The Joint Application of Photovoltaic Generation and Distributed or Concentrated Energy Storage Systems in a Low Voltage Distribution Network: A Case Study

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***Abstract*—Over the last decades, Distributed Generation (DG) was presented as a possible alternative for integrating renewable energy sources into the electrical system. This resulted in the continuous growth of the investment and interest of small consumers in acquiring ways to generate their energy through mini-distributed generation. However, with the high DG penetration in Low Voltage Distribution Networks (LVDN), technical challenges are being observed and, in some instances, the worsening of indexes related to Power Quality (PQ) and economic conflicts. In this context, this work presents the improvements achieved by integrating Photovoltaic DG (PV-DG) with Energy Storage Systems (ESS). Proposed scenarios are analyzed in which the storage occurs in a distributed way, with an ESS connected to each PV-DG, or in a concentrated way, with a single ESS connected to the main transformer's secondary side. The energy stored during prolonged periods of residential consumption is also analyzed to evaluate the ESSs' capacities to retain the PV-DG surplus and supply the increases in power demand. In general, the combination of these distributed resources displayed improvements in voltage levels, unbalance and reduced technical losses. The concentrated ESS demonstrated a better use of both its storage capacity and energy. However, the voltage unbalance has increased due to the inverter's operation that connects it to the grid.**

***Index Terms*—Distributed energy resources, Photovoltaic distributed generation, Energy storage system, Low voltage distribution grid, Power quality.**

I. Introduction

Establishing an active effort for the energy matrix transition to reduce carbon and polluting gas emissions has made Distributed Generation (DG) increasingly common worldwide and present in the electricity grid. With an excellent generation potential from solar radiation, Photovoltaic Distributed Generation (PV-DG) has been highlighted in Brazil. According to the Brazilian Photovoltaic Solar Energy Association [1], from 2012 to November 2021, the country had installed a generation capacity of 11.5 GW, 63% of which corresponds to DG. The association also reports that 76.1% of these units are connected to residential consumers.

This reality reflects how technology has been integrated into the country. The development of renewable sources growth is of great public interest, and to a certain extent, the decentralization of generation is also beneficial for companies responsible for the electricity sector. Therefore, the National Electric Energy Agency (ANEEL), through normative resolution [2], regulates the mini and micro DG, the net-metering credit system and its validity for up to 60 months. Such normative ensured the consolidation of a new business model based on small PV-DG commercialization. Since installing these systems in consumer units presents a guaranteed financial return to their users, there is a growing increase in their presence in Low Voltage Distribution Networks (LVDN).

On the other hand, this increasing penetration of PV-DG in the electrical system may present some technical challenges. Due to energy generation being restricted to daytime, there may be no correspondence between the energy generation and local consumption curves [3]. This situation may cause a surplus of generated power that is not consumed and needs to be injected into the grid. There is then the emergence of a reverse power flow that, at high levels, could cause overvoltages, increases in losses and failures in protection devices [4]. Also, due to the solar radiation intermittence caused by shading, adverse effects may impair the indicators associated with a good Power Quality (PQ) [5].

With the establishment and popularization of DG as a viable alternative to reduce costs in electricity consumption, it has become the center of conflicting economic interests [6]. The companies are responsible for managing the energy distribution and claim that consumers with on-grid PV-DG do not reasonably bear the grid operation and maintenance costs, which reduces their profits. On the other hand, marketers and technology users argue that consideration should be given to DG's benefits to the electrical system with savings and a reduction in polluting gas emissions.

Given this situation, seeking alternatives to alleviate the technical challenges imposed by the progressive insertion of PV-DG while guaranteeing a profitable network operation for all interested parties is necessary. Therefore, this research suggests the integration of Energy Storage Systems (ESS), as a Distributed Energy Resource (DER), together with PV-DG. Such technology has become increasingly accessible and is widely used in some countries [7].

The ESS can, for example, be used to level the demand curve, storing energy in periods of lower consumption and

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cooperating to supply it when it assumes higher values [8]. Considering its application with micro DG, storage is carried out using the Pv-DG output surplus, and unloading would occur at the end of the day when residential demand increases [9]. Such a strategy would diminish technical problems caused by a high reverse power flow, reducing losses and allowing a redistribution of locally generated energy at more opportune moments.

Previous research found that, for an LVDN with high PV-DG penetration, the assimilation of ESS proved to be effective in preventing reverse power flow, ensuring an improvement in voltage levels, unbalance, and losses [9]–[11]. However, even though the prosumer's PV-ESS combination has been proven effective in absorbing the active power surplus, there is an economic contradiction. Since there isn't any governmental policy or stimulus for the ESS integration at the user's connection point, the payback time is too high [12]. Even though some options may make this viable for the prosumers, like adopting a dynamic tariff and the direct remuneration of the active power injected at the grid [13]. While the latter proposition enables the individual application of the DER by the prosumers, there is also the possibility of a collective approach where the ESS is integrated into the network to supply many users of a specific area on the distribution grid and even allows them to negotiate their energy surplus [14].

In this article, the objective is to verify how different combinations of these PV-ESSs, considering individual or concentrated ESSs, behave in the face of consumption variation and generation profiles over six days in a residential distribution network located in Brazil. From a technical perspective, the primary purpose is to observe the active power balance between the grid, the loads, and the DERs, considering the Brazilian southeast specificity, like daily demand profile, solar generation potential, and PV-DG sizing. It was also considered that the network used could be located in a region with more significant movement during work days, with residential occupation only during the week, or a summer region with vacation homes occupied only on weekends. In these scenarios, covering an extended period, these situations would result in other charging and energy dispatch behaviors regarding each ESS configuration. Given the many PV-DG conditions of excess energy, evaluating the installed storage capacity, it is possible to determine a good composition, individual or concentrated, for the ESSs in each situation. Such notes are obtained by observing the active power profiles of each system component (consumption, generation, and storage) and the energy accumulated in the ESS.

