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Computational Platform in OpenDSS for Simulation of Aggregators and Urban Virtual Power Plant

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ABSTRACT: The purpose of this article is to present a computer simulation of a fictitious project of a Virtual Power Plant, or Virtual Power Plant (VPP), in a housing estate buildings in the city of Recife-PE, Brazil. The location was chosen because it has buildings with regular sizes, excellent solar irradiation throughout the year and a power distribution grid around each block. Although theoretical, the project can be implemented because each building of the proposed model would act as a VPP aggregator with photovoltaic solar generation and energy storage in batteries composing the Distributed Energy Resources (DER) for energy supply. The modeling of the system is being developed with the OpenDSS program, OpenSource license, commonly used by Distribution Service Operators, together with the Python language. The buildings will be grouped into subgroups and groups with simulation of three scenarios to observe the performance of the aggregators to provide a load of 40kW of the distribution network. The results demonstrate that the aggregators have an important contribution in the supply of electric energy and the association of more aggregators increases the reliability of the system. Computer simulations of the proposed scenarios help to understand the interaction between different energy sources, contributing to studies and planning of electrical systems.

KEYWORDS: Virtual power plant, Distributed energy resources, Aggregators, Opendss, Python.

1. INTRODUCTION

The Paris Agreement, signed during the 2015 United Nations Conference on Climate Change (COP-21), defined goals to reduce greenhouse gas emissions, aiming to limit global warming to levels below 2°C by the end of the 21st century [1]. Brazil voluntarily assumed commitments to reduce the release of CO_2 into the atmosphere. During the 2021 COP-26, held in Glasgow, Scotland, the Paris Agreement was debated and countries reinforced their commitments. The Brazilian government has committed to expanding the targets previously established, with a new target of 50% reduction in greenhouse gas emissions by 2030 and total carbon neutralization by 2050 [2]. An efficient way to achieve these goals is to invest more and more in more sustainable energy sources.

Table 1 presents the percentages of the types of energy sources in Brazil and in the world in a general context. It is noted that Brazil has an energy matrix almost corresponding to 50% of renewable sources and 50% of non-renewable sources. It is also noted that the matrices used by most countries in the world are non-renewable. Table 2 presents the percentages of the matrices for the generation of electric energy from which it is obtained that in Brazil more than 74% of the sources come from renewable resources in contrast to the sources used in the world. All tables use comma as a decimal separator.

Brazil has several challenges dealt with in the National Energy Plan 2050, which is the set of studies and guidelines for long-term strategies for the country's energy sector [3].

Table 1 – General energy source in Brazil and in the world.

	Percentage (%) Brazil		Percentage (%) World
Source	Base year 2020	Base year 2021	Base year 2019
Renewable			
Biomass	19,10	16,40	9,30
Hydraulics	12,60	11,00	2,60
Charcoal and firewood	8,90	8,70	0,25
Other renewables	7,70	8,70	1,50
Renewable total	**48,30**	**44,70**	**13,65**
Non-renewable			
Petroleum and derivatives	33,10	34,40	31,10
Natural gas	11,80	13,30	23,00
Mineral coal	4,90	5,60	27,00
Nuclear	1,30	1,30	5,00
Other non-renewable	0,60	0,70	0,25
Non-renewable total	**51,70**	**55,30**	**86,35**
GENERAL TOTAL	**100,00**	**100,00**	**100,00**

Source: BEN 2021 [4], BEN 2022 [5] e IEA 2019 [6].

Table 2 - Energy source for the production of electricity in Brazil and in the world.

Source	Percentage (%) Brazil		Percentage (%) World
	Base year 2020	Base year 2021	Base year 2019
Renewable			
Hydraulics	65,20	53,40	16,10
Biomass	9,10	8,20	2,40
Wind	8,80	10,60	5,28
Solar	1,70	2,50	2,58
Other renewables	0,00	0,00	0,34
Renewable total	**84,80**	**74,70**	**26,70**
Non-renewable			
Natural gas	8,30	12,80	23,50
Mineral coal	3,10	3,40	36,80
Nuclear and others	2,20	5,60	10,20
Petroleum and derivatives	1,60	3,50	2,80
Non-renewable total	**15,20**	**25,30**	**73,30**
GENERAL TOTAL	**100,00**	**100,00**	**100,00**

Source: BEN 2021 [4], BEN 2022 [5] e IEA 2019 [6].

