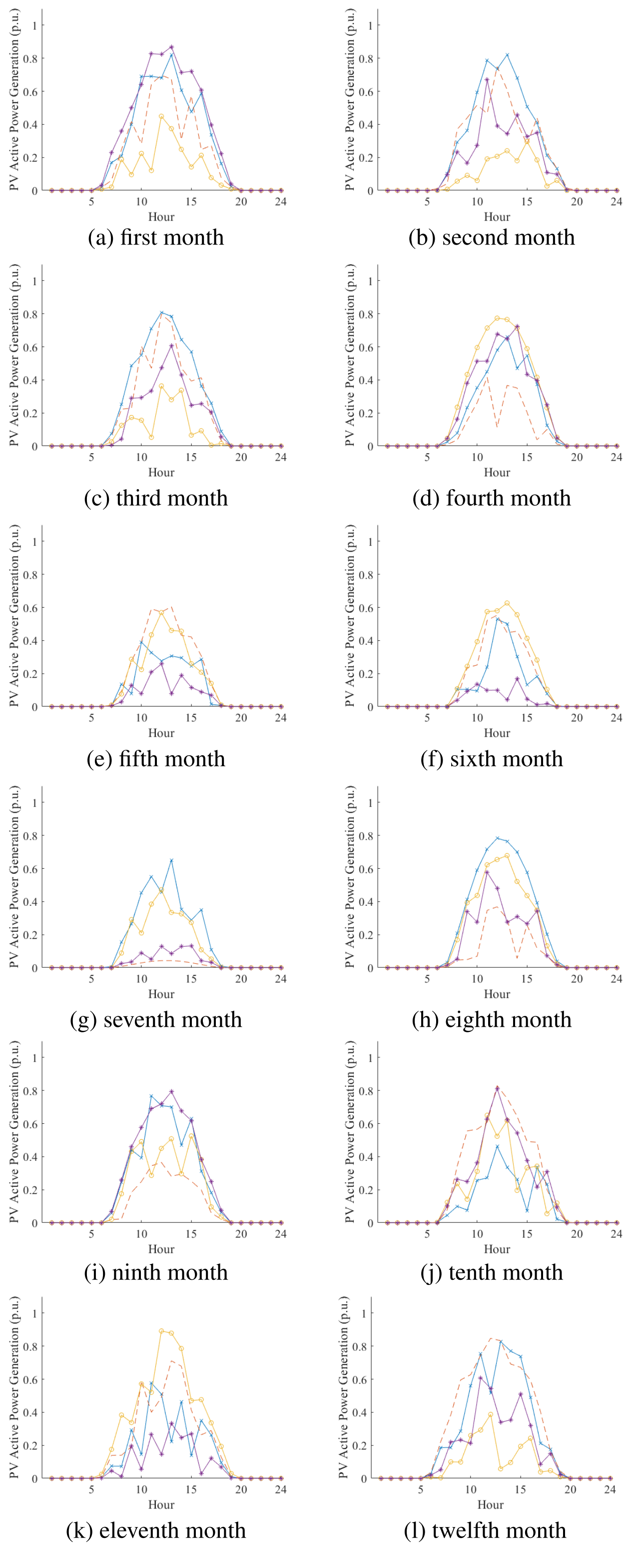

FIGURE 6. Generation profiles for each month throughout a year.

Therefore, it can be verified that adjusting the power factor of the PV inverter and capacitor bank operation

TABLE 2. Summary of the results for the federal university of ABC (US$).

Case	Minimum	Average	Maximum
I	396,082.96	402,211.81	409,057.61
II	395,924.06	402,097.15	408,969.94
III	395,862.96	402,042.73	408,913.40
IV	395,862.14	402,040.53	408,912.68

can provide more flexible solutions to the problem. For instance, solutions obtained solely through inverter power factor adjustment (see Case II) have an average electricity bill more significantly than in Case IV. Since inadequate coordination between the PV inverter and capacitor bank operation may bring problems for MV prosumers, according to (1), the proposed approach can offer more suitable solutions.