II. The Test System

Next, this section details the modeling and dimensioning of the considered DERs.

A. Low Voltage Distribution Network

All computer simulations were performed via OpenDSS using its daily mode. Part of an LVDN located in Brazil's southeastern region was used, composed of 41 buses (Fig. 1). The LVDN is responsible for maintaining the power supply to 34 consumers through a 45 kVA three-phase delta-star transformer with grounded neutral [15].

All loads are connected to one, two, or three phases. They are of the PQ type (defined as active and reactive powers) and have an inductive power factor (pf) of 0.85. The power consumed by these loads varies over time since each consumer unit is associated with a daily demand curve sampled at 15-minute intervals, totaling 96 points. Each load profile is given in p.u. and is based on the rated active power of each consumer.

B. PV-DG Model and Dimensioning

The simulated DGs are all the PV type and follow the base model from OpenDSS. Fig. 2 represents the PV system diagram. Each generator comprises photovoltaic panels and an AC-DC inverter arrangement with operating characteristics. Weather conditions (temperature and solar irradiation) are the input variables and are represented by daily curves.

The solar radiation (Ir) is converted into DC electrical power (P_{dc}) by the PV modules. However, this process is subject to a correction factor (fc) that depends on these devices' operating temperature (T). As they are composed of cells built from semiconductor materials, the modules present a voltage drop at higher temperatures that cause a reduction in the element's power output. The inverter output depends on the pf and the efficiency coefficient (η), subject to the proportion of the input power (P_{dc}) and the rated power of the inverter (P_{mpp}). The equations 1 and 2 present the relations between these powers.

$$P_{dc}(t) = fc(T) \cdot Ir(t) \tag{1}$$

$$P_{pv}(t) = fp \cdot \eta(P_{dc}) \cdot P_{dc} \tag{2}$$

It is important to note that fc and η vary, respectively, in relation to an input condition (T) and an output variable of the PV modules (P_{dc}). These behaviors depend on the implemented module and inverter models and are characterized by functions in the OpenDSS code. This modeling is also the native PV system of the simulation software.

The fast popularization and adherence to mini and micro PV-DG in Brazil are due to the business model practiced by companies that sell these systems. The standard procedure for sales representatives to calculate the rated power of generating units is based on the customer's daily consumption. The arithmetic mean of energy expenditure in kWh in the last 12 months is considered. This value is then divided by the average annual irradiation of the site and multiplied by the efficiency of the PV system. This results in an estimated value of the generation capacity needed to supply all the customer's active power demand in one day, always considering a unitary pf.

Seeking to emulate commercial sizing practices, the PV-DGs were specified according to the proportion between active power consumption and daily generation capacity at each connection point. Such values are represented by the time functions $P_c(t)$ and $P_{pv}(t)$. Therefore, the design consists of these two curves' ratio average value in 24 hours.