Regarding the transmission of the system, the replacement of the electrical system infrastructure as it ages when the assets have expired technical and regulatory useful lives are mentioned. This will require significant investments, followed by a planning of this replacement. For some equipment, the decrease in capacity is potentiated by the massive insertion of variable renewable sources into the grid, which implies different and more severe charging and operating cycles when compared to the original equipment designs.

With technological advances in Intelligent Electrical Grids, Distributed Generation and Distributed Storage, it is expected that the electrical system will gain flexibility, become more dynamic to instantaneous operational requirements, and accommodate variations in generation, mainly from photovoltaic and wind sources. The incorporation of different forms or storage technologies will bring a new dynamic to the operation of the electrical system, which makes this issue an important aspect to be considered.

The distribution system planning will need to be evaluated with integration with the high voltage grid, contemplating the reversal of the direction of power flows during some periods, that is, of the low/medium voltage grid, in which there will be Distributed Generation. Given this situation, it makes sense to study the association of Distributed Generation with Distributed Storage as a way to smooth energy demand peaks, improve the operation of the electrical system and reduce the need to build new transmission lines [3].

Technological development in recent years has improved or allowed new ways of generating energy. Distributed Generation, or simply DG, is a term to designate the generation of electrical energy carried out close to the consumer, regardless of power, technology used or type of energy source. This concept encompasses more modern measuring, control and command equipment that manage the operation of generators and control of loads according to energy demand [7].

With the need to reduce dependence on fossil fuels and the increasing precaution in the use of renewable energy sources to maintain natural resources, in the year 2040 about 30% of the world's electricity will be supplied by wind and solar photovoltaic energy. This category of Distributed Generation is classified as Variable Renewable Energy (VRE) and will become the main source of electricity in the European Union in 2030 and in the United States, China and India in 2035 [8]. For the implementation of a photovoltaic system, a complete study of the solar generation capacity involves solar irradiation over a year at the installation sites of photovoltaic panels. This study can be developed with data maps or some solar irradiance prediction methodology [9].

VRE systems have become economically accessible to consumers of different sizes, enabling them to generate part or all of the energy needed for their own demand. In this way, consumers are also becoming energy producers. In technical literature there is a neologism called "prosumer" resulting from the fusion of the words "producer" and "consumer", meaning one who produces and consumes [10]. In an electrical system, it acquires the meaning of who generates and also consumes energy.

Distributed Storage, or simply DS, is the use of technologies for energy storage, with the objective of supply and management, voltage control, frequency control, load balancing and others. It is composed of sources of different types such as electrical, electrochemical, chemical, mechanical or thermal with advantages and disadvantages that must be evaluated in each use case [11]. Of these, the Battery Energy Storage System - BESS stands out, consisting of electrochemical batteries composed of lead-acid, lithium-ion, sodium-sulfur batteries, for having an acceptable cost, high efficiency, low operating response time, among other characteristics [12].

Distributed Energy Resources (DER) are defined as technologies for the generation and/or storage of electric energy, located within the limits of the area of a given distribution concessionaire, usually next to consumer units, behind the meter [13]. The DERs include Distributed Generation (DG), Distributed Storage (DS), electric vehicles (EV) and charging structure, energy efficiency and Demand Response (DR). DR in restructured markets can be defined as the ability of a consumer to modify its load to maintain the security of the electrical system or in response to electricity prices or some financial incentive [14].

Smart grid

Smart Grid is a concept that combines the entire energy generation and distribution system in a single grid. This technology has been proposed as a promising solution to increase energy efficiency and improve consumption management in buildings. Such benefits are usually associated with the ability to accurately forecast energy demand. [15]. One of its features is Intelligent Metering, which together with Information Technology communication systems allows real-time monitoring of energy consumption. These and other features enable use in Bidirectional Communication Systems, Distributed Generation, Distributed Storage, Demand Response, Data Security/Cybersecurity and others [16]. The adoption of the Smart Grid involves technical and regulatory aspects adopted in each country [17] and is an important item in the search for more efficient electrical grids [18].

