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Metaheuristic for the Allocation and Sizing of PV-STATCOMs for Ancillary Service Provision

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Abstract: In addition to active power generation, photovoltaic inverters can be used to provide ancillary services to grids, including reactive power compensation. This paper proposes a metaheuristic approach based on particle swarm optimization for the allocation and sizing of photovoltaic inverters that perform the complementary functions of static synchronous compensator (PV-STATCOM) units. The objective of the aforementioned approach is to reduce the initial investment cost in the acquisition of PV-STATCOM units. The proposed methodology considers both the daily load curve and generation and is applied to a 33-bus test system. The methodology is validated based on an exhaustive search algorithm and tested over 1000 consecutive simulations for the same problem; consequently, the methodology produces low standard deviations and errors, indicating its robustness. The methodology demonstrates an improved grid voltage profile throughout the day when applied to the 33-bus test system. Furthermore, the photovoltaic inverter efficiently performs its main function of active power generation. As a major contribution, the proposed methodology may assist investors in determining the allocation and sizing of PV-STATCOM units to perform the ancillary service of reactive power compensation in grids

Keywords: PV-STATCOM; ancillary service; reactive compensation; photovoltaic distributed generation

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1. Introduction

Modern electrical power systems have necessitated the development of new solutions and services to satisfy the growing demand for electrical energy resulting from population growth, technological developments, and the search for quality of life.

Active power generation in distribution systems has been increasingly supported by distributed generation (DG), particularly photovoltaic distributed generation (PVDG). However, meeting the demand for reactive power has remained a challenge [1,2].

This paper discusses the technical, economic, and environmental aspects of DG units integrated into electrical systems [3]. Additionally, here, DG units are connected to a medium-voltage system, creating a microgrid and thus improving voltage levels and reducing losses.

A majority of the reactive power demands from distribution systems can be met by utilizing flexible resources based on grid-connected inverters [4]. This solution benefits distribution system operators and creates new business opportunities in the sector. For example, PVDG inverters rely on solar irradiance; consequently, they remain idle for the majority of the day, and the unused capacity can be used to provide grids with a variety of ancillary services, such as reactive power supply [5].

PV-STATCOMs are photovoltaic inverters that perform the functions of a static synchronous compensator (STATCOM). The underlying technology performs the same functions as a conventional STATCOM or an equivalent-sized static var compensator (SVC) [6]. The concepts and applications of PV inverters as PV-STATCOMs have been extensively covered in a previous study [7].

In reference [8], the authors presented one of the first practical applications of photovoltaic inverters for grid voltage adjustment, and the authors of reference [9] conducted further studies. The findings indicated that the volt–var and volt–watt controls could be used to adjust the voltage levels of a grid.

A photovoltaic inverter was used experimentally as a PV-STATCOM in reference [10]. The technology proved capable of performing dynamic voltage control 24/7, similar to a conventional STATCOM unit but at a 50-times lower cost.

The coordinated control of eight PV-STATCOM units located in a grid in Turkey was proposed in references [11,12]. The modified levy flight-based firefly algorithm was used to determine the PV-STATCOM settings for the next day based on the temperature, irradiance, and load predictions. The objective was to reduce energy losses and costs without compromising regulatory voltage limits. Consequently, technical–economic benefits were obtained at all loading levels, and the benefits of the method were more significant when applied to networks with higher reactive energy consumption.

Notably, appropriate allocation and sizing of DG units can maximize the associated technical, economic, and environmental benefits [13]. Moreover, with proper allocation and sizing, power system reliability and quality can be improved, investments and operating costs may be reduced, and harmful environmental effects of centralized power generation can be mitigated [14]. Particularly, the coordination and optimized control of the resources dedicated to reactive compensation provide technical and environmental benefits, including loss reduction, voltage improvement levels, and maintenance of emission levels [15].

In reference [16], the authors used an index based on sensitivity analysis to quantify the influence of PV-STATCOMs on voltage recovery during the post-fault period in a grid while considering the fast voltage recovery characteristics of PV-STATCOM units. Here, the allocation and sizing of PV-STATCOMs considered the proposed index and the minimization of annual costs associated with DG operation, and the mixed-integer linear programming model was applied. Furthermore, in reference [16], the authors demonstrated that PV-STATCOMs could efficiently recover post-fault voltage sags when properly sized and allocated.

To reduce power losses, minimize costs, and improve voltage levels, the authors of reference [17] proposed using the particle swarm optimization (PSO) algorithm with the power-loss index for sizing and allocating PV-STATCOM units in a grid. When the applied methodology was compared to other metaheuristic approaches, the adapted PSO achieved the best results and the shortest convergence time. However, the authors [17] did not consider the allocation of multiple PV-STATCOM units.

The DSTATCOM is a conventional STATCOM applied to electrical distribution systems. A few studies [18–20] have optimized the locations and sizes of DSTATCOM units to reduce power losses and improve voltage levels in a grid. Typically, PV-STATCOM can perform DSTATCOM functions while generating active energy during the solar radiation period.

The major contributions of this study can be summarized as follows:

- The proposed metaheuristic for the allocation and sizing of PV-STATCOM units is simple and novel. Regardless of the differences in application, the proposed metaheuristic is simpler than others found in the literature [16]. The metaheuristic is based on PSO, which is known to produce better computational and convergence results [17].
- No comparable studies that consider the allocation and sizing of PV-STATCOMs for providing reactive compensation as ancillary services to the grid have been reported to date. Thus, in this study, PV-STATCOM units were studied, allocated, and sized for the provision of ancillary reactive compensation services, and the compensator was made responsible for maintaining the voltage levels within the desired thresholds throughout the rated period.
- The proposed metaheuristic aims to size and allocate a PV-STATCOM with the lowest possible power, which is also capable of performing ancillary services, thereby minimizing the cost of initial investments in PV-STATCOM acquisition.

- The methodology is used to test a 33-bus system. This system was chosen because it has been extensively studied, which makes the validation with other methodologies easier.

This study assumes a novel approach by considering the provision of continuous ancillary services by PV-STATCOMs. It also develops a novel methodology for the allocation and sizing of multiple PV-STATCOM units acting simultaneously.

2. Ancillary Services

According to the International Electrotechnical Commission (IEC 60050-617), ancillary services are services that are deemed necessary for electrical power system operations and are provided by the system operator and/or users of the power system [21].

The Federal Energy Regulatory Commission defines ancillary services as services necessary to support the transmission of capacity and energy from resources to loads while maintaining reliable operation of the Transmission Provider's Transmission System in accordance with Good Utility Practice [22].

According to the Federation of the European Electricity Industry, ancillary services are services necessary for the operation of a transmission or distribution system, and these include balancing and services used by a transmission system operator or distribution system operator for steady-state voltage control, rapid reactive current injections, the inertia for network stability, short-circuit current, black start capability, and islanding capability; however, these do not include congestion management [23].