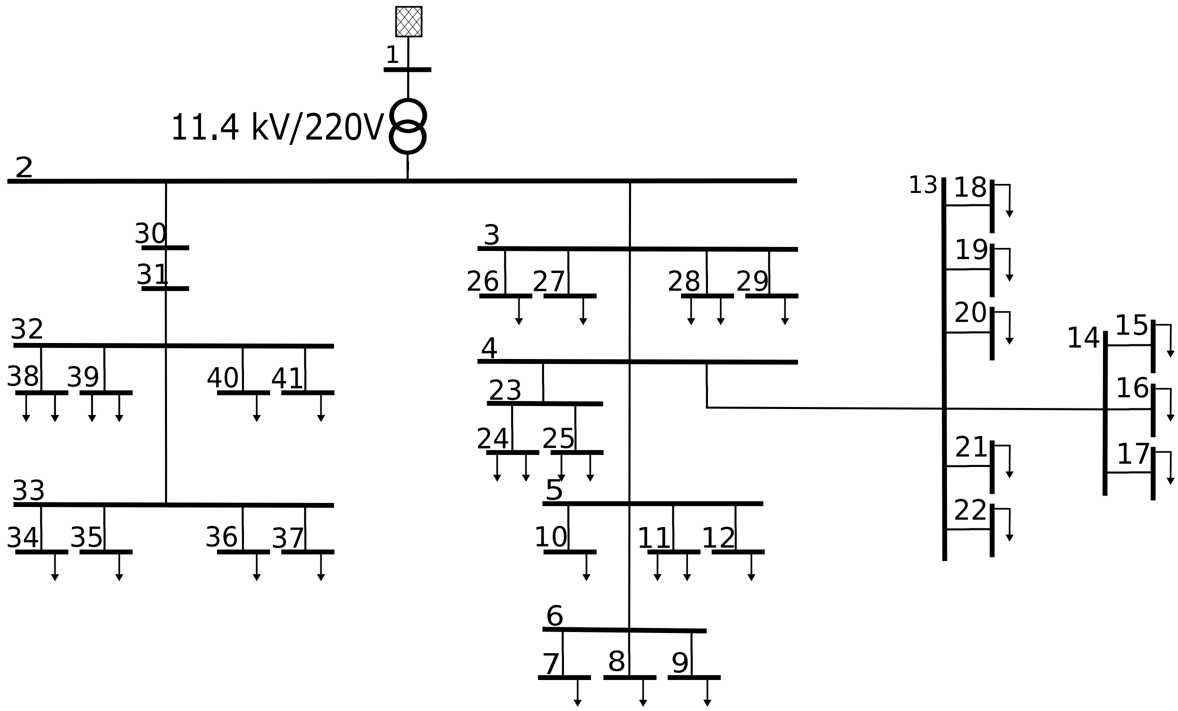


Fig. 1. Low voltage distribution network

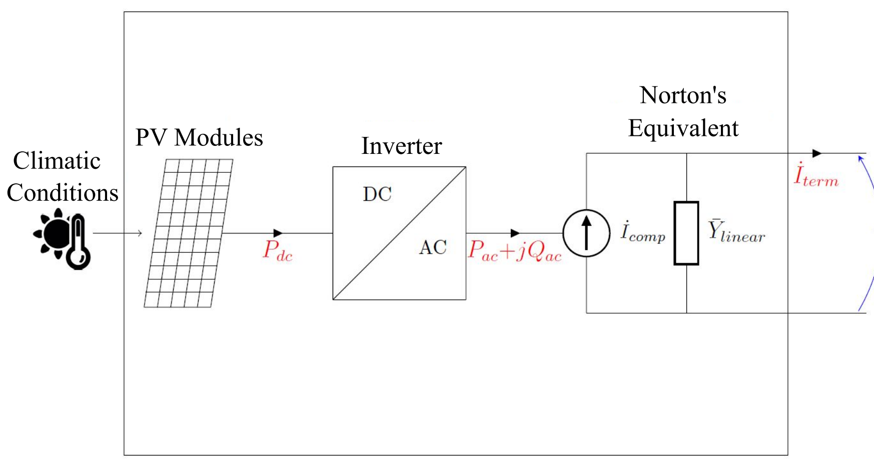


Fig. 2. PV system's diagram as described in the OpenDSS software.

C. ESS's Sizing, Model and Management

The individual ESS must ensure the storage of all prosumers' surplus generation. This way, it is necessary to consider the PV-DG operation and residential consumption within 24 h. Knowing that the electric power will be generated only during the day, the calculation consists of obtaining the total surplus energy between 8 am and 4 pm. Such a range is used when the reverse power flow may occur. The capacity of each ESS is given by 3.

$$E_{ESS} = \int_{8}^{16} P_{pv}(t) - P_c(t)dt \tag{3}$$

As with the PV generator, OpenDSS has a base model for the storage component. The ESS model is composed of an ideal energy storage, a series of an element that describes the charge (ch) and discharge (dch) associated losses, another in parallel showing the losses due to inactivity, and a component that abstractly indicates the operating state of the storage system (loading, unloading and idle) and the bidirectional inverter. The ESS diagram is shown in Fig. 3.

The energy stored will depend on the power at the terminals of the ideal storage (P_{str}). In turn, this value depends on the input (P_{in}) and output (P_{out}) powers, the charging (η_{ch}), discharging (η_{ch}) and inverter efficiency (η_{inv}). It is also necessary to consider the ESS power demand and the resources needed to integrate it into the grid. This consumption is also called idle losses (P_{idl}) and is a percentage value of the nominal power of the ESS. It is observed that idle losses are present in all ESS operating states and are still subject to loading and unloading efficiencies. The equation describing

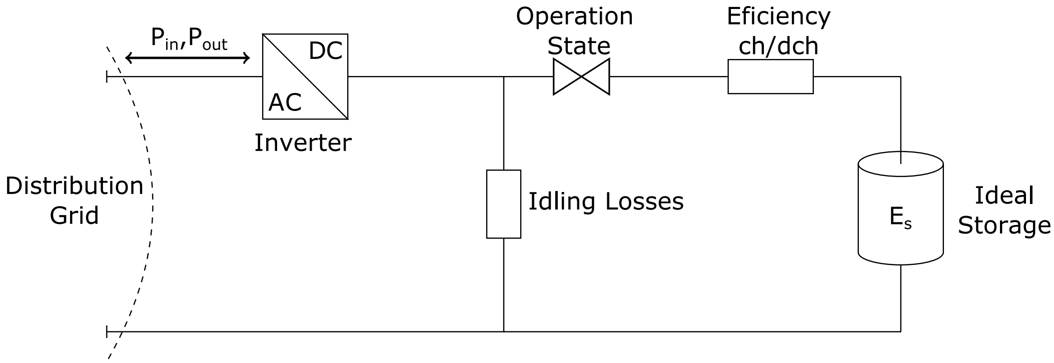


Fig. 3. ESS diagram in OpenDSS.

the power stored in time is given by 4.

$$P_{str}(t) = \begin{cases} \eta_{ch} \times [P_{in}(t) \times \eta_{inv}(t) - P_{idl}] \\ P_{idl} \\ \frac{P_{out}(t)}{\eta_{dch} \times \eta_{inv}(t)} + \frac{P_{idl}}{\eta_{dch}} \end{cases} \quad (4)$$

The individual ESS management was based on a peak load-shaving strategy [16]. The simulations comprise the execution of a total of 96 power flows. It's necessary to define at the beginning of each simulation the power applied to the ESS input terminals (P_{ESS}). This way, the power that will be stored or extracted from the ESS is calculated in the previous load flow. As in 4, the equation 5 defines the management proposal, taking into account each of the three operating states separately.

$$P_{ESS} = \begin{cases} P_c(t+1) - P_{pv}(t+1), \text{ if } P_L < 0 \\ 0, \text{ if } U_l \geq P_L \geq 0 \\ P_L(t) - U_l, \text{ if } P_L \geq U_l \end{cases} \quad (5)$$

The aim is to store all surplus PV generation in the ESS. Therefore, when the power measured at the prosumer coupling point (P_l) is lower than zero, the ESS is loading and needs to absorb the difference between consumption (P_c) and generation (P_{pv}). These data are already known for all simulation instants, so their values in (t+1) are used. This is done because the output power of the PV-DGs has sudden variations during the day, and by using the information from the next moment, it is possible to obtain more stable management. The ESS will be inactive when the power measured at the prosumer connection point is equal to or greater than zero and lower than the established threshold (U_l). This means that there is no surplus to be stored and the power demand of the network is lower than the delimited consumption. For all simulated cases, a 30% threshold of the nominal load of each consumer unit was established. The ESS also goes to inactivity when it reaches its minimum (12.5%) or maximum load. These last two cases are not demonstrated because OpenDSS guarantees they are respected.