Microgrids

The combination of several types of DG gives rise to hybrid plants that are seen as a way to optimize the use of the transmission grid, as well as reduce the daily and monthly variability of sources such as wind and solar [19]. The integration of various resources of Distributed Generation, Distributed Storage and loads as a complete, interconnected electrical system, gives rise to Microgrids that act within well-defined electrical limits and as a single controllable entity [20][21].

Virtual Power Plants and Aggregation

The Virtual Power Plant (VPP) is a concept not yet pacified among the various authors [22]. There are some who approach it as an autonomous microgrid. Others define a VPP as an aggregation of different types of Distributed Energy Resources composed of generation and storage units that may be dispersed at different points in the distribution grid, but which operate as a single power plant, by a centrally controlling entity. The design of a VPP must allow for a more efficient integration of renewable energies and be able to contribute to a reliable and environmentally oriented energy supply [23]. Due to physical decentralization, the VPP must make use of telecommunications networks and Smart Grids.

Aggregators are groups of agents in an electrical system made up of consumers, producers and prosumers to act as a single entity. Operators of a VPP aggregate DERs to behave like a traditional Power Plant with attributes such as energy supply capacity and others, to participate in energy markets or ancillary services. In order for a suitable environment for aggregators to act in a VPP to occur, technical and regulatory requirements and definitions of action by the agents involved are necessary [24].

Differences between Virtual Power Plants and Microgrids

The concepts of VPPs and microgrids have several similarities, but there are important points that allow a differentiation [25]:

- Locality – In a microgrid, the DERs are located within the same local distribution grid and aim to meet mainly local demand. In a VPP, DERs are not necessarily located on the same local grid and are coordinated over a wide geographic area. VPP's aggregate production participates in traditional trading in energy markets.
- Size – The installed capacity of microgrids is usually small (from a few kW to several MW), while the rated power of a VPP can be much higher.
- Service – A microgrid focuses on satisfying local consumption, while a VPP treats consumption only as a flexible resource that participates in the aggregate commercialization of energy via remuneration by energy distributors.

Regulation in Brazil

In April 2012, ANEEL (*Agência Nacional de Energia Elétrica*) Normative Resolution nº 482/2012 came into effect, which deals with Distributed Micro and Mini Generation, which allows consumers to generate their own electricity from renewable sources or via qualified cogeneration and even provide the surplus for the locality's distribution grid [26].

Normative Resolution nº 687/2015 amends Resolution nº 482 and modules 1 and 3 of the Distribution Procedures (*Procedimentos de Distribuição de Energia Elétrica no Sistema Elétrico Nacional – PRODIST*). The normative deals with the limit increase from 1 MW to 5 MW, changing the validity of credits from three to five years and creating the modalities of projects with multiple consumer units, shared generation and remote self-consumption [27].

In January 2022, Law nº 14.300/2022 was published, which is the legal framework for Micro and Mini energy generation. The law gives legal certainty to consumer units that produce energy from renewable sources, such as photovoltaic solar, wind, hydroelectric and biomass [28].

2. METHODOLOGY

To demonstrate the aggregation of Distributed Energy Resources for the composition of a VPP, a fictitious but applicable project of photovoltaic solar generation with distributed storage will be presented in a housing estate buildings in the city of Recife-PE, located between Recife Avenue, Jean Emile Favre Street, Silveira Neto Street and Saldanha Marinho Street. The location was chosen because it has a large number of buildings with regular sizes, well distributed, in an open area with excellent solar irradiation throughout the year and with an energy distribution grid around each block.

Each building has 18,20m x 7,50m in blocks of 20 or 14 buildings per block, resulting in 136 buildings as shown in Figure 1. As a way of achieving modularity in energy generation and storage, the buildings will be separated into groups and subgroups as shown in Figure 2. Group A will be divided into 4 subgroups with 5 buildings each. The same applies for groups B, C and D which are similar. Group E will be divided into 4 subgroups so that two of these subgroups will have 4 buildings and the other two will have 3 buildings each. Groups F, G and H are similar to group E. Photovoltaic solar

Figure 1 – Top view of residential buildings chosen for the project. **Source:** Authors (2022) with computational resources from Google Maps.