Ancillary services that can be provided by DG include the following: frequency and voltage control, congestion management, improvement of power quality, reduction in power losses, black start, and islanded operation [24].

According to reference [25], regional transmission organizations, independent system operators, and industry experts collectively agree on the need for legislative reforms and changes to facilitate the combination of available renewable resources and satisfy different load profiles. While these reforms are under discussion, the entities collectively agree that additional operational flexibility of resources will be required to reliably satisfy load demands as the resource mix evolves to include more climate-dependent variable energy resources.

This paper describes a novel methodology adopted for the sizing and allocation of multiple PV-STATCOM units to provide ancillary reactive compensation services to a distribution system.

3. Proposed Methodology

During the daytime, solar power generation leads to an increase in the grid voltage, and in some cases, this increase can be excessive, resulting in overvoltage. The most severe overvoltage violations occur at low loads and high generation rates [26]. Notably, periods of higher power consumption rarely coincide with periods of higher energy generation, and undervoltage is common during these times. Consequently, depending on the consumption and generation patterns, the same grid may experience both overvoltage and undervoltage periods.

This study used the quasi-static time series method [27] to simulate the daily power flow while considering the load and generation curves. The daily power flow was used to determine the times of greatest overvoltage and undervoltage violations.

PV-STATCOM units were allocated and sized to provide the grid with ancillary reactive compensation. The following two scenarios were created: one during the highest overvoltage violation, and the other during the highest undervoltage violation. The PV-STATCOM units that satisfied the demand in the most critical scenario were deemed capable of satisfying the demands in scenarios that demanded less reactive power. Thus, given the intermittence of load and generation, the sized PV-STATCOM units were expected to be capable of satisfying all scenarios, as none of the scenarios would require greater reactive compensation than the one used for sizing, as depicted in Figure 1. Typically, a

PV-STATCOM remains idle during periods of lower solar radiation or at nighttime, when reactive compensation is not required.

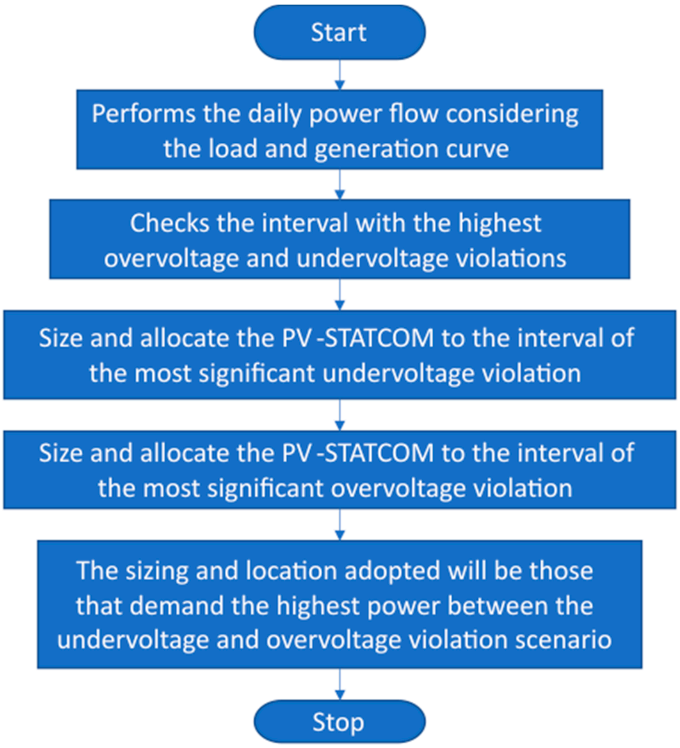

Figure 1. Proposed methodology.

As stated, the proposed metaheuristic for the allocation and sizing of PV-STATCOMs is based on PSO. The PSO was selected because it has demonstrated satisfactory results when applied to problems similar to those addressed in this study [17,28,29].

According to reference [30], the cost of a PV-STATCOM is related to its rated power. Thus, the presented methodology has an objective of minimizing the reactive power required to adjust grid voltages to the desired thresholds, thereby minimizing the initial acquisition costs of the PV-STATCOM.

For the objective function (*OF*), Equation (1) indicates the following: $minQ$ is the objective function of reactive minimization, N is the number of PV-STATCOM units to be installed, Q^i_{STC} is the power of PV-STATCOM i required to perform reactive compensation, and *Penalty* corresponds to a high value received for not satisfying at least one of the restrictions.

$$OF: \ minQ = \sum_{i=1}^{N} Q^i_{STC} + Penalty \tag{1}$$

Subject to restrictions:

- Current threshold of conductors:

$$I_{cond} = I_{max} \tag{2}$$

- Only one PV-STATCOM per bus:

$$N^i_{STC} = \{0 \ or \ 1\} \forall i \in 1, \ 2, \ldots, N_{bus} \tag{3}$$

- Installation on load buses only:

$$Bus^i_{type} = PQ \tag{4}$$

- All buses must serve the voltage limit:

$$V^i_{min} \leq V^i \leq V^i_{max} \quad (5)$$

where, I_{con} denotes the current in the conductor, I_{max} denotes the maximum current that the conductor can hold, N^i_{STC} denotes the number of PV-STATCOM units in bus i, and Bus^i_{type} denotes the bus type.

The fitness function used in PSO receives the voltage levels and candidate buses as input data and returns the reactive power required to perform compensation. If any of the restrictions are not met, the *Penalty* value is returned as 9999 Mvar, as indicated in Figure 2.

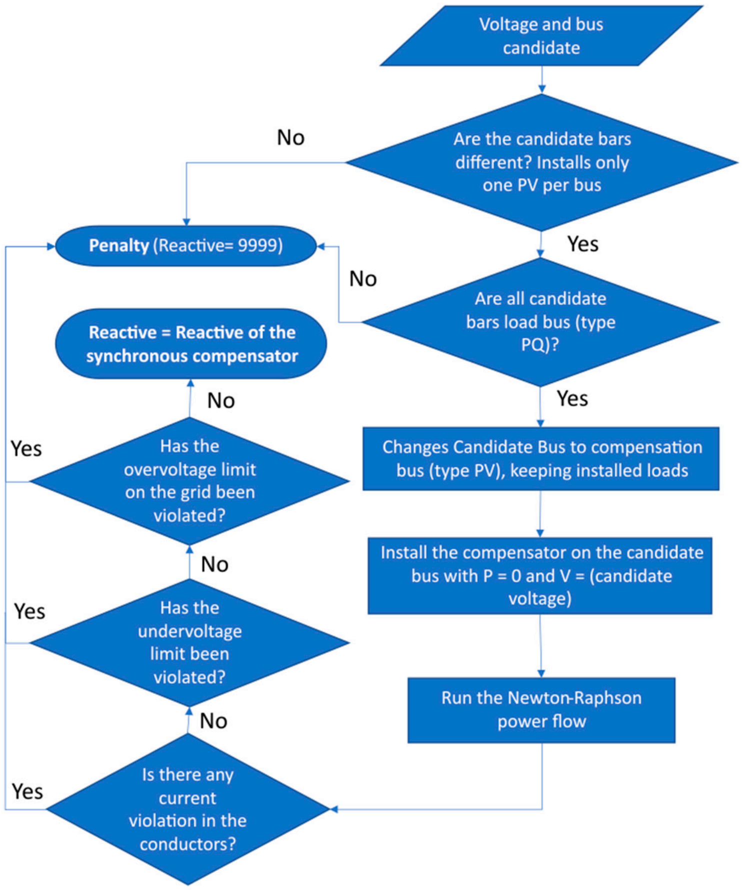

Figure 2. Fitness function: PSO.