On the other hand, the discharge of the ESS occurs when a supply is needed to limit the import of energy from the grid. Therefore, when P_l exceeds the value of U_l, the ESS has an output power equal to the difference. It is also important to emphasize the established convention. The input power (charge) has negative values, and the output (discharge) is always positive.

In contrast, in opposition, the concentrated ESS (single point of installation) has a different management tool. The storage controller, native to OpenDSS, was used in its peak load shave mode. Still, it works very similarly to the management method proposed earlier. The network will choose a bus, which will be the monitoring point, and two cutoff limits, a lower and an upper. This way, the ESS charge and discharge states will be controlled so that the active power at this monitoring point is always within a value between these two limits. For all simulations performed, monitoring occurs on the secondary of the three-phase transformer, with limits of 0 and 7 kW. The storage capacity of the concentrated ESS is the sum of all the individual ESSs.

III. Simulations Framework

Initially, a comparative study is proposed, carrying out a set of simulations in a daily period with four different DERs configurations.

The first simulation consists of the original test system analysis, in which all consumers are passive. Then (second situation), a PV-DG is added at each consumption point, converting network users into prosumers. In the third situation, individual ESSs are installed together with the DGs. Finally (fourth situation), the individual storage of each prosumer is disregarded and gives way to a single ESS concentrated and located at the beginning of the feeder (secondary of the three-phase transformer).

The first two cases are a basis for comparing the two different ESS connections. The first evaluates the test system's original functioning, and then the impacts of the full presence of PV-DG at the connection points of prosumers are observed. Then it becomes possible to verify if the ESS improves the distribution network operation and which configuration has the best results.

For all cases with PV-DG's presence, a high daily solar irradiation was considered for all units, with an average of 6 kWh/m². The influence of the reference voltage, measured on the network's first bus, was also verified. The values assigned were the nominal voltage (1 p.u.), a higher rating of 1.025 p.u., and the upper voltage limit (1.05 p.u.).

After comparing the proposed scenarios, new simulations were made, considering an extended period of 6 days. In these, the PV-DGs presence at all consumption points is evaluated together with the two different ESS configurations. Demand profiles, PV generation, and particular consumption behaviors involving weekdays and weekends are also considered. Such situations were adopted to analyze the behavior of energy stored in ESSs, considering vacation and dormitory houses (occupied only during weekdays).

IV. Results Analysis

A. Comparative Study of DER Configurations in 24h

Table I presents the maximum and minimum voltage percentage variations concerning V_{base} and the percentage Unbalance Factor (UF) for all considered situations. The absolute (kWh) and percentages losses on the lines, transformers, and the entire LVDN are also displayed.

With the integration of PV-DG in every residential consumer totaling an installed power of 43.2Kwp (144% of transformer capacity), it can be seen that there is almost no variation in the minimum voltage ratings. However, there is a maximum overvoltage of 3.92%. Due to this high variation and the unequal connection of the PV-DGs between phases, the maximum UF in the original network was 0.44%, increasing to 0.57%. As the prosumers' local generation is not fully consumed or stored, the surplus is injected into the grid, increasing the energy flow in the lines reaching the medium voltage primary system through the transformer. This situation increases line losses, which go from 2.27 to 4.14 kWh, and in the transformer, from 2.02 to 3.67 kWh.

The ESS connected to the PV-DG into the electrical system provides substantial improvements. Overvoltage is completely eliminated, as the ESS can store all surplus of locally generated energy. The minimum voltage drop is also reduced, from 4.88% to 3.69%, given that the ESS discharges at peak consumption times and thus relieves the grid demand. The UF also shows a decrease standing at 0.29%. With the network's extinction of power injection and consumer demand reduction, the line and transformer losses are also reduced to 2.14 kWh. Although these losses are lower in absolute values than the original network's operation and the integration of traditional PV-DGs, it is only smaller in percentage value than in the second case. This is because even if the losses are reduced, the energy circulation in the system also decreases.

The concentrated ESS presents the best results when analyzing the load curve at peak hours, resulting in a lower minimum voltage drop. However, such an ESS configuration cannot eliminate the overvoltage entirely, which reaches a maximum percentage value of 1.15 p.u. The unbalance increases due to the operation of the inverter responsible for the integration of the ESS, which can only inject the same power value in each phase. Finally, the case with the concentrated ESS presents the highest total losses in the lines and the lowest one in the transformer. This occurs because the ESS is connected at the beginning of the system's secondary network, thus reducing the demand for imported power from the primary network that passes through the transformer and preventing reverse flow. Even so, there is a bidirectional flow of power in the lines, which allows the charging and discharging of the ESS, which leads to an increase in the conductor's losses. In short, the amount of energy lost in the concentrated ESS situation is very close to the original condition of the system.

All results discussed so far concern a reference voltage with the nominal system value (1 p.u.). It is worth mentioning that the behaviors of the different configurations are repeated very similarly for the reference voltages at 1.025 and 1.05 p.u. However, increasing the system's reference voltage level brings about some changes. The maximum and minimum voltage variations are reduced, and the total energy losses decrease. Nonetheless, overvoltage situations are more subject to a violation of the regulated upper voltage limit. Since this is a Brazilian network, we use PRODIST standards, which dictate that the maximum voltage should not be higher than 105% of the rated voltage [17].

B. Prolonged Behavior and Continuous Residential Occupation (144 h)

Next, the two ESS configurations were re-evaluated for 144 hours of continuous operation, comprising a period between Thursday and Tuesday.