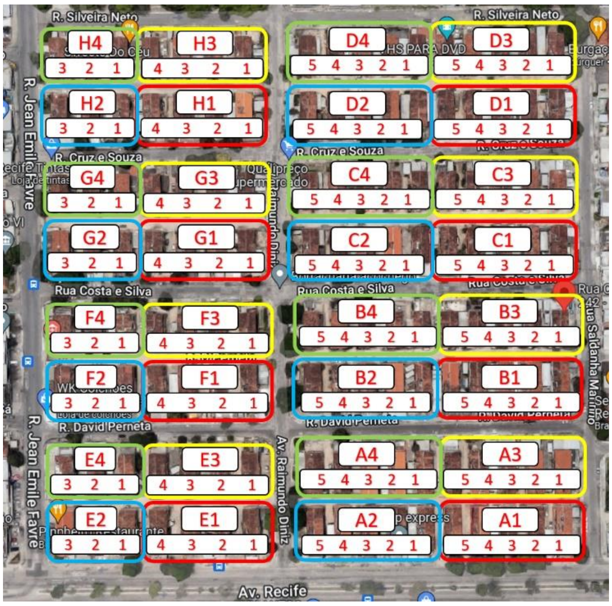

Figure 2 - Top view of buildings with power generation block. **Source:** Authors (2022).

generation will consist of panels measuring 1,00m x 1,65m and Distributed Storage will have lead-acid batteries installed in the vicinity of each building. Thus, each building will become an aggregator with energy generation and storage.

The chosen panels have a power of 300Wp. Both the size and the power of each panel were defined as they are items normally available from energy suppliers, although there are already panels with powers greater than the one used in this example.

Table 3 shows the division of the buildings of the generation block A and the subgroups, divided into A1, A2, A3 and A4. Generation blocks B, C and D have the same number of panels as generation block A. Block E and its subgroups are similar to generation block F, G and H that have the same number of panels. In this configuration, the maximum peak generation power will be 300 kWp for blocks A, B, C and D; and 210 kWp for blocks E, F, G and H; which will result in a maximum total capacity of 2.040 kWp, as shown in Table 4. In distributed storage, a BESS with 40kWh will be considered for autonomy of 10kW for 4h per building.

The presented arrangement allows simulating a Virtual Power Plant where each residential building would act as an aggregator of Distributed Energy Resources from Distributed Generation and Distributed Storage. The monitoring of electrical magnitudes such as voltage, current and power flows would occur with smart energy meters with Smart Grid technology. The VPP operator would monitor all meter data and dispatch the stored energy according to the load demand of the power distribution grid. The data about the injected power into the grid would be analyzed by the VPP controller and entities responsible for energy distribution to make the financial remuneration for the service provided.

With this arrangement, a computer simulation will be performed with the Open Distribution System Simulator

Table 3 - Number of photovoltaic solar panels per buildings of block A1, maximum peak power (Wp) in the generation of block A1 and the sum of total power A.

Description	Nomenclature	Photovoltaic panel	Number of panels per building	Peak Power per panel (Wp)	Total peak power of the building (Wp)
Generation block A1					
Building 01	**A1-1**	1,00m x 1,65m	50	300	15.000
Building 02	**A1-2**	1,00m x 1,65m	50	300	15.000
Building 03	**A1-3**	1,00m x 1,65m	50	300	15.000
Building 04	**A1-4**	1,00m x 1,65m	50	300	15.000
Building 05	**A1-5**	1,00m x 1,65m	50	300	15.000
Generation block A1 total (Wp)					**75.000**
TOTAL A (A1+A2+A3+A4) (Wp)					**300.000**

Source: Authors (2022).

Table 4 - Maximum generation power per aggregator building.

Description	Total peak power (Wp)
Maximum block A generation (Wp)	300.000
Maximum block B generation (Wp)	300.000
Maximum block C generation (Wp)	300.000
Maximum block D generation (Wp)	300.000
Maximum block E generation (Wp)	210.000
Maximum block F generation (Wp)	210.000
Maximum block G generation (Wp)	210.000
Maximum block H generation (Wp)	210.000
TOTAL (A+B+C+D+E+F+G+H) (Wp)	**2.040.000**

Source: Authors (2022).

program, or OpenDSS [29]. The software was developed by Electric Power Research Institute, EPRI, and is a distribution systems simulation tool designed to support the integration of Distributed Energy Resources and grid modernization of the electrical system [30]. This program can be controlled from a variety of existing software languages and platforms such as Python, C#, R, MATLAB, among others [31].

