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Impacto de la integración simultánea de DER, RD y EAEE en una red de distribución

Impact of the simultaneous integration of DER, DR, and BES strategies in a distribution network

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Resumen

La integración desmedida de los recursos energéticos distribuidos a las redes de eléctricas ha producido impactos en los perfiles de tensión y las pérdidas de potencia, entre otros. Sin embargo, los programas de respuesta de la demanda o las estrategias de ahorro energético en edificaciones son iniciativas empleadas para mejorar el perfil de demanda. Por ello, este trabajo busca analizar el impacto de la integración simultánea de los recursos energéticos distribuidos, los programas de respuesta de la demanda y las estrategias de ahorro energético en edificaciones en una red de distribución. Una co-simulación en Python y PowerFactory es empleada para simular los escenarios de operación de forma automática. Como resultado se observa que la integración simultánea de las iniciativas favorece parámetros como los niveles de tensión, las pérdidas de potencia y la cargabilidad del transformador. No obstante, es necesario establecer límites de integración de recursos para evitar afectaciones en la operación de las redes eléctricas.

Palabras clave: co-simulación; EAEE; impactos; DER, RD.

Abstract

The massive integration of distributed energy resources into electricity networks has impacted voltage profiles and power losses, among others. Nevertheless, demand response programs or energy saving strategies in buildings are initiatives used to improve the demand profile. Therefore, this paper seeks to analyze the impact of the simultaneous integration of distributed energy resources, demand response programs, and energy saving strategies in buildings in a

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distribution network. A co-simulation in Python and PowerFactory is used to simulate operating scenarios automatically. As a result, the simultaneous integration of the initiatives favors parameters such as voltage levels, power losses, and transformer loading. However, it is necessary to set limits on the integration of resources to avoid affecting the operation of electricity networks.

Keywords: BES strategies; co-simulation; DER; DR; impacts.

1. Introduction

The continuous increase in energy demand and greenhouse gas emissions and the technical and environmental constraints in expanding centralized generation have boosted the strengthening of initiatives related to the global energy transition [1], [2]. Among the initiatives implemented, the integration of distributed energy resources (DER), such as photovoltaic systems (PV), electric vehicles (EV), and battery-based storage systems, is one of these. Other initiatives associated with demand are demand response schemes (DR), which contribute to reducing the impact of demand peaks [3]; likewise, energy saving strategies in buildings (BES strategies) are identified whose objective is to improve energy consumption through the use of environmental conditions [4], [5]. However, integrating these initiatives has led to physical and operational changes in the electricity networks, which leads to positive and negative impacts [6]–[9].

The impacts produced by the DER in the distribution networks are divided into three groups: impacts on the voltage profile [10]–[12], impacts on *Hosting Capacity* [13]–[15] and impacts on power quality parameters in particular harmonic voltage and current distortion indices [16]–[19]. For example, Zeraati and Golshan [10] demonstrated that a high integration of PV inverters into the grid can cause effects on voltage regulation and unbalance. Also, Johansson *et al.* [13] mention that excessive integration of DER into the electricity grid can lead to congestion problems and increase peak demand in the case of electric vehicles.

On the other hand, using demand response schemes has had positive effects, such as improvements in voltage profiles, the reliability indices of the electricity grid, and the reduction of active power losses [20]. Furthermore, Dehghani and Vahidi [21] conclude that a demand response program is essential in the lifetime index of distribution network drivers.

In the same way, the BES strategies application can be approached in different ways, such as the mitigation of solar gains with shading on facades, thermal insulation or green roofs [22]–[26], use of environmental conditions, ventilation and natural lighting [27], on-site power generation [28], among others. Likewise, this set of strategies reduces the energy consumption of buildings by up to 50%, causing a variation in the demand profile [4], [5], [23], [24].

Despite the above, studies on the impacts of these initiatives tend to focus on specific aspects, such as analyzing a single variable of interest, such as voltage regulation, or applying a single initiative in distribution networks. Therefore, it is necessary to study the integral application of the DER, DR programs, and BES strategies in distribution electricity networks to evaluate the impacts of their simultaneous integration at different penetration levels. Thus, this article presents an analysis of the impacts of the individual and simultaneous integration of DER, DR scheme, and BES strategy in electrical parameters of a distribution network, taking into account a co-simulation methodology between PowerFactory and Python to run load flows automatically.