The results of a single three-phase prosumer are presented for the first configuration. Since it is at the connection point, it is possible to verify the flow of active power between consumption, storage, and generation and its relationship with energy loading from the local ESS. The active power in the distribution transformer was observed since it will indicate the total power flow of the network, given then the possibility of understanding the operation of the ESS.

1) High Daily Solar Irradiation: For the first scenario, it is assumed that the PV generation profile is repeated every day and has the same average irradiation considered previously (6 kWh/m²). This means that there is a high daily PV generation, and the ESSs need to store a high energy surplus. In Fig. 4, the power and the ESS loading of a prosumer connected to the three phases of the network are presented.

The high energy generation, combined with the local ESS, can supply the load satisfactorily in the first two days, reducing consumption to the established limit of 30% of the rated load. However, with the increased consumption on the weekend, the PV-ESS set cannot maintain the same load level observed previously. This reflects less energy stored between Saturday and Monday. At the beginning of the last day, the unit starts operating again with higher levels of stored energy and, consequently, a more significant reduction in consumption from the grid.

Then, in Fig. 5, the responses for the same situation are presented, now for a concentrated ESS. It is observed that the upper limit of 7 kW in ESS management was maintained, which shows its effectiveness. The energy stored during this period was sufficient to supply the grid. However, in two moments, the ESS reached its maximum load on Friday's late afternoon and Tuesday. Therefore, the stored energy was 196 kWh in these intervals that lasted 105 and 135 minutes, respectively. This led to reverse power flows, with the entire surplus of local PV generation being injected into the medium voltage grid.

TABLE I
IMPACT INDEXES ON THE LVDN'S OPERATION

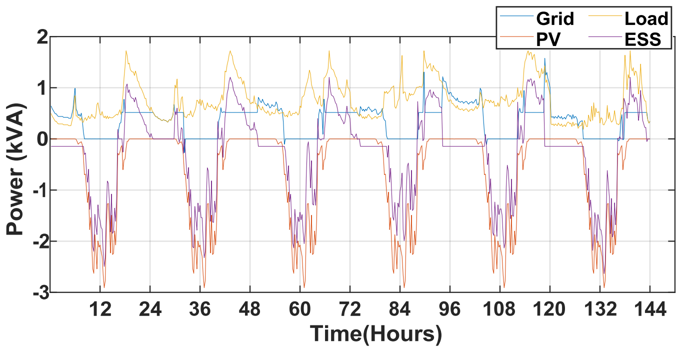
Vbase (p.u)	Indexes		Original Network	PV-DG	PV-ESS	Concentrated PV-ESS
1	Rate (%)	V_{min}	-4,94	-4,88	-3,69	-3,54
		V_{max}	0,00	3,92	0,00	1,15
		UF	0,44	0,57	0,29	0,69
	Losses (kWh)	Lines	2.27 (0.82%)	4.14 (1.06%)	1.13 (0.92%)	3.19 (2.66%)
		Transf.	2.02 (0.73%)	3.67 (0.95%)	1 (0.82%)	0.96 (0.7976%)
		LVDN	4.3 (1.54%)	7.84 (2.01%)	2.14 (1.75%)	4.14 (3.46%)
1.025	Rate (%)	V_{min}	-4,80	-4,75	-2,93	-3,44
		V_{max}	0,00	3,81	0,00	1,12
		UF	0,42	0,54	0,33	0,66
	Losses (kWh)	Lines	2.16 (0.78%)	3.94 (1.01%)	1.08 (0.88%)	3.03 (2.53%)
		Transf.	1.92 (0.69%)	3.52 (0.90%)	0.96 (0.78%)	0.91 (0.76%)
		LVDN	4.08 (1.46%)	7.45 (1.92%)	2.04 (1.66%)	3.94 (3.29%)
1.05	Rate (%)	V_{min}	-4,68	-4,62	-2,86	-3,36
		V_{max}	0,00	3,67	0,00	1,08
		UF	0,40	0,52	0,32	0,63
	Losses (kWh)	Lines	2.05 (0.74%)	3.72 (0.96%)	1.03 (0.84%)	2.88 (2.41%)
		Transf.	1.83 (0.66%)	3.32 (0.86%)	0.91 (0.74%)	0.87 (0.72%)
		LVDN	3.88 (1.39%)	7.04 (1.82%)	1.94 (1.58%)	3.75 (3.13%)

2) Variable Daily Solar Radiation: Up to this point, high generation was considered every day, which would be an optimistic situation regarding the use of PV-DGs, and conservative regarding the ESSs' capacity to store excess energy. However, both solar irradiation and ambient temperature are subject to variations depending on the weather conditions of the place. It is recalled that these two factors directly influence the PV power output. Based on this reality, the simulations were repeated, now considering daily irradiation and temperature profiles.

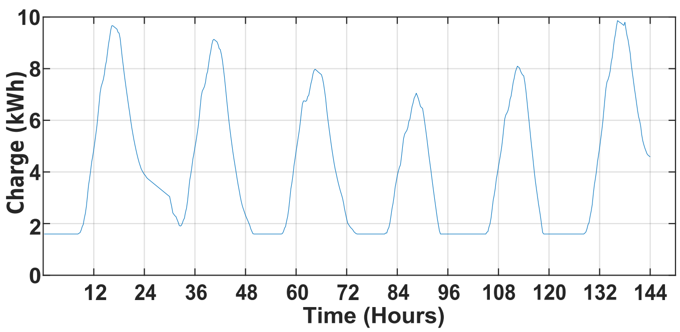
Fig. 6 presents results for an installation with a local ESS. Concerning the daily operation of the PV-DG, there is a peak in the output power. However, with a reduced duration on Thursday and Sunday. There are a few drops caused by shading on Friday and Saturday. Such days also present, respectively, medium and high generation levels. On the other hand, the remaining days indicate the variation of solar irradiation's influence, showing low power values on Monday and high values on Tuesday.