Figure 3 shows the simplified electrical arrangement of subgroup A1, which is composed of buildings A1-1, A1-2, A1-3, A1-4 and A1-5 as already shown in Figure 2. The charge controller was omitted from the scheme and the AC side of the inverter is connected to the bus labeled A1-1, which in turn is connected to the A1 bus. The complete arrangement is described in Figure 4.

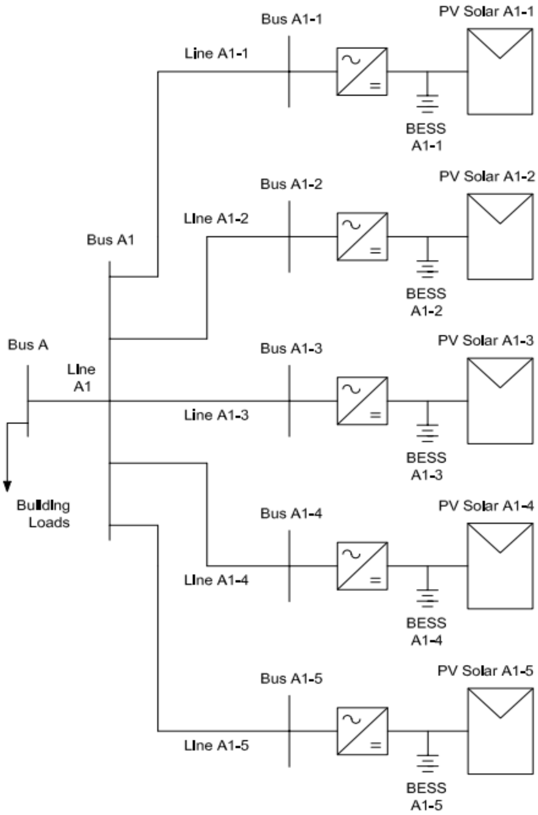

Figure 3 - Simplified electrical arrangement of subgroup A1.
Source: Authors (2022).

With the modeling of the proposed system, it is possible to simulate different scenarios for the VPP. It is possible, for example, to verify if a certain number of connected aggregators will be able to supply a certain load demand need of the distributor, among others. Table 5 presents some simulation scenarios. The general code is under development and the scenario simulations code, developed in OpenDSS and Python, is available in a GitHub repository with instructions for use [32].

3. RESULTS AND DISCUSSIONS

In a traditional electrical system, power flows go from a centralized generation to the loads. With Distributed Generation, which is carried out close to the loads, the needs

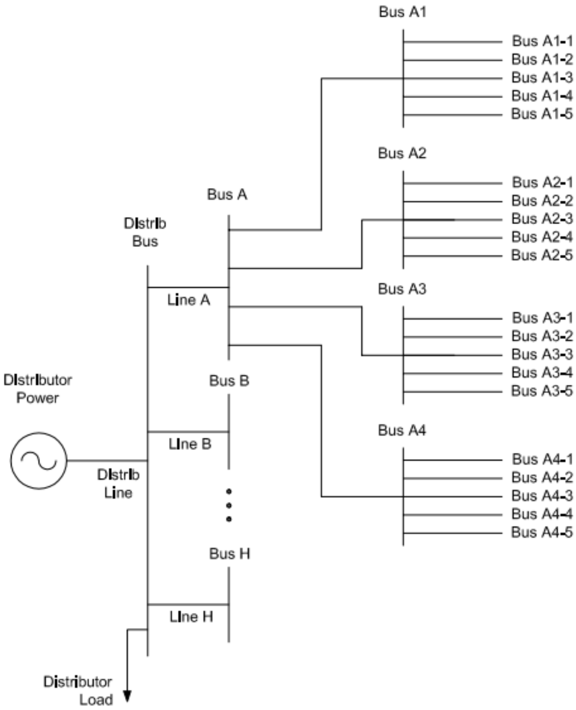

Figure 4 - Complete electrical arrangement containing groups, subgroups, buses and lines.
Source: Authors (2022).

Table 5 - Scenarios for simulation in 48 hours of aggregators of DERs in the composition of the VPP.