Photovoltaic Inverter Modeling as a PV-STATCOM

In the optimization step, the power flow was obtained using the Newton–Raphson method. The PV-STATCOM was defined as a synchronous compensator, implying that the installation bus of the PV-STATCOM belonged to the PV type. The active power of the synchronous compensator was null, and the voltage and the installation bus were determined based on PSO. The reactive power to be injected or absorbed by the PV-STATCOM was returned by the Newton–Raphson method.

The openDSS software was used for modeling and simulation of the photovoltaic inverter acting as a PV-STATCOM for the considered application.

In the openDSS simulation, the *VarFollowInverter* variable was set to *true*, allowing the inverter to operate during the day and night, and the variable *WattPriority* was set to *false*, indicating that reactive power compensation was a priority for the photovoltaic inverter [31].

Note that the maximum reactive power (Q_{max}) is limited by the rated power of the inverter (S_{max}) and by the active power generated at that instant (P_{gen}), according to Equation (6).

$$Q_{max} = \sqrt{S_{max}^2 + P_{gen}^2} \quad (6)$$

The volt–var compensation curve is depicted in Figure 3; where, V_{min} denotes the minimum voltage produced without the need for reactive compensation, V_{max} denotes the maximum voltage produced without the need for reactive compensation, and V_{ref} denotes the reference voltage (normally, 1 p.u. is used).

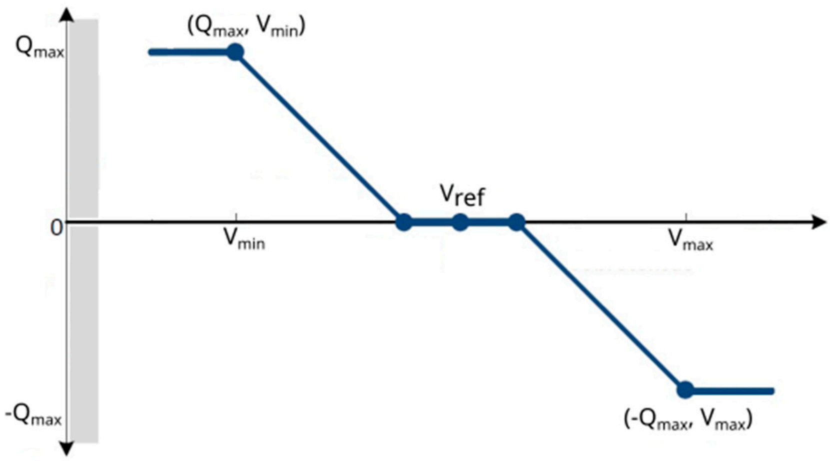

Figure 3. Volt–var curve.

4. Base Case Considerations

The proposed methodology was applied to a 33-bus test system (Figure 4). Note that the 33-bus system is capable of serving a total load of 4.3694 MVA with an average power factor (PF) of 0.85 lagging [32].

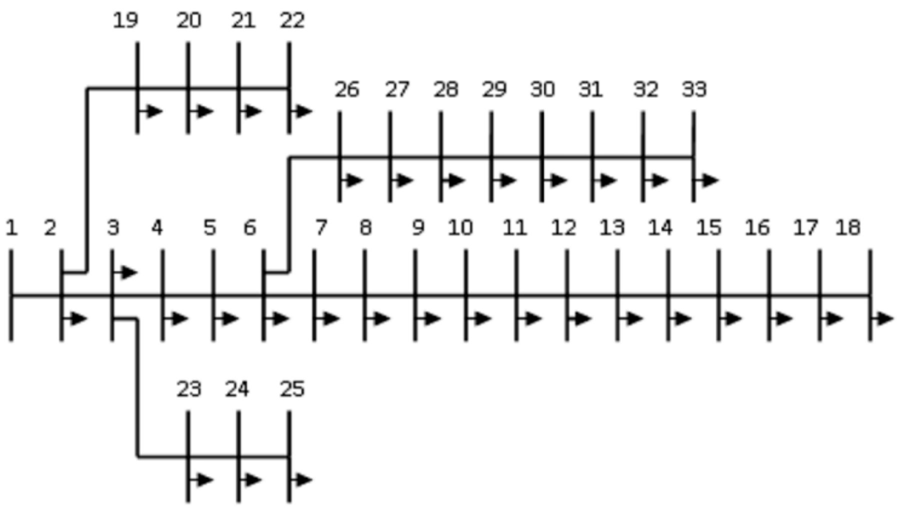

Figure 4. A 33-bus distribution system.

All the buses are assumed to have the same load curve in the simulation, with the PF of each load remaining constant throughout the period. The loads are represented by constant-power models.

Figure 5 presents the load curve; here, the peak consumption occurs at 8:00 p.m. at 100% of the load capacity.

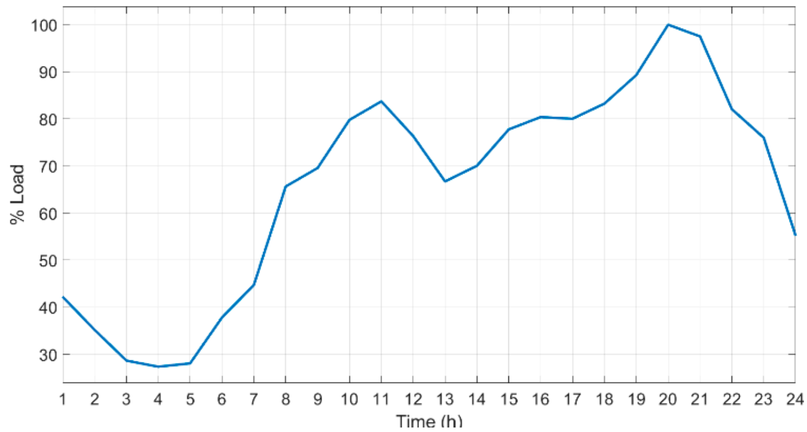

Figure 5. Load curve.