It is noteworthy that at no time does the inversion of the active power flow occur at the prosumer's connection point with the grid. The ESS stores all excess energy even on the highest PV generation days. This occurs because there are days when generation is low, thus resulting in a low energy surplus or even absence, and, consequently, the ESS charge is also reduced. Most of the time, the combination of these resources cannot guarantee the maximum limit of power coming from the network either. It is possible to observe such a situation between Monday and Tuesday. This interval starts with the ESS having a minimum and inactive load until the next day's early morning. Then, the stored charge increases until it almost reaches its maximum capacity, which is only not reached because it is placed in a discharge condition at the end of the simulated period.

Again, the concentrated ESS is evaluated for the uncertain PV generation situation. The values of interest are represented in Fig. 7. For this situation, the ESS reaches its maximum capacity on Thursday and Tuesday afternoons. Both days start with the minimum storage level. However, on these same days, a large amount of energy is coming from the DG, and therefore, the ESS is fully charged. Once the storage capacity runs out, there is a reverse power flow in the transformer. Mostly, the combination of local PV-GDs and concentrated ESS ensures that the active power consumption limit of the grid remains at 7 kW at peak consumption time. However, in the early hours of Saturday, the ESS is completely discharged for a short time, and the ESS management cannot maintain this limit. This also occurs on Monday, as the PV generation on this day is very low.

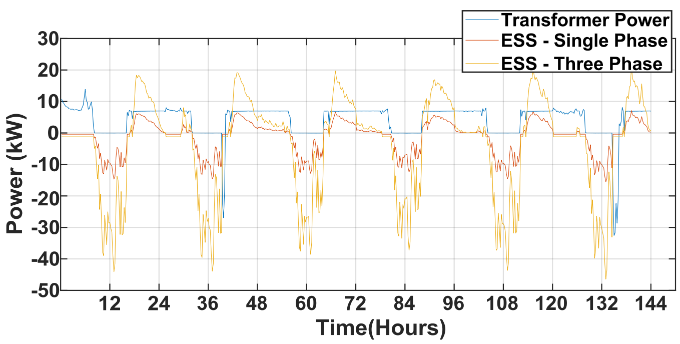


(a) Active power.

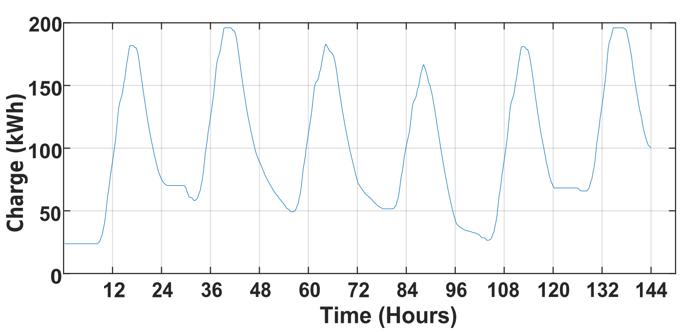


(b) Stored energy.

Fig. 4. Three-phase prosumer's measurements with high PV output.

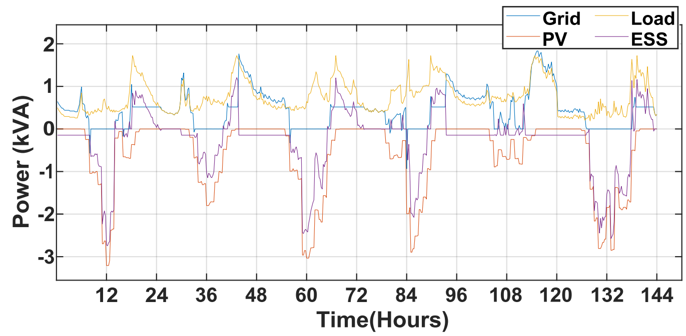


(a) Active power.

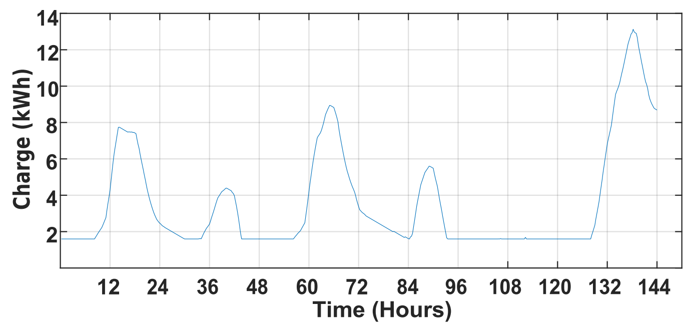


(b) Stored energy.

Fig. 5. Concentrated ESS's measurements with high PV output.

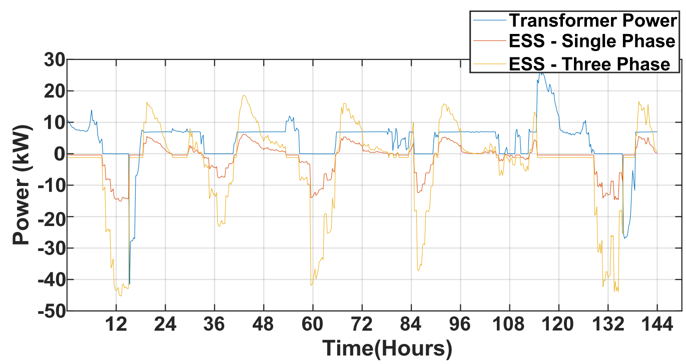


(a) Active power.