Scenario	Connected aggregator	Type of connected DER	Load characteristics
01	None	None	Residential profile load with 40kW
02	A1-1, A1-2, A1-3, A1-4, A1-5	Distributed Generation (DG)	Residential profile load with 40kW
03	A1-1, A1-2, A1-3, A1-4, A1-5	Distributed Generation (DG) and Distributed Storage (DS)	Residential profile load with 40kW

Source: Authors (2022).

for computer simulations on power flows and short-circuit studies are increased.

Figure 5 presents the results of scenario 01 and contains the graphs of voltages, currents and active powers in the Distribution Line connected to the Distribution Bus to supply energy the distributor load. The same figure also shows the graph of the active power on Line A also connected to the Distribution Bus. In this scenario, no aggregator is active and all electrical power comes from the Distribution Service Operators. In Figure 5 b) and c) it can be seen that the period between 18:00h and 22:00h corresponds to the peak period with the highest demand for current and power, respectively, with a small decrease in voltage as shown in Figure 5 a). The results of scenario 02 are represented in Figure 6, scenario 03 in Figure 7, with the same electrical magnitudes shown in Figure 5.

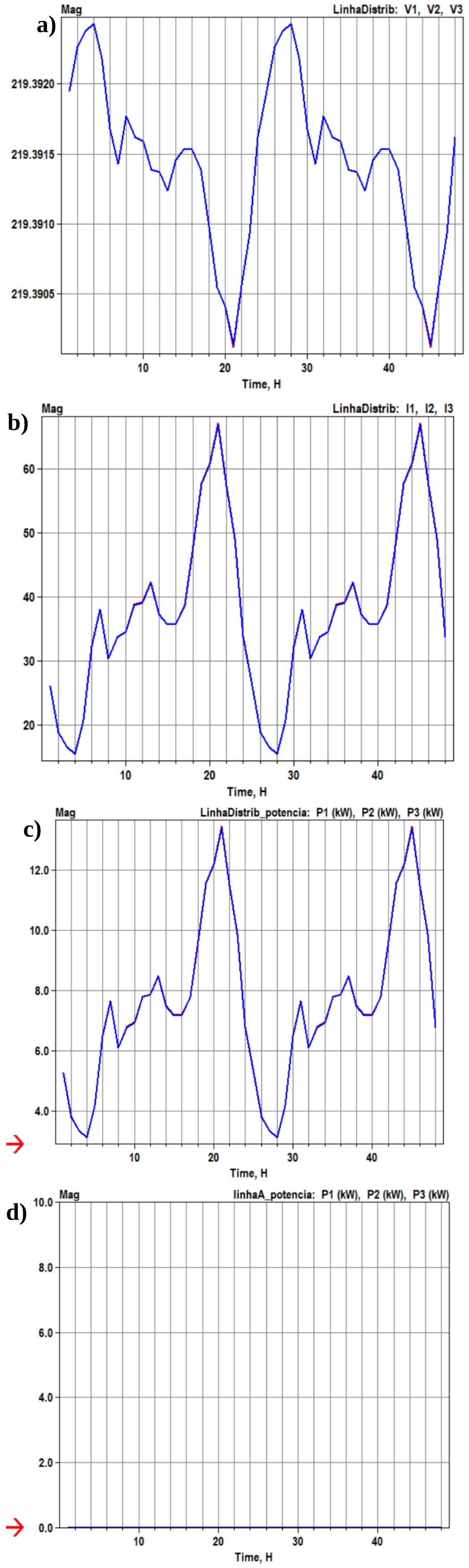

Figure 5 – Graphics in scenario 01: a) voltage (V) in Distribution Line; b) current (I) in Distribution Line; c) active power (kW) in Distribution Line; d) active power (kW) in Line A.
Source: Authors (2022).