The computational times for solving each case are always less than 20 minutes and are considerably lower than the 60-minute time commonly used to calculate the FP. This computational time allows the solution to be adopted to avoid penalties in day-ahead energy management. Another advantage is that the methodology provides less wear and tear on the reactive power compensation device, as their controller will only change every 1 hour when minimizing the penalties.

C. DISCUSSION OF THE RESULTS FOR THE CAMPUS SANTO ANDRÉ OF THE FEDERAL UNIVERSITY OF ABC

Table 2 presents the annual's results for the Campus Santo André of the Federal University of ABC. This table shows the minimum, average and maximum electricity bills for Cases I–IV's.

In Table 2, it can be verified that the highest electricity bill value is registered in the case where the PV inverter only injects active power into the system. In addition, the Adjustment of the power factor of the photovoltaic inverter and capacitor bank operation reduces the amounts paid by prosumers in Cases II and III, respectively. The most favorable result is achieved in the case IV, where these devices operate simultaneously.

It's worth highlighting that the annual outcomes exhibit minimal variation across Cases I to IV. This suggests that injecting reactive power from the PV inverter or the capacitor banks has a modest impact on the electricity bill value. This is explained by the power factor at the PCC consistently staying above the predefined limit ($f_R = 0.92$) for the majority of intervals, thus avoiding penalties. Additionally, as shown in Table 2, the reduction in the electricity bill could be considered marginal. Consequently, if the penalty for excessive reactive power consumption constitutes a small percentage of the total electricity bill, the prosumer might choose not to operate reactive power compensation devices. However, prosumers' decision to renounce power factor correction actions at the PCC could result in new challenges for distribution system operators, as presented in Section IV-D.

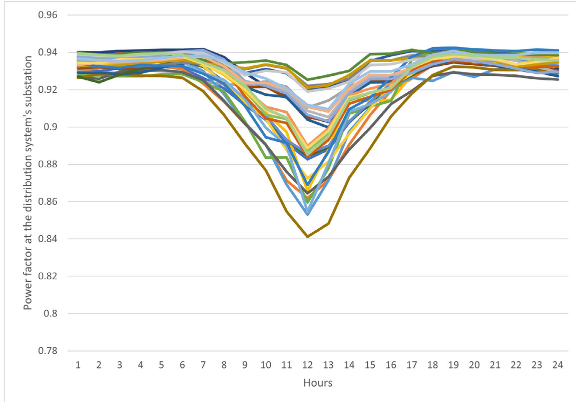

FIGURE 7. Power factor at the substation considering PV generation operating with unity power factor.

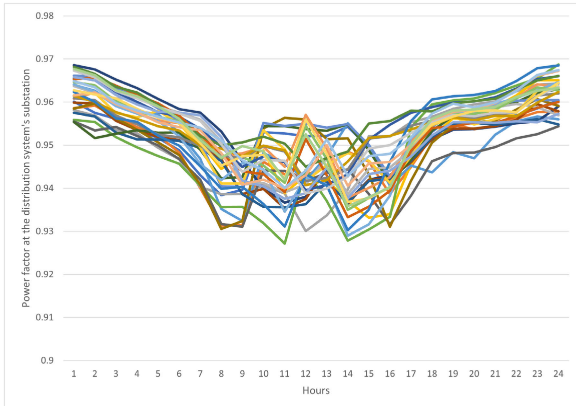

FIGURE 8. Power factor at the substation considering the proposed approach.

D. DISCUSSION REGARDING THE POWER FACTOR AT THE SUBSTATION THAT CONNECTS THE DISTRIBUTION AND TRANSMISSION SYSTEMS

Figure 7 and Figure 8 present the power factor variation at the substation that connects the distribution and transmission systems for all days of the third month. Figure 7 illustrates the outcomes considering PV systems operating with a unity power factor. In contrast, Figure 8 presents the obtained results when allowing the PV inverter power factor adjustment and the operation of capacitor banks.