During the peak consumption hours, the lowest voltage on the grid is 0.9131 p.u., and it occurs at bus 18, as illustrated in Figure 6.

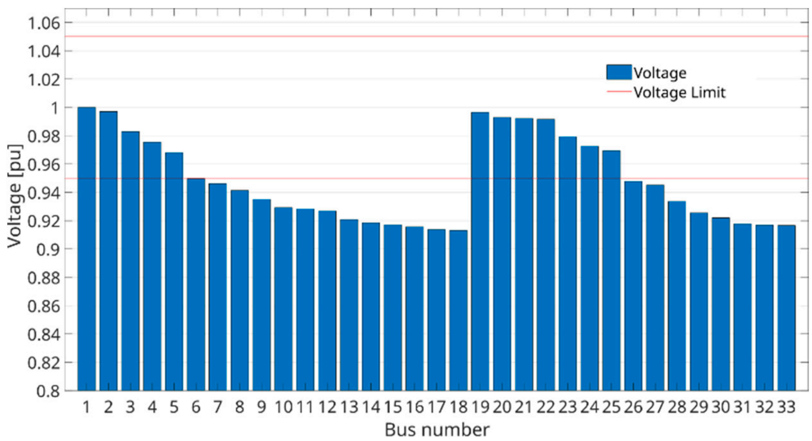

Figure 6. Voltages at peak load hours.

Note that PVDG units are not installed in the base case. Figure 7 illustrates the solar power generation curve for the PV-STATCOM.

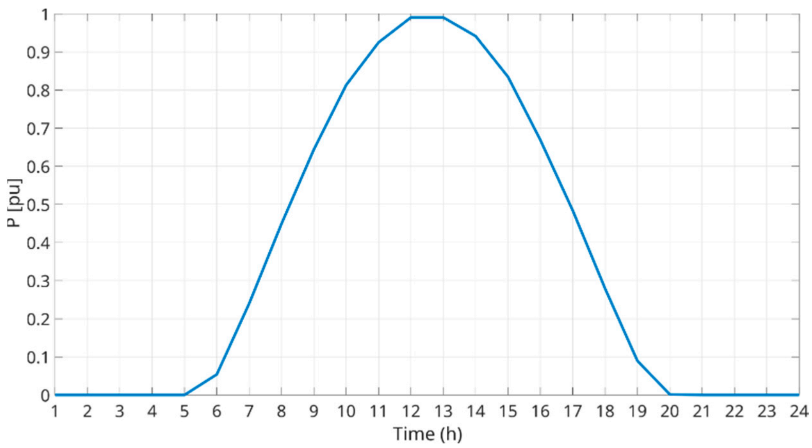

Figure 7. Generation curve of the PV-STATCOM.

Given the initial consideration of the base case, the voltage levels of the system are to be adjusted so that they are within the established threshold of 0.95 p.u. for undervoltages and 1.05 p.u. for overvoltages at all times of the day.

5. PSO Adjustments

As mentioned before, the proposed methodology is based on PSO to determine the allocation and sizing of PV-STATCOM units, which perform reactive power compensation in a grid by maintaining voltage levels within the established thresholds.

The *particleswarm* library from Matlab® ([33]) was used with the following settings for PSO application:

- Search space:
  - All load buses (Bus_{PQ}) are candidates to receive the PV-STATCOM:

$$\forall\, Bus_{PQ}\ :\ Bus_{STC} \tag{7}$$

  - The synchronous compensator voltage must be within the admitted limits:

$$V_{min}\ \leq\ V_{STC}\ \leq\ V_{max} \tag{8}$$

  where V_{min} denotes the lowest voltage accepted for the system, V_{max} denotes the highest voltage accepted, Bus_{STC} denotes the bus on which the PV-STATCOM unit will be installed, and Bus_{PQ} denotes the system load bus.
- Particle swarm size:

$$Sw_{size} = 10 \cdot N_{STC} \cdot N_{bus} \tag{9}$$

  where Sw_{size} denotes the particle swarm size to be adopted, N_{STC} denotes the number of PV-STATCOM units to be installed, and N_{Bus} denotes the number of buses in the system.

Note that Equation (9) was empirically defined for the specific base case. The equation considers that the number of possible combinations increases depending on the number of buses in the system and the number of PV-STATCOM units to be used. The foregoing equation can be improved in future research for application to larger systems.

The fitness function used by PSO is presented in Figure 2. The stopping condition is expected to occur when 10 iterations in a row are obtained without any change in the results.

6. Allocation and Sizing

To demonstrate the proposed methodology, reactive compensation was performed for the base case, considering the use of one, two, and three PV-STATCOM units. Note that the values of 0.95 p.u. and 1.05 p.u., respectively, were accepted as the minimum and maximum voltage levels.

Notably, metaheuristics is a random method that solves a given problem; however, it does not guarantee the optimal solution [34]. The standard deviation and error data, with the PSO adjustments described in Section 4, were determined by exhaustively running simulations for allocation and sizing in the base case consisting of one, two, and three PV-STATCOM units, yielding the values listed in Table 1.

Table 1. PV-STATCOM's Sizing.

N_{STC}	$\overline{\sum Q_{STC}}$ **(Mvar)**	**Std Dev**	**Error**
1	3.674	0.0069	2.20×10^{-4}
2	1.541	0.0060	1.89×10^{-4}
3	1.532	0.0198	6.26×10^{-4}

To obtain the data presented in Table 1, 1000 (one thousand) consecutive simulations were performed using the proposed methodology. The obtained values were compared with those obtained using an exhaustive search algorithm that considered all possible combinations in all the system buses. When compared with the exhaustive search algorithm, the values obtained via the proposed methodology were within the margin of error and were thus considered satisfactory. The results will be further discussed in the sections that follow.

Although the issues associated with DG are stochastic, the problem here is approached deterministically. In this work, the PV-STATCOM is responsible for reactive compensation of overvoltage or undervoltage; in this regard, the PV-STATCOM sized to meet the most critical periods between the scenarios will also meet the other periods, regardless of the stochastic of the events.

Note that although the problem is approached deterministically, metaheuristics are based on random variables; thus, with each new simulation, the metaheuristic takes a different path until it finds a solution. The results presented in Table 1 indicate that the restrictions and stopping conditions of the method are satisfactory. Notably, with the application of the proposed metaheuristic, the swarm particles were not observed to be stuck to the valleys or peaks of the function, nor did they diverge to a solution far from the expected one.

Note that the ideal number of PV-STATCOM units to be used was not investigated in this study, as it is a subjective study and must consider the investor's profile and grid structure.