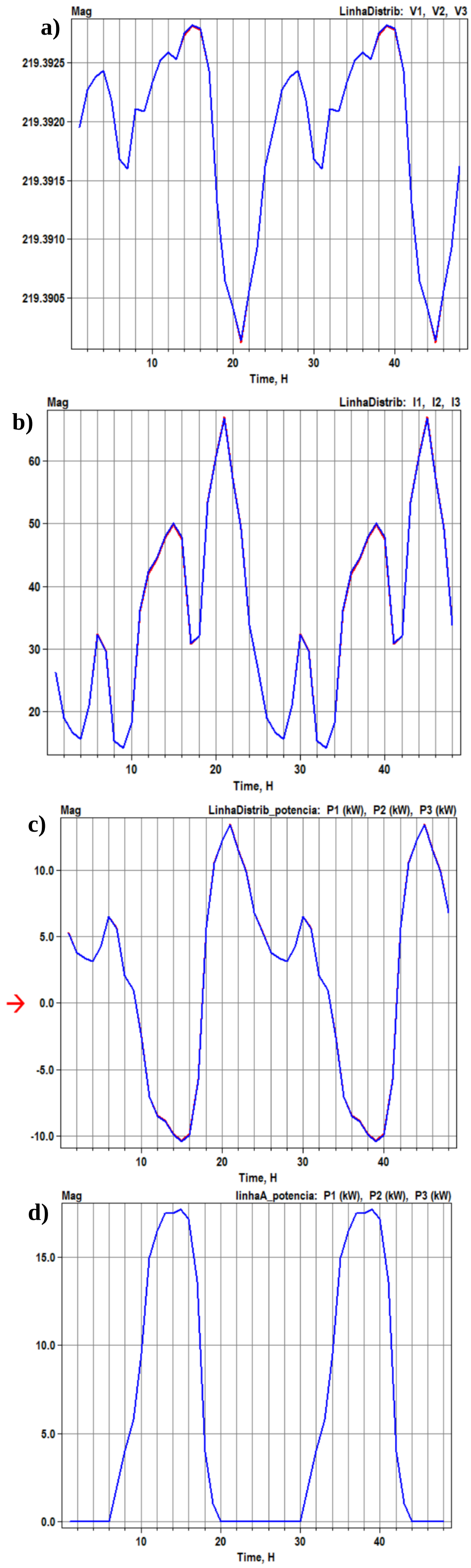

Figure 6 – Graphics in scenario 02: a) voltage (V) in Distribution Line; b) current (I) in Distribution Line; c) active power (kW) in Distribution Line; d) active power (kW) in Line A.
Source: Authors (2022).

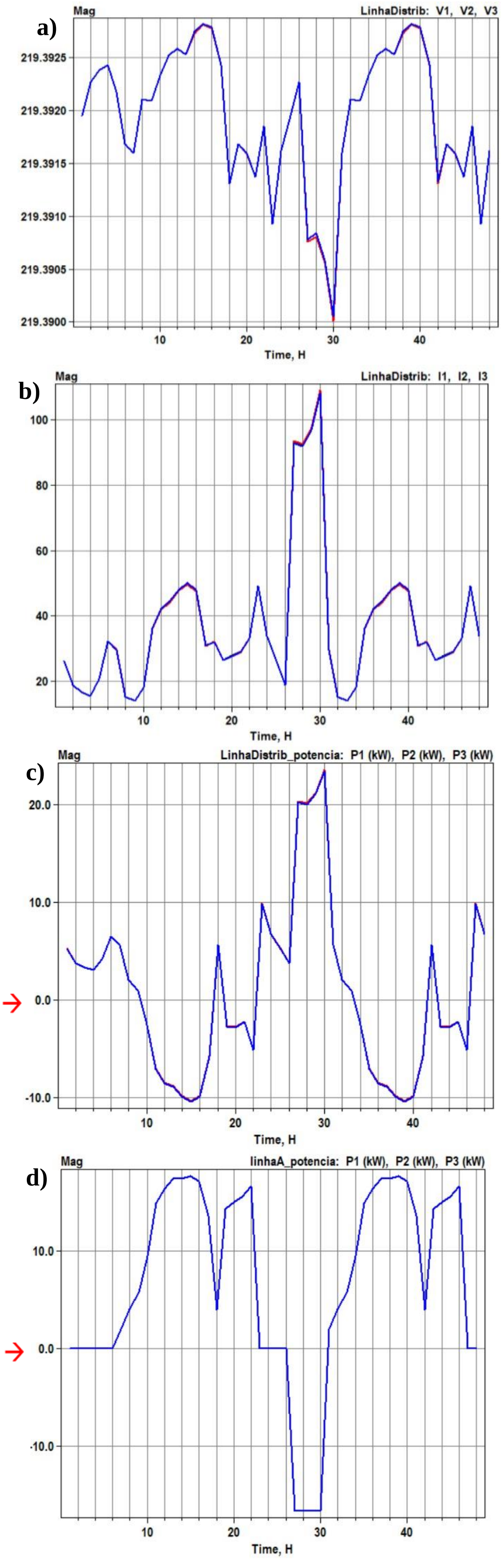

Figure 7 – Graphics in scenario 03: a) voltage (V) in Distribution Line; b) current (I) in Distribution Line; c) active power (kW) in Distribution Line; d) active power (kW) in Line A.
Source: Authors (2022).