2. Methodology

Section 2.1 includes a description of the grid as a case study; Section 2.2 describes the co-simulation process between PowerFactory and Python used to obtain the results of simulations; Section 2.3 presents the DER models and load profiles applying a DR scheme and a BES strategy used in PowerFactory; finally, the simulation scenarios are presented in Section 2.4.

2.1. Case of study

The distribution grid used as a case study is located in the city of Bucaramanga, in the Los Pinos neighborhood. This electrical network has radial topology with a single four-wire three-phase transformer with a capacity of 112.5 kVA, voltage 13.2 kV / 220-127 V (Δ/Y), and feeds 98 customers: 80 residential, 12 commercial, and 6 industrial. Figure 1 shows the single-phase diagram of the selected electrical network, which has 43 nodes where some loads are concentrated.

The power grid has three main branches: R1, the upper branch; R2, the central branch; and R3, the lower branch. Figure 2 shows the three branches selected to analyze the impacts of DER, DR scheme, and BES strategy in the single-phase diagram of the network.

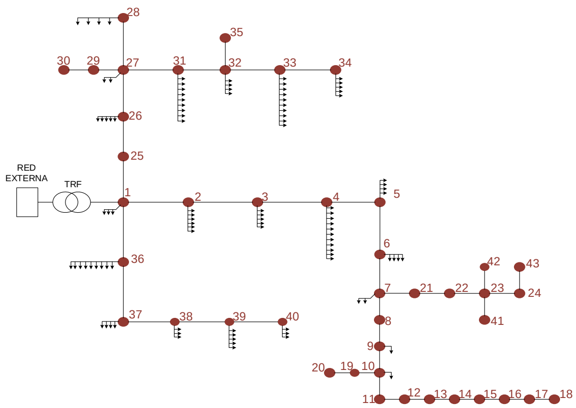


Figure 1. Single-phase grid diagram of case study. Source: Authors.

2.2. PowerFactory-Python co-simulation

A co-simulation process can be defined as the interaction between two or more simulation software that allows working cooperatively by exchanging information during execution [29]–[32]. PowerFactory executes load flows under specific generation and demand conditions at specified time intervals (day, week, month, or year).

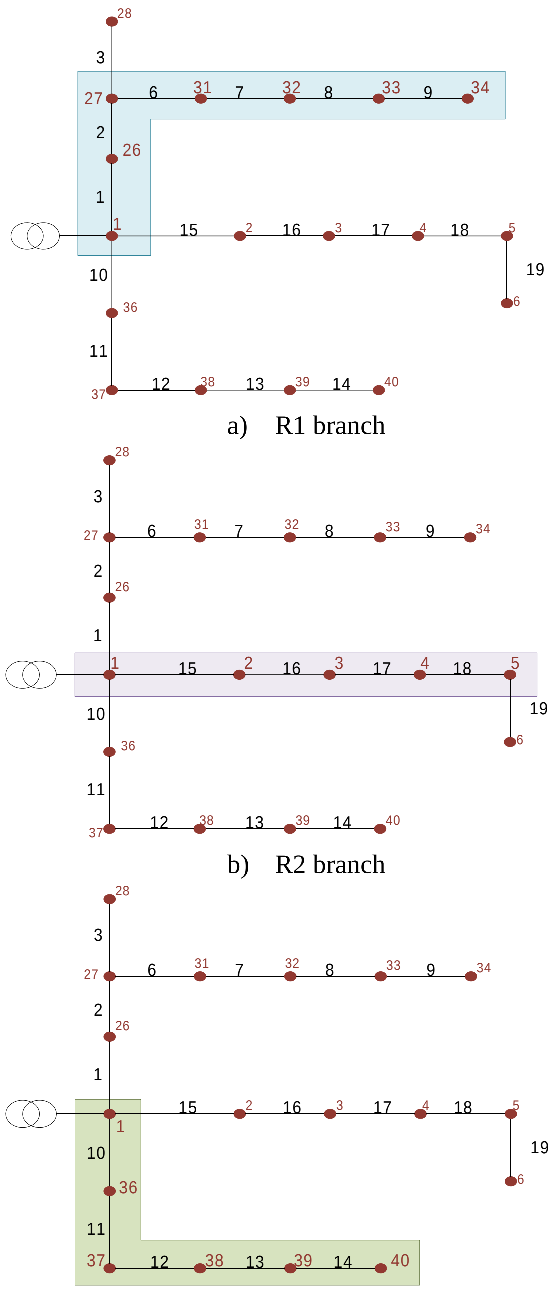
The parameters must be defined for each element of the electrical network, management rules for storage systems, activation and deactivation of elements, and extraction of results must be established.