6.1. Allocation and Sizing of One PV-STATCOM Unit

In Figure 8, the voltage levels of buses 18 and 33 are displayed before the PV-STATCOM unit is installed. The buses are located at the end of the grid and present undervoltage violations in the interval from 8 a.m. to 11 p.m.

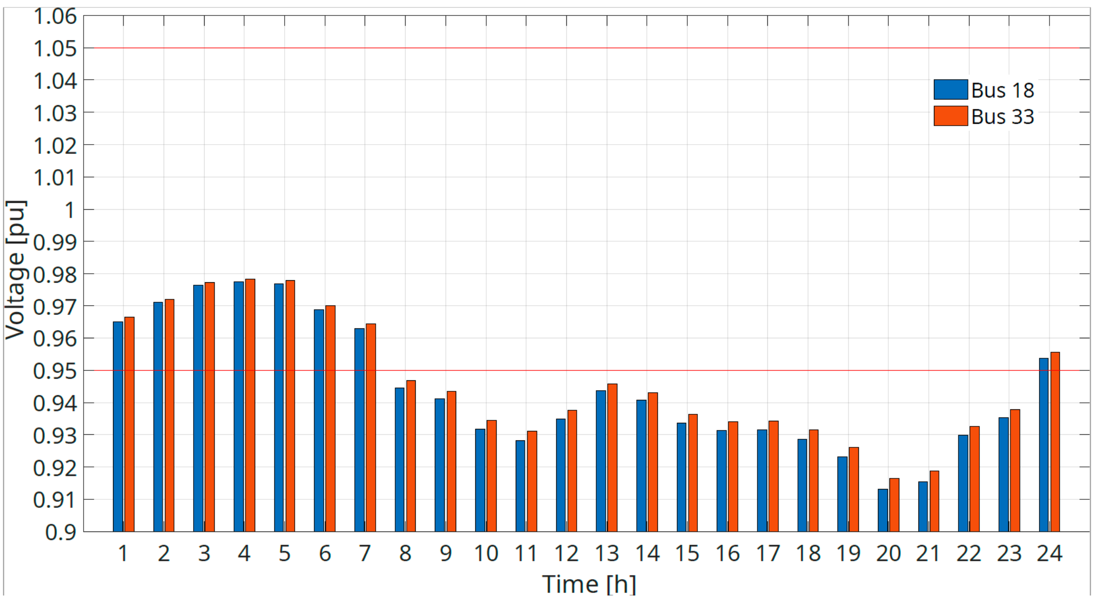

Figure 8. Voltage levels on buses 18 and 33 without a PV-STATCOM.

As indicated in Table 1, the PV-STATCOM unit installed on bus 7 is required to have 3.674 MVA of power for reactive compensation in the base case. Figure 9 indicates that when the proposed methodology is applied, all voltage levels in the grid remain within the established thresholds.

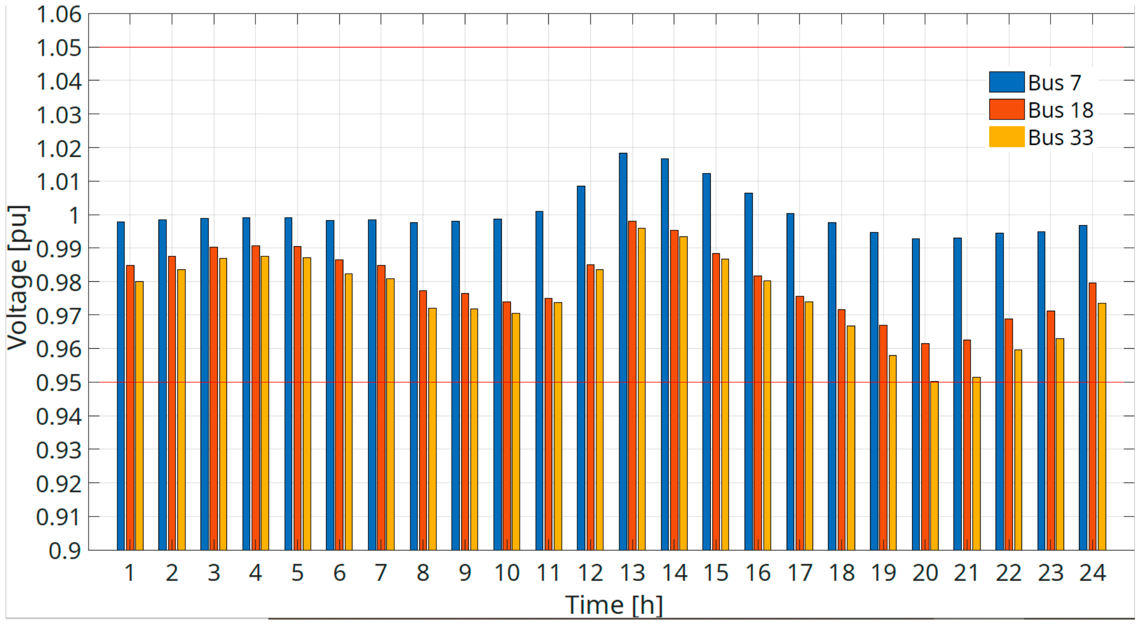

Figure 9. Voltage levels with the PV-STATCOM installed on bus 7.

Notably, PV-STATCOM units supply active power to the grid during periods of high solar irradiance. Typically, PV-STATCOM units control voltages during periods when reactive compensation is required. Figure 10 illustrates the active and reactive powers of the PV-STATCOM unit installed on bus 7. Note that active power injection into the grid helps adjust voltage levels during periods of higher solar irradiance, while reactive compensation occurs during periods of lower solar irradiation without compromising the active power generation.