The standard practice involves separate areas of responsibility for transmission system operators (TSOs) and distribution system operators (DSOs) regarding power system operation. In this context, the TSO defines a minimum power factor that the DSO must not violate at the TSO/DSO connection point. Values below this minimum are considered excessive reactive power consumption, resulting in penalizations applied to the DSO [48]. To meet this power factor requirement, DSO must acquire reactive power compensation devices [48]. In this sense, Figure 7 shows that the power factor at the point of transmission and distribution connection exhibits low values when PV systems only inject active power into the network. Critical values emerge at time intervals when PV generation provides the most significant active power contribution, i.e., when PV systems almost entirely meet the prosumers' load. Consequently, distribution systems with several prosumers exhibiting a low power factor at the PCC could lead to a degradation of the power factor at the TSO/DSO substation.

From Figure 8, it is possible to conclude that adjusting the power factor of PV inverters and the operation of capacitor banks improved the power factor of the substation of the transmission and distribution systems at the point of connection. However, it is essential to highlight that the primary motivation behind prosumers adjusting these devices is mainly to avoid economic penalties from (6) and (7). Thus, the actions taken by prosumers might improve the power factor at the substation, but these adjustments also bring a cost to the consumer. If the charge for reactive surpluses were made directly by the flow of reactive power demanded from the network and not by the power factor measured at the PCC, distribution companies would not penalize prosumers.

In practice, the consumer will be unfairly penalized because reducing the network's demand for active power will benefit the network. During the past decades, distribution utilities have applied penalties for low power factors to penalize consumers who demand large volumes of reactive energy. Penalizing prosumers for a low power factor when they have not changed their reactive energy demand curve could force this class of consumers to install more compensation equipment that is not necessary, which could increase the operation voltage in the local power network of the consumer.

This paper seeks to contribute at the level of prosumer revenue; at this level, the simulations are performed in steady state. For this reason, a power factor stability analysis is outside the scope of the work, as it would require dynamic simulations to be carried out. On the other hand, power flow have shown that there are no considerable changes in the voltage levels of the electrical network. As explained in [49], the voltage stability problems arising from the insertion of distributed generation only begin to be observed in PV generators with capacities equal to or higher than 2 MW. In some urban areas with vertical growth, connecting PV solar generators with this capacity is difficult.

E. DISCUSSION ABOUT INCENTIVE PROGRAMS FOR PROSUMERS TO IMPROVE THEIR POWER FACTOR

Currently, in several countries, distribution companies carry out studies on the impact of connecting distributed generators before authorizing the connection request [50], [51]. Due to international requirements and standards, current PV inverters must have the option of operating their power factor at values other than unity. However, when a consumer makes this adjustment to their PV inverter, the compensation value for their active power demand will be lowed, resulting in a higher payment on the electricity bill. If such a consumer sets a power factor equal to one, the consumer will have to pay the fine for excess reactive. Although discussion of penalty schemes is beyond the scope of this work, it can be seen from the results that the distribution company will have a more significant impact with penalties, as their fine is a function of your net revenue value, as shown in [52]. Based on the above, the proposed methodology could help in the implementation of an incentive program that can assist in connection studies of PV systems, showing a value that allows the reduction of penalties to consumers and showing the regulatory agencies the amounts that they would charge within the penalty scheme for low power factor to the distribution company and consumers.

Therefore, a financial incentive program to improve electrical grid quality indicators based on the demand response program can be applied by regulatory agents [53]. In the case of Brazil, the current penalty system is not enough to encourage consumers to e.g. change the power factor of the photovoltaic inverter; consequently, other incentives are needed. An example of this program is the possibility of applying a compensation program to improve various quality indicators in the electrical network, such as improvement in power losses, improvement in voltage level and improvement in power factor in the substation. When the utility notices an improvement in these indicators, credits arising from non-penalties for non-compliance with technical standards would be distributed to prosumers in proportion to their contributions.