On the other hand, Python's role in the co-simulation process is to automate the assignment of specific parameters to network elements, the execution of load flows, and the extraction of results [29].

Figure 3 presents an overview of the methodology used to execute deterministic load flows. Blue blocks represent the time characteristic information needed to define load demand profiles and daily solar irradiance and temperature data; the purple blocks are associated with the general modeling of the electrical grid and the DER; the orange blocks belong to the previous information that must be known for the operation of the batteries in the software; Finally, yellow blocks are those processes of interaction between the two software to run a deterministic load flow.

Input data to PowerFactory and Python, such as daily temperature profiles, solar irradiance, electric vehicle, and loads demand profiles, are imported from Excel files; instead, element-specific parameters such as nominal voltage and nominal power, among others, are manually entered into PowerFactory.

The electrical variables chosen as results of deterministic load flows are defined in PowerFactory and extracted by Python in Excel files for each described scenario.



a) R1 branch

b) R2 branch

c) R3 branch

Figure 2. Main branches of the network of the neighborhood Los Pinos. Source: Authors

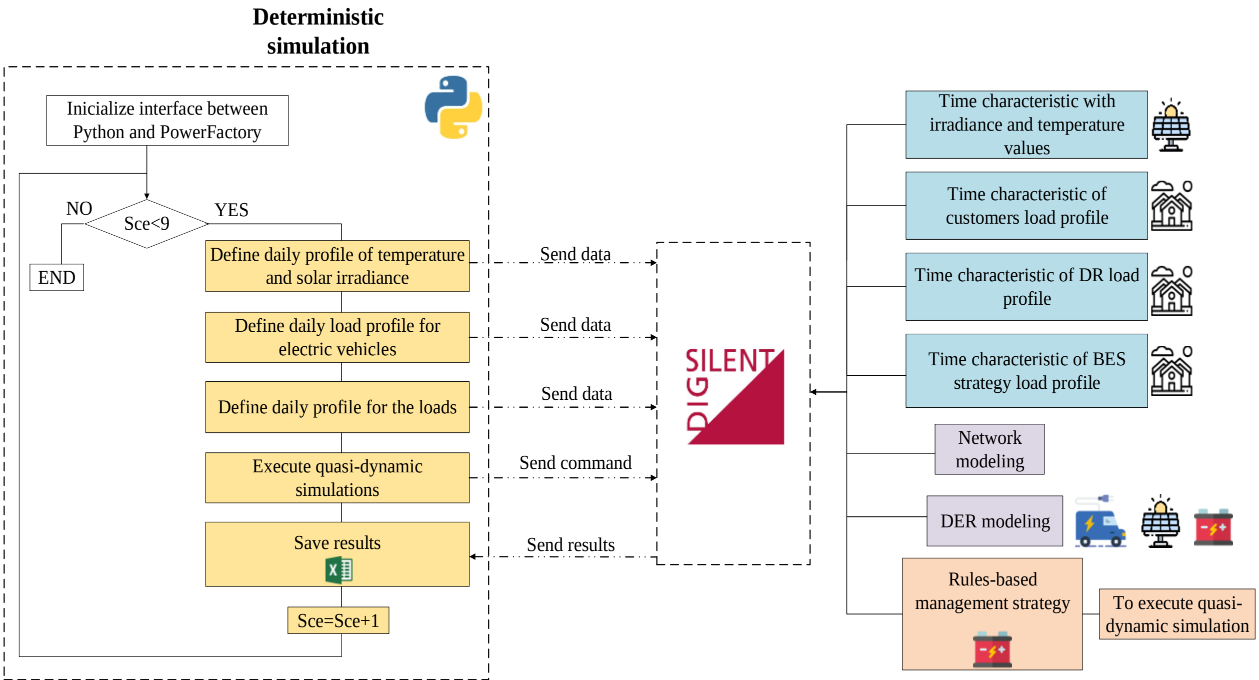


Figure 3. Methodology scheme to execute deterministic load flows in PowerFactory-Python co-simulation. Source: adapted from [29].