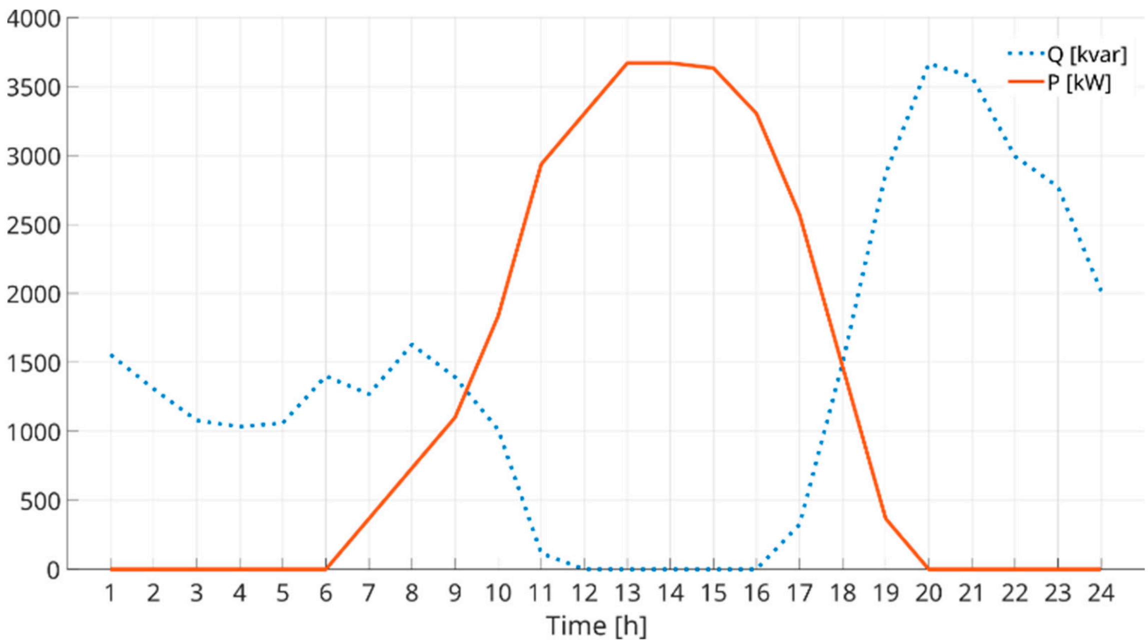

Figure 10. Active and reactive powers supplied by the inverter installed on bus 7.

6.2. Allocation and Sizing of Two PV-STATCOM Units

For two PV-STATCOM units, the application of the proposed metaheuristic indicates that the PV-STATCOM units must be installed on buses 17 and 31 with rated apparent powers of 607.1 kVA and 924.4 kVA, respectively.

Figure 11 presents the voltage levels after installation of the two PV-STATCOM units. As with the installation of a single PV-STATCOM unit, when two PV-STATCOM units are installed using the proposed methodology, all the voltage levels in the grid remain within the established thresholds. However, when installing two units, the total power required to perform reactive compensation is reduced compared to that for a single unit.

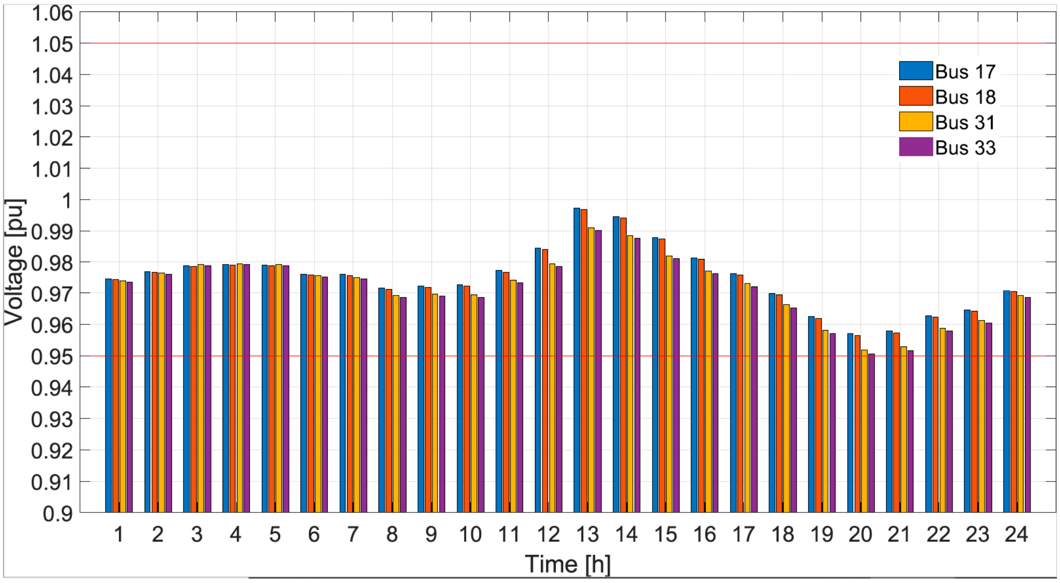

Figure 11. Voltage levels with the installation of PV-STATCOM units on buses 17 and 31.

The active and reactive powers supplied by the inverters installed on buses 17 and 31 are depicted in Figures 12 and 13, respectively. The PV-STATCOM units on both buses act almost simultaneously, even when acting independently, generating active power and providing reactive power compensation to the grid.

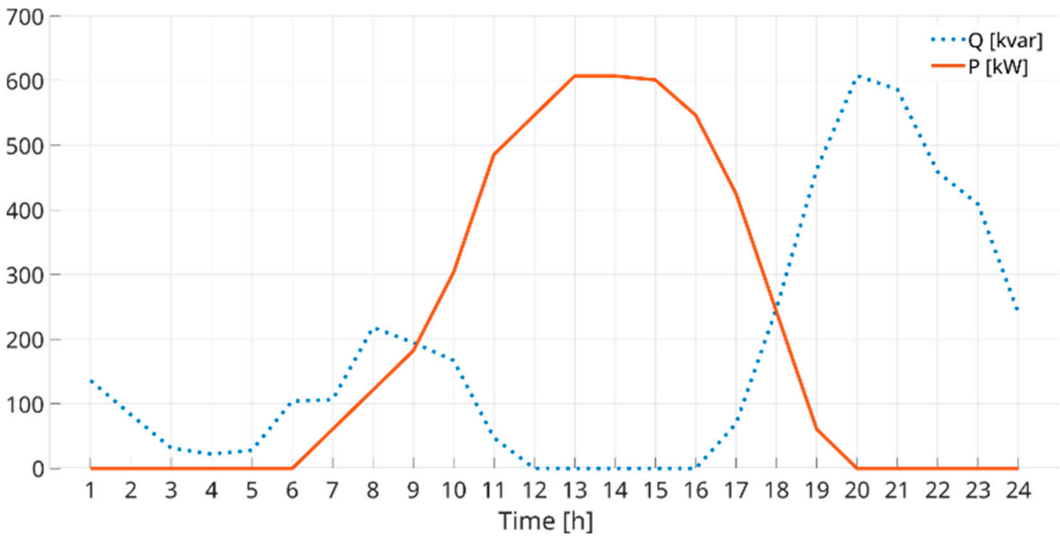

Figure 12. Active and reactive power supplied by the PV-STATCOM installed on bus 17 - System with two PV-STATCOM.