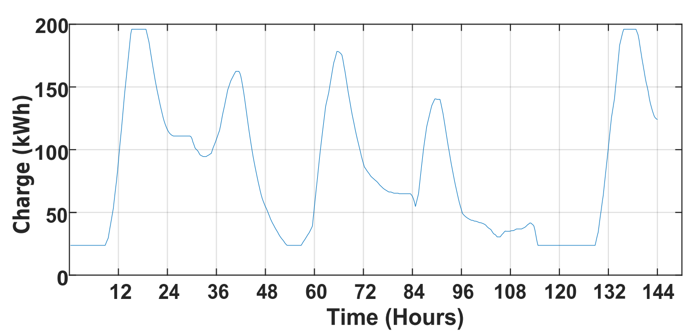


(b) Locally stored energy.

Fig. 6. Three-phase prosumer's measurements with variable PV output.



(a) Active power.



(b) Stored energy.

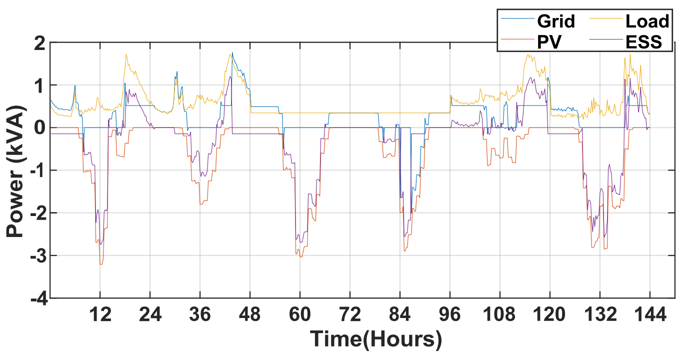
Fig. 7. Concentrated ESS's measurements with variable PV output.

C. Prolonged Behavior and Interrupting Residential Occupation

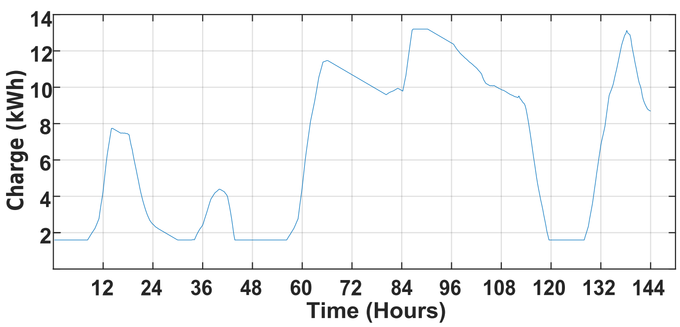
The following simulations assume that the consumers' installations are occupied only on specific days of the week (weekdays or weekends). On days when they are empty, the load is fixed at 20% of the installed rated power. This would represent the consumption of equipment with a continuous operation that cannot be turned off.

1) Weekday's Occupation: In the following Figs. 8 and 9, residences are considered to be occupied on weekdays and empty on weekends.

Fig. 8 presents the powers at the connection point of the prosumer and the behavior of its connected ESS. On Thursday and Friday, the PV-GD's active output power is insufficient to limit grid consumption by 30%. However, excess energy is stored on the weekend due to low consumption and higher PV generation. The maximum load of the ESS is reached at 2:45 pm on Sunday, which results in an active power injection into the grid until 6:15 pm. However, with the resumption of regular consumption on Monday and low PV generation, all the stored energy is used and reaches its minimum level at 23:30. On Tuesday, the ESS is already fully loaded again.



(a) Active power.



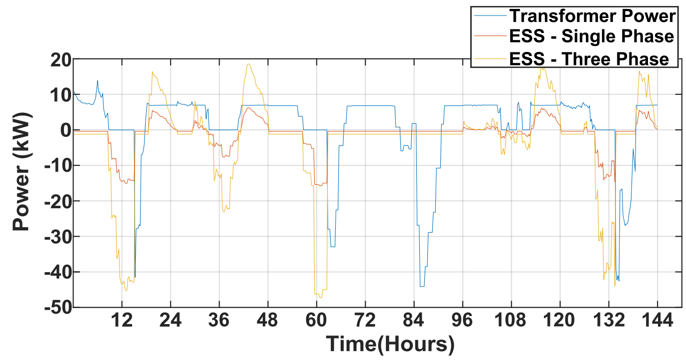
(b) Locally stored energy.

Fig. 8. Three-phase prosumer's measurements with variable PV output and weekdays consume.

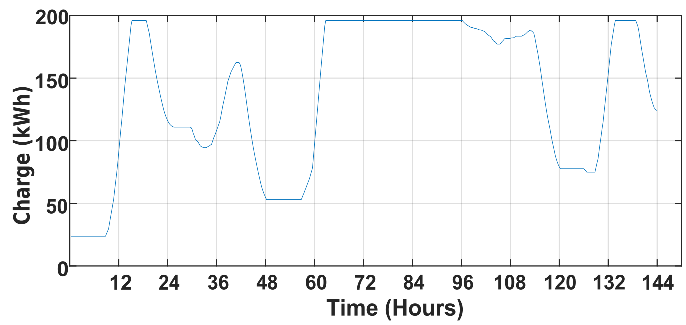
Considering the same conditions of consumption and PV generation, the concentrated ESS's behavior and the resulting powers of the entire network are evaluated in Fig. 9. The ESS is already fully charged on the first day, with all surplus energy provided by the 34 prosumers. In this way, the ESS is inactive until the PV generation ceases and then goes into discharge mode to alleviate the peak demand in the late afternoon.