2.3. DER, DR scheme y BES strategy in PowerFactory

PowerFactory is a software that allows modeling electrical networks with an interface where it is possible to select each component, for example, conductors, loads, and transformers. It also makes it possible to easily enter the characteristic parameters of the elements, such as nominal voltage, nominal power, topology, distances, etc. In the case of DER, DR, and BES strategy modeling, the tool allows you to define time characteristics with demand profile information for PV systems, EVs, and loads; for batteries, the software enables you to define storage management rules.

2.3.1. DER models

A. Photovoltaic systems

The model used by the software ensures the delivery of maximum power from a PV system and is represented by the connection of the PV panels with the inverter. The input parameters required are the technical specifications of the PV panels, inverter specifications, solar irradiance and temperature time data, the geographical location of the site, and the orientation of the solar modules [33], [34]. Figure 4 presents the curves of solar irradiance and temperature as a function of time (time characteristics in the PowerFactory vocabulary) used in the PV system model. These solar irradiance and ambient temperature curves are deterministic profiles of the city of Bucaramanga.

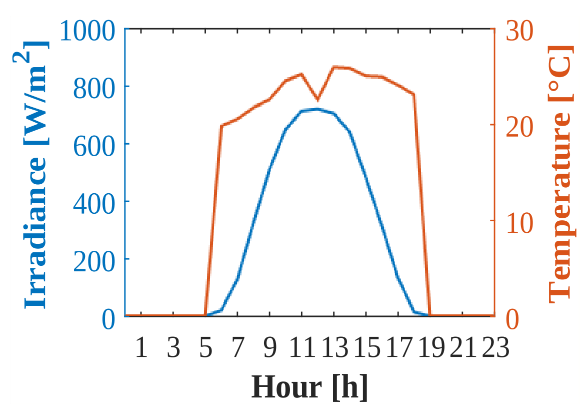


Figure 4. Time characteristics of environmental variables. Source: Authors.

B. Electric vehicles

In the case of electric vehicles, the software considers these devices as general loads, allowing the introduction of time characteristics related to the demand profile of the charging station of electric vehicles. For the creation of the time characteristics, several parameters should be taken into account, such as the charging power of the vehicle batteries, the battery capacity of the vehicle, and the energy consumed. Likewise, variables such as the distance traveled by the vehicle, the recharge time, and the arrival time at the recharging point must be defined.

Considering the mentioned variables and parameters, we calculate a profile of arrival and duration of charging of the device throughout the day. Figure 5 describes an example of the profile containing the arrival information and charging time for ten electric vehicles. This shows when vehicles arrive to begin the charge and how long they last to have a full charge. For example, two vehicles arrive at Hour 16 and require 1 hour of charging, or the vehicle that arrives at Hour 20 and takes 4 hours of charging. In this way, the time characteristic related to the demand profile of the electric vehicle is generated.

It should be noted that electric vehicle load profiles are randomly created and assigned in the electric grid without considering any application of demand response schemes.

Electric vehicle	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0
2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0
3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0
4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	0	0	0
5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0
6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0
7	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0
8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0
9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0
10	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1

Hour

Figure 5. Arrival profile and charging duration for 10 electric vehicles. Source: Authors.

C. *Batteries*

PowerFactory allows simulations with battery banks as energy storage systems. The software storage systems model requires establishing battery management rules for operating scenarios. It is necessary to perform quasi-dynamic simulations and obtain power results from the conductors or lines to which the batteries are connected. Figure 6 shows an example of a specific operating scenario's power curve in a day.

Then, with the information in the figure, we continue establishing active storage power and power parameters. Table 1 lists the battery management rules for operation scenario 1, where the four cells obtained from the curves in Figure 6 are indicated. The information concerning the initial power, the battery State of Charge (SOC), and nominal powers should be established based on the information of the batteries or take as reference the data provided by the software.

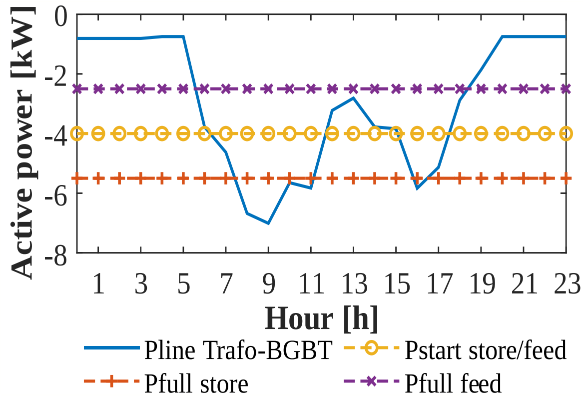


Figure 6. Active line power for scenario 1. Source: Authors.