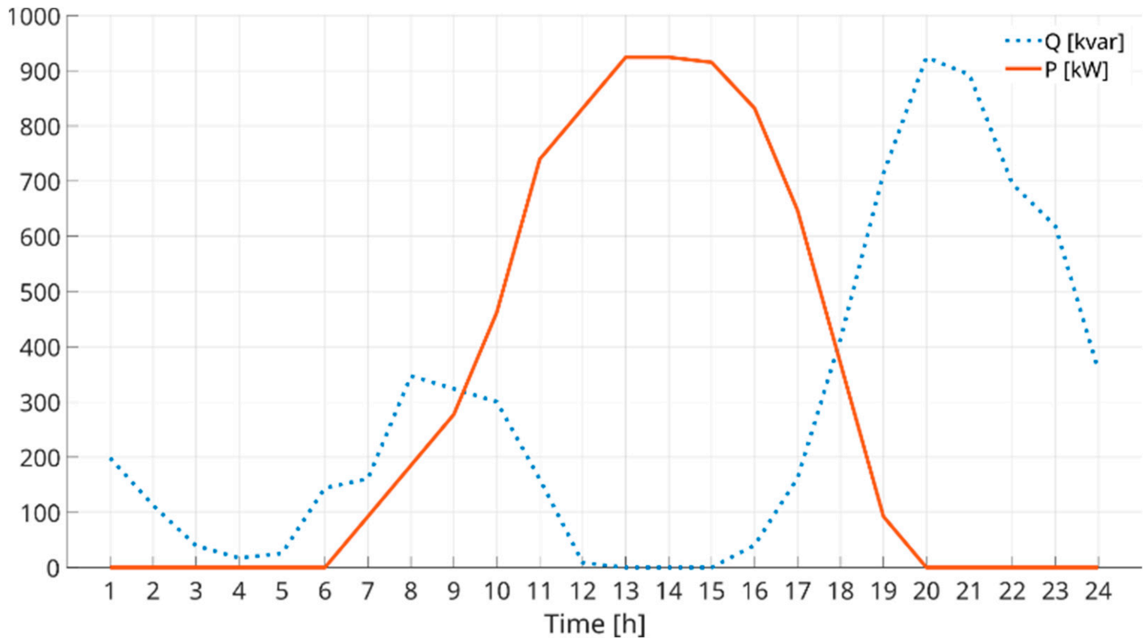

Figure 13. Active and reactive power supplied by the PV-STATCOM installed on bus 31.

6.3. Allocation and Sizing of Three PV-STATCOM Units

Further, when three PV-STATCOM units were installed, the best candidate buses were identified as buses 14, 17, and 33. The rated powers of the PV-STATCOM units installed on the buses were 293.2 kVA, 302.9 kVA, and 933.8 kVA, respectively. The voltage levels after installation of the three PV-STATCOM units are presented in Figure 14.

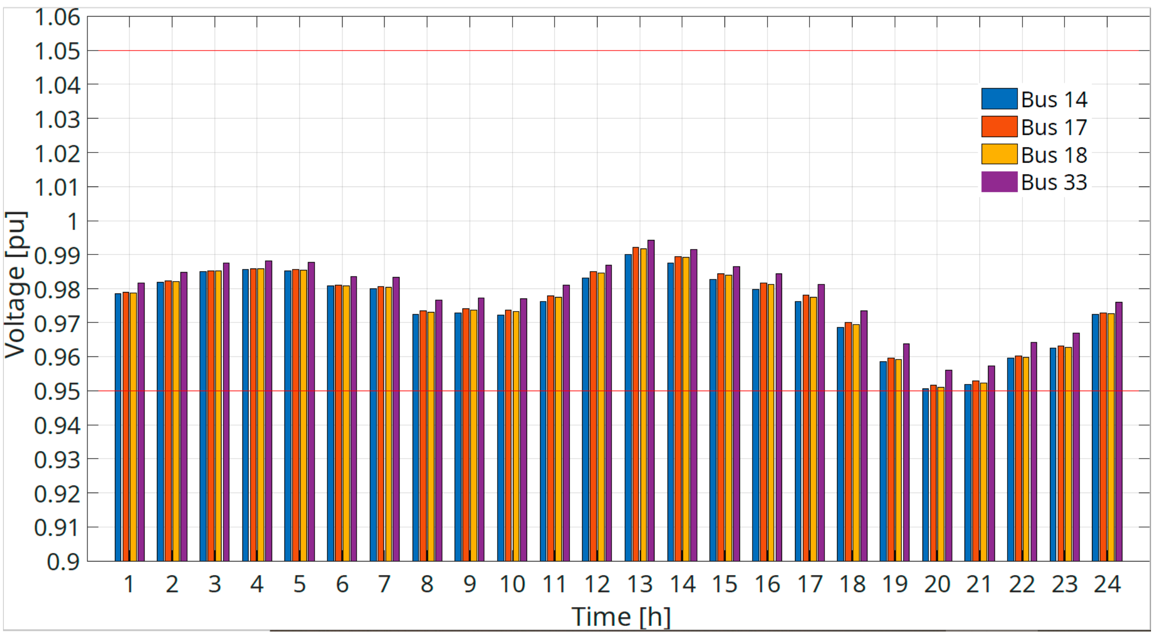

Figure 14. Voltage levels after installation of three PV-STATCOM units.

Considering the voltage levels in the grid after reactive compensation, the results obtained with three PV-STATCOM units closely resemble those obtained with two units.

The powers supplied to buses 14, 17, and 33 are depicted in Figure 15, Figure 16, and Figure 17, respectively. The PV-STATCOM units perform their functions in a coordinated manner even with independent controls, maintaining the voltage levels within the established thresholds throughout the period.

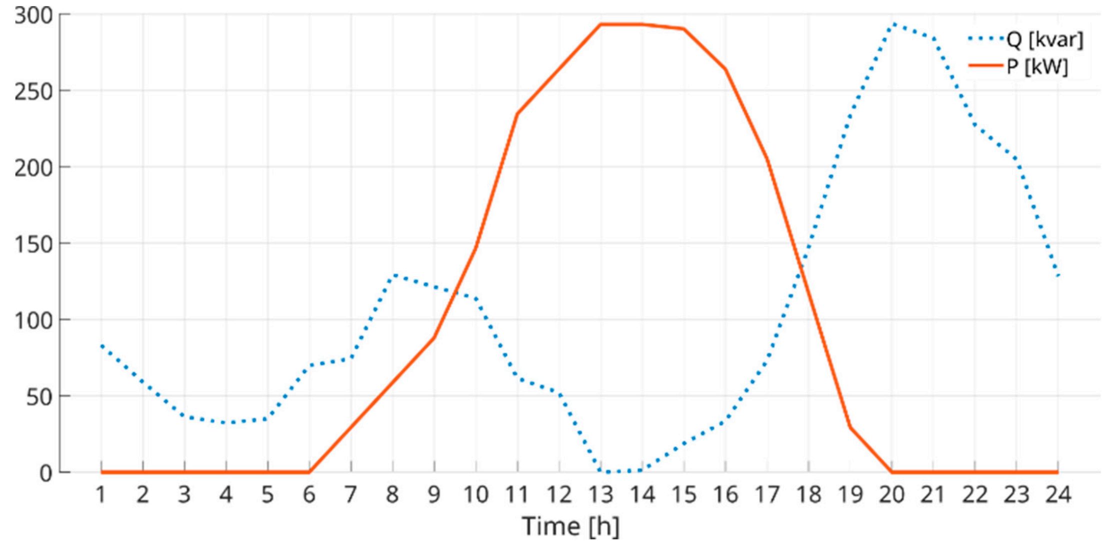

Figure 15. Active and reactive power supplied by the PV-STATCOM installed on bus 14.