At the beginning of the weekend, with the houses empty, the high surplus of energy generated and the total consumption lower than 7 kW make the ESS reach its maximum charge, going into inactivity. This causes the emergence of a reverse power flow at the transformer on the weekend afternoons. The ESS remains out of operation until early Monday, the day when consumption returns to its usual behavior and relies on a small contribution from the DG-PVs. Then, on Tuesday, the ESS is fully loaded.

2) Weekend Occupation: Inverting the logic and assuming that the facilities are used only on weekends, Fig. 10 presents



(a) Active power.

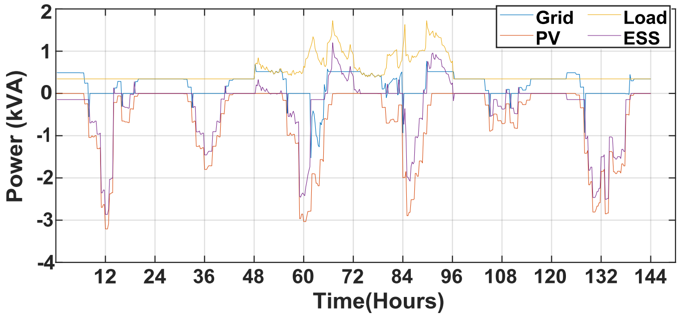


(b) Locally stored energy.

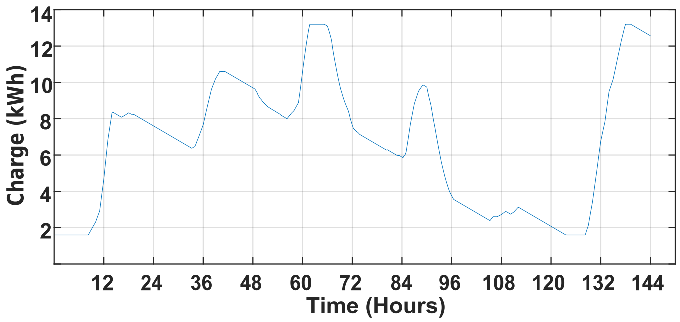
Fig. 9. Concentrated ESS's measurements with variable PV output and weekdays consume.

the conditions of three-phase connected prosumers. The ESS starts the simulation period with minimal charge. In the first 48 hours, the PV-DGs show a low generation. Consequently, the ESS can store all surplus energy until early Saturday afternoon. Only in the late afternoon, with the decay of the power supplied by the PV-GD, the reverse power flow ceases, and the ESS starts operating again to maintain the grid's power limit demand. On Monday, the energy reserve continues to be used, and it runs out at the end of the day. When there is no more energy to keep the ESS functioning, it starts to demand power from the network. This results in a slight increase in the power measured at the prosumer's connection point. Finally, the ESS is fully charged with the high PV generation on the last day.

Fig. 11 presents the measurements for the situation with a concentrated ESS in which the residences are only occupied on the weekend. The ESS starts with minimal load, but with low consumption and high generation, it is quickly loaded. The maximum charge and the ESS idle state are maintained until the weekend starts, when consumption increases and is no longer constant. However, with high PV generation on Saturday, the storage is fully charged again and remains inactive until the end of the day. From this point forward, the power reserve is used during the weekend. At the beginning of weekdays, there is also the vacancy of properties and the return of constant consumption to 20%. The ESS is then fully charged on Tuesday afternoon and remains idle. Overall, the concentrated ESS demonstrated a better use of its capacity and stored energy.

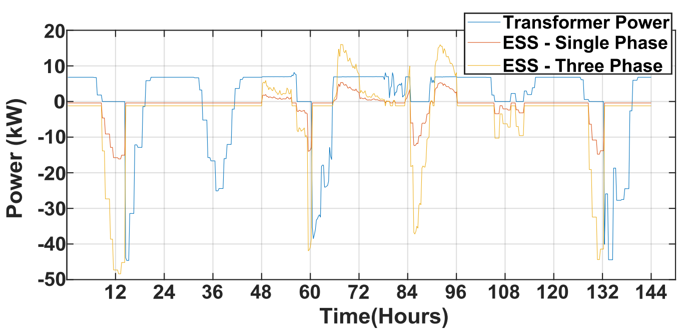


(a) Active power.

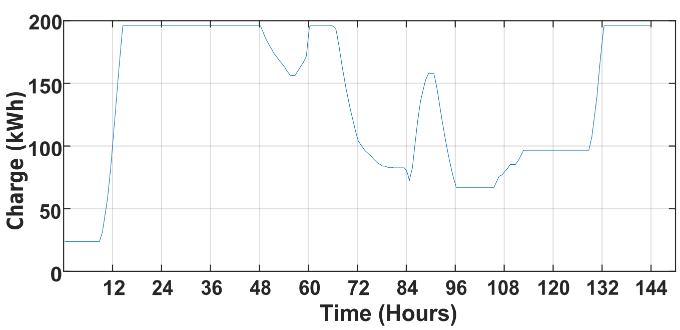


(b) Locally stored energy.

Fig. 10. Three-phase prosumer's measurements with variable PV output and weekend consume.



(a) Active power.



(b) Locally stored energy.

Fig. 11. Concentrated ESS's measurements with variable PV output and weekend consume.

V. Conclusion

The daily PV generation variation has a higher impact on stored energy levels in situations with individual ESSs compared to its concentrated version, making it difficult to act on reducing demand for grid power. Still, the ESS often cannot store all the excess energy and also goes into a state of inactivity. However, the situations put into simulation are very specific and idealized, as all present units have the same occupation and consumption patterns.

However, with adequate sizing and management for more practical situations, the ESS could serve the entire network to limit the total consumption curve within the stipulated limits. This operation can also maintain the current net-metering compensation system since it is possible to keep the exact measurement and credit system or even enable new business strategies for the distribution company and the communities of consumers. A concentrated ESS would also guarantee the maintenance of the current GD-PV market's growth.

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