Table 1. Battery management rules for operation scenario 1.

Parameter	E1
Eini [kWh]	15
SOCini [%]	50
SOCmin [%]	20
SOCmax [%]	90
Pstore nominal [kW]	4
Qstore nominal [kVAr]	2
Pfull store [kW]	-2,5
Pstart store [kW]	-4
Pfeed nominal [kW]	4
Qfeed nominal [kVAr]	2
Pstart feed [kW]	4
Pfull feed [kW]	5,5
Orientation	1

Source: Authors.

2.3.2. DR scheme model

The Colombian regulation presents the demand response program in resolutions CREG 063 of 2010, CREG 011 of 2015, and CREG 098 of 2018. The scheme applied by the program is called Voluntary Desconectable Demand (DDV), which refers to the energy consumption that users voluntarily reduce. The program is implemented by network operators, who are the representatives of users interested in participating voluntarily. There must be a critical condition where the stock market price is higher than the price of shortages to use the scheme. Given this condition, the network operator will ask the user to disconnect from the electrical system for a range of hours in the day.

In this case study, the critical operating condition is assumed to apply the DDV scheme for two hours a day (8 am - 10 am), and the selected customers are stratus four residential customers, with biphasic topology, and the location within the network is distributed. According to Colombia's socioeconomic classification, stratum four users are middle-sector users who do not benefit from subsidies or cost overruns on utility rates. Figure 7 describes the average demand curve of stratus four customers to whom the DDV scheme applies.

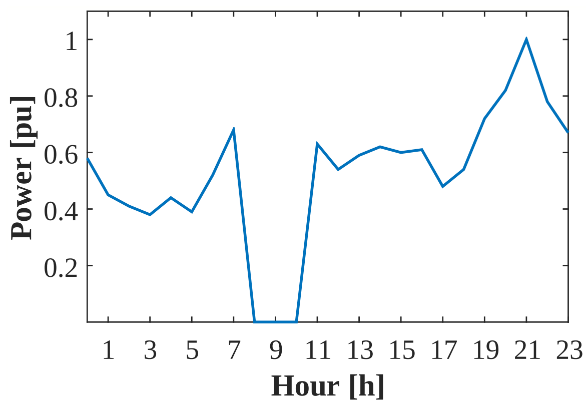


Figure 7. Average demand curve for stratus 4 customers applying DDV scheme. Source: Authors.

2.3.3. BES strategy model

Buildings are one of the main sources of energy consumption. In tropical areas, energy-saving strategies focus mainly on mitigating solar gains (e.g., thermal insulation, shading, green roofs) [22], [35], [23]–[26], exploiting environmental conditions (e.g., natural ventilation and lighting) [27], on-site power generation (mainly renewable energy) [28], improved energy efficiency of building systems [27], [36], [37] and automation of lighting and climate control systems [38], among others.

For the implementation of energy saving strategies in buildings (BES strategies), four saving strategies were previously analyzed with energy simulations in the DesignBuilder software, and in this way, it is determined which has the most significant impact on the average demand curve of a residential customer of stratus 4. The strategies taken into account are listed to continuation:

- Without air conditioning
- Shading
- Efficient air conditioning
- Efficient lighting

Figure 8 shows the results obtained from the energy simulation, in which it is evidenced that the strategy of most significant impact on the demand curve is without air conditioning (without AC, orange line - -+- -), decreasing by more than 20% the peak of demand in hours of the night (21 hours).

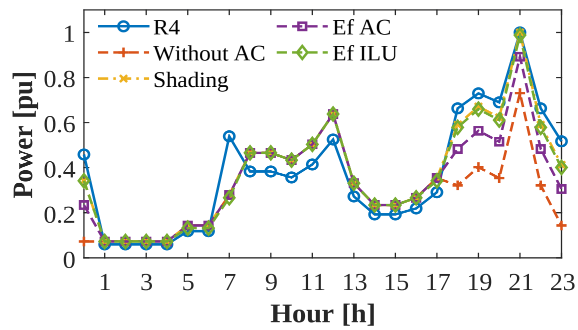


Figure 8. Average demand curves for stratus 4 customers applying BES strategies. Source: Authors.