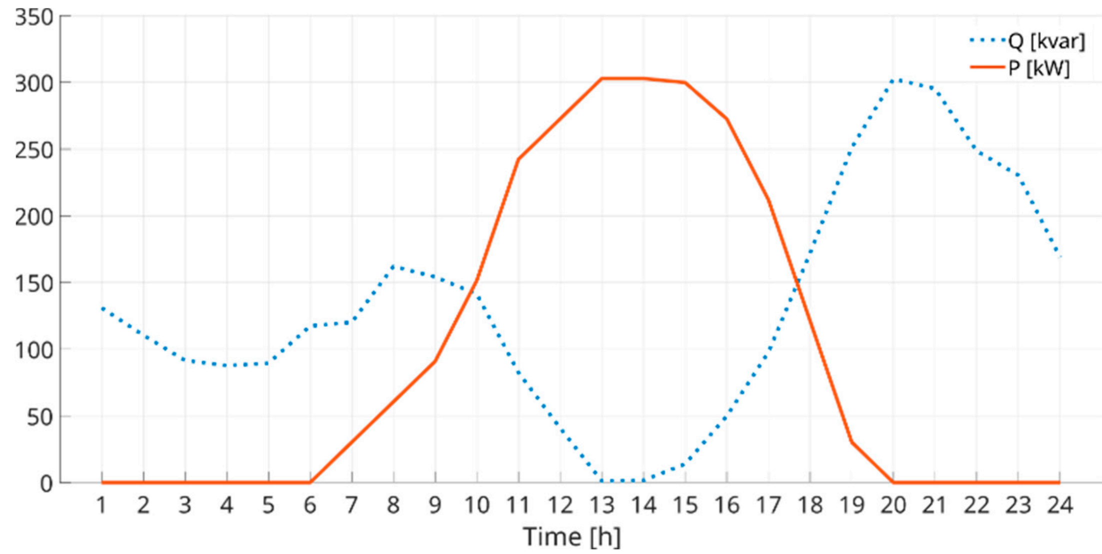

Figure 16. Active and reactive power supplied by the PV-STATCOM installed on bus 17 - System with three PV-STATCOM.

Notably, the total amount of reactive power required to perform compensation was significantly reduced for the scenario with two PV-STATCOM units compared to that with a single unit. The difference between the two-unit and three-unit scenarios was minimal. However, when three units were installed, reactive compensation was divided across the PV-STATCOM units with lower power, and this can be a competitive advantage for investors.

The allocation and dimensioning of the PV-STATCOMs, in addition to reducing the initial investment cost, allow the inverters to act simultaneously without competing with each other. In all simulations performed, the PV-STATCOMs participated proportionally in the reactive compensation.

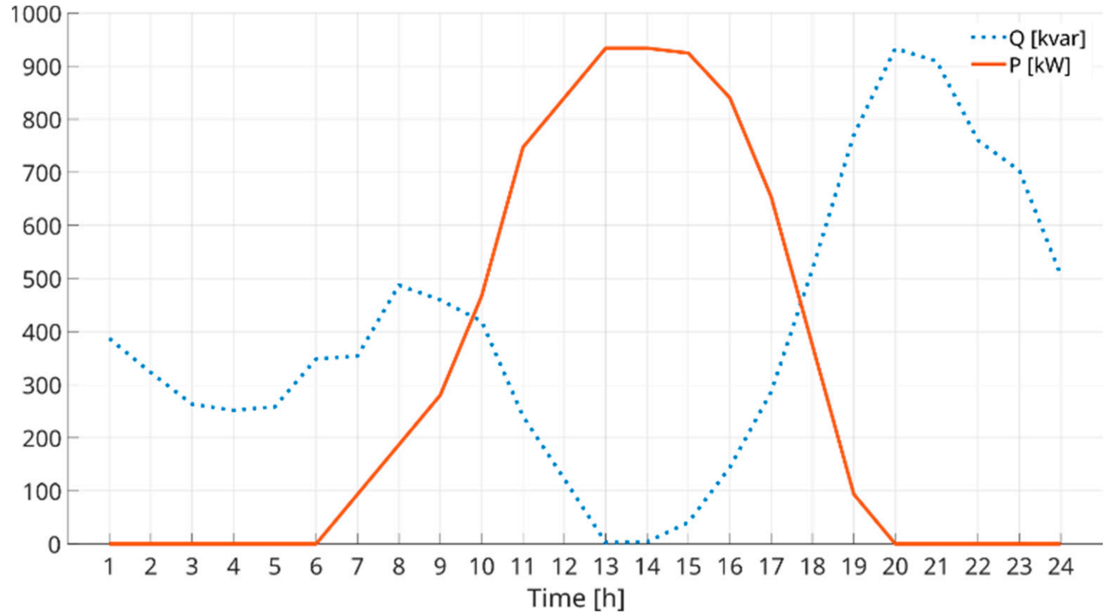

Figure 17. Active and reactive power supplied by the PV-STATCOM installed on bus 33.

7. Conclusions

We proposed a metaheuristic based on the PSO algorithm. The approach allocated and sized PV-STATCOM units to provide reactive compensation to a grid as an auxiliary service. Its objective was to reduce the initial cost of purchasing PV-STATCOM units.

The results obtained using the proposed methodology were compared with those obtained using an exhaustive search algorithm and were concluded to be satisfactory. A few errors and low standard deviation were noted. Furthermore, the methodology could be used to size and allocate multiple PV-STATCOM units operating simultaneously.

A PV-STATCOM sized to provide compensation at the time of the greatest voltage violation was deemed sufficient to serve the demands of reactive compensation at other times of the day. The PV-STATCOM was capable of performing reactive compensation throughout the day while continuing to perform its main active power generation function.

Reactive compensation using the PV-STATCOM unit required a 3.674 MVA inverter. When using two units, 607.1 and 924.4 kVA inverters are required, totaling 1.532 MVA. Moreover, for three units, the total power required is 1.530 MVA. Note that the greater the number of PV-STATCOMs, the lower the total reactive power and inverter size required for reactive compensation services. This study did not discuss the ideal number of PV-STATCOM units to be used. However, a larger number of PV-STATCOMs requires the availability of installation sites, among other factors, which depends on the profile of the investor.

The proposed methodology can assist in the planning, sizing, and allocation of PV-STATCOM units that are developed to perform the ancillary service of reactive compensation. These could be installed by energy distribution companies or investors in the sector.

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