One way to implement programs of ancillary service is to consider improving the power factor of prosumers as an ancillary service that the electrical system operator agents could contract. However, the definition of market rules for ancillary services for small generators has faced many barriers, as explained in [54]. Among these barriers, it could be mentioned that the incentive value may be low if the operator agent offers the exact value to all small generators. In addition, analyzing the locations that can benefit most from the services provided by such generators can obtain more attractive values for owners or consumers, as presented in [55].

This paper analysis is at the level of prosumer billing at medium voltage, reducing the penalties that the distribution company applies for the low power factor that appears on the electricity bill as a penalty for reactive power excess. Additionally, this proposal can help distribution companies in connection with studies for new distributed generators or consumer energy management. Likewise, in an energy market environment, simulations are carried out days before the end of electricity billing to define actions that can reduce the bill [56]. As previously discussed, the proposal is being executed offline in a preventive manner to avoid penalties in electricity billing due to the low power factor. On the other hand, the proposed methodology could analyze unforeseen changes and their impact on the electricity bill level through the prosumer's generation and demand curves. As shown in [57], some large consumers have operation centers that follow the generation and demand curves to reduce the impacts of operations not predicted in offline studies.

Finally, The financial analysis of the potential economic implications for distribution companies resulting from the reduction of penalties for reactive energy consumption is being addressed as future work.

V. CONCLUSION

This work presented a new coordinated approach based on the variable neighborhood search (VNS) meta-heuristic, and the Fibonacci search method (FSM) algorithm for the electricity bill reduction problem by reducing excess reactive power consumption penalizations for medium voltage (MV) prosumers with photovoltaic (PV) generation. The coordinated approach included the adjustment of PV inverters' power factor and the operation of switchable capacitor banks. In addition, an analysis of the variation in power factor in the substation that connects the transmission and distribution systems were realized. This analysis is carried out while considering PV systems operating with a unity power factor and applying the proposed approach.

The results showed a more significant reduction in the electricity bill when considering both the adjustment of the PV inverter power factor and the operation of capacitor banks simultaneously. Moreover, applying the proposed approach also improves the power factor at the transmission and distribution point of connection.

By calculating the electricity bill of MV prosumers, it becomes possible to visualize the impact of excessive reactive power consumption fees on electricity expenses. Consequently, total electricity costs can be reduced by alleviating the penalties imposed on MV prosumers due to low power factors at the point of common coupling (PCC). The extent of these penalties depends on various factors, including the load curve of the prosumers. Therefore, if these economic penalties constitute only a marginal portion of the overall electricity bill, MV prosumers might choose not to take actions involving equipment adjustments to improve the power factor at PCC. This decision could be influenced by the economic investment required for planning and operating these devices. However, disregarding these actions by prosumers could introduce new challenges to distribution system operators (DSOs). Transmission system operators (TSOs) impose penalties on DSOs when the power factor at the TSO/DSO substation drops below a predefined value. As shown in the results section, MV prosumers' PV systems, which only inject active power into the network, lead to inappropriate power factor values at the substation that connects the transmission and distribution systems. Consequently, it is essential to alert distribution companies to potential future issues.

Finally, it is worth saying that even when power factor values at the prosumers' PCC are above the minimum limit, MV prosumers still have the potential to improve the power factor value at the TSO/DSO substation by adjusting the power factor of their PV inverters. However, without incentives, the motivation for MV prosumers to engage in reactive power compensation is limited. Hence, a program of incentives was proposed that offers a mutual advantage to both parties. Therefore, DSOs might consider incentivizing MV prosumers to actively cooperate on power factor regulation at the TSO/DSO connection point.

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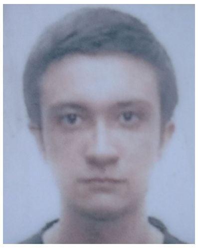

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