In Figure 6 d) the characteristic curve of the Solar Distributed Generation with power supply on Line A to the Distribution Bus at times when there is the sunlight. This injected power can be observed in c) through a strip of the graph below the zero axis, indicated by an arrow on the abscissa axis, which corresponds to the quantity of energy supplied by the aggregators to the load. Despite the contribution of DG in the supply of energy throughout the day, it is noted that there is no relief in current and power demand at peak times, as shown in Figure 6 b) and c).

Scenario 03 with DG and DS is represented in Figure 7. In d) the characteristic curve of the junction between Solar Distributed Generation and Distributed Storage in batteries with power supply on Line A to the Distribution Bus is shown. Similar to scenario 02, in Figure 7 c) the graph range below zero represents a quantity of energy that was not supplied by the energy concessionaire, but by the aggregators.

In scenario 03, there is a relief in peak hours due to the energy supply promoted by the DS with action after sunset as shown in Figure 7 b) and c). In the simulations, OpenDSS considers that the batteries start the work cycle already properly charged and the recharge of this set occurs at dawn, which is the period of lowest energy demand. Note that during this period, the batteries will behave as loads and it is necessary to distribute their recharge cycle between the hours of dawn. Despite the energy cost for recharging, DS is important on rainy days or when the DG does not provide energy at full capacity. The aggregation of more subgroups in addition to those simulated in the scenarios allows increasing the capacity and reliability of the system in different situations.

The load power with a residential profile of 40kW is shown in Figure 8 and is the same for the three scenarios presented. Table 6 presents the short-circuit values simulated in scenarios 01 and 03, demonstrating the importance of reviewing the protection systems in the use of DERs. The simulations also present reports of voltage, current, power flow and others that help in the implementation of the project and the planning of the electrical system.

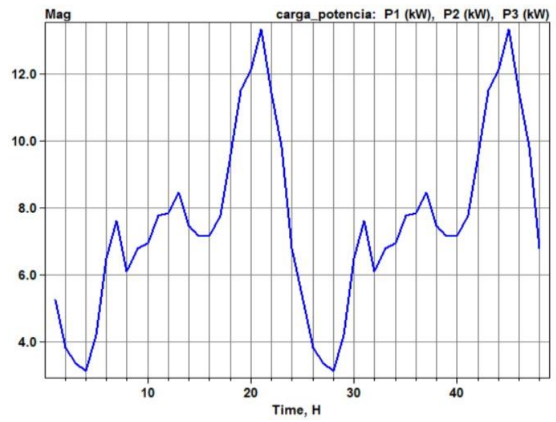

Figure 8 – Active power (kW) on load.
Source: Authors (2022).

Table 6 – Short circuit current (I) in scenarios without and with DERs.

Bus	3 phases (I)	1 phase (I)	L-L (I)
Scenario 01			
Distributor	3494	1612	3057
A	1993	916	1744
Scenario 03			
Distributor	6815	3531	5909
A	8525	8144	7354

Source: Authors (2022).

4. CONCLUSION

The modeling of the proposed system and the simulations of scenarios allow us to observe the performance of aggregators in the supply of electricity to meet increases in load demand in the distribution network. The observation of Figures 5, 6 and 7, indicate that the combination of several aggregators makes it possible to have a quantity of energy that can be controlled, therefore dispatchable. The various aggregators allow an increase in system reliability, but introduce increased complexity in the operation [3]. Computer simulations of scenarios help to understand the interaction between different energy sources contributing to power flow studies, design of short circuit protection and planning of electrical systems.

The project model presented allows modularity in the implementation of DERs in the VPP. Owners of each building can finance the acquisition of generation and distributed storage items or they can rent space such as the roof and battery storage area to the VPP administrator. There are several business modalities in addition to energy supply, such as ancillary services for frequency control [11], which can be applied in the integration of aggregators for the composition of a VPP, but which depend on technical and regulatory requirements for its operation and administration [24].

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