2.4. Simulation scenarios

The characterization of the impact of the integration of the considered initiatives is determined from a comparative analysis between scenarios. Table 2 lists nine scenarios defined according to the individual and simultaneous participation of DER, DR scheme, and BES strategy for two levels of penetration: low (25%) and high (100%). Note that Scenario 0 corresponds to the operation of the distribution network without penetration of technologies.

Table 2. DER, DR and BES integration analysis scenarios.

Scenarios	DER	DR	BES
0	-	-	-
1	25%		
2		25%	
3			25%
4	25%	25%	25%
5	100%		
6		100%	
7			100%
8	100%	100%	100%

Source: Authors.

Considering the total number of residential customers in the network, it is defined as 100% penetration to half of the customers. Table 3 describes the number of integrated devices per penetration level.

Table 3. Number of DER, DR and BES devices according to penetration level.

Penetration level	DER			DR	BES
	PV	EV	B	Residential customers	
25%	10	10	10	10	10
100%	40	40	40	40	40

Source: Authors.

3. Results

This section analyzes the results obtained for variables of interest such as voltage profiles (Section 3.1), voltage imbalance (Section 3.2), transformer chargeability (Section 3.3), and power losses (Section 3.4).

3.1. Voltage profile

The voltage profile of the three main branches is analyzed for the simultaneous integration scenarios of DER, DR, and BES (scenarios 4 and 8) and critical integration hours (hours 12 and 18).

Figures 9 and 10 present each operating scenario's voltage profiles per branch. These show a gray stripe indicating the voltage limits established in the Colombian Technical Standard -NTC 1340 of 2013, which states that for low voltage electrical networks, the maximum voltage value in percentage of the nominal value is +5, and the minimum voltage value in percentage of the nominal value is -10.

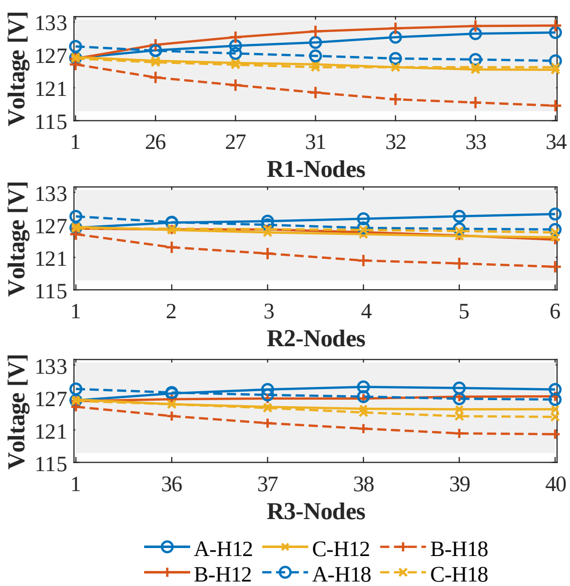


Figure 9. Voltage profile of scenario 4. Source: Authors.

Considering the main transformer's characteristics, the band's lower and upper limits are 116.84 V and 133.35 V.

Figure 9 shows the voltage profile for operating scenario 4, where a decrease in the phase B voltage is observed at a value close to 121 V on the R2 and R3 branches as the node moves away from the feeder at 18 hour, which refers to the time of connection of electric vehicles to the electrical grid. Similarly, it can be seen that the voltage in phase A increases to 127.7 V on the R2 and R3 branches at noon, at which time PV systems are generating their maximum power by high levels of solar irradiance.

On the other hand, Figure 10 presents the voltage profile in scenario 8, with a 100% penetration of DER, DR, and BES. It can be seen in the figure that phases A and B are the most affected in the three branches. On the R1 branch, the voltage in phases A and B during hour 12 increases above 130 V as the node moves away from the feeder, contrary to hour 18, where the voltage in phase B decreases to the lower boundary of the gray stripe (116.84 V). The increase in voltage on the R2 and R3 branches at hour 12 is not as noticeable as the decrease in the voltage level at hour 18 by integrating electric vehicles. It is observed that phase B is the most affected of the three phases, with voltage values close to 120 V in the last nodes of the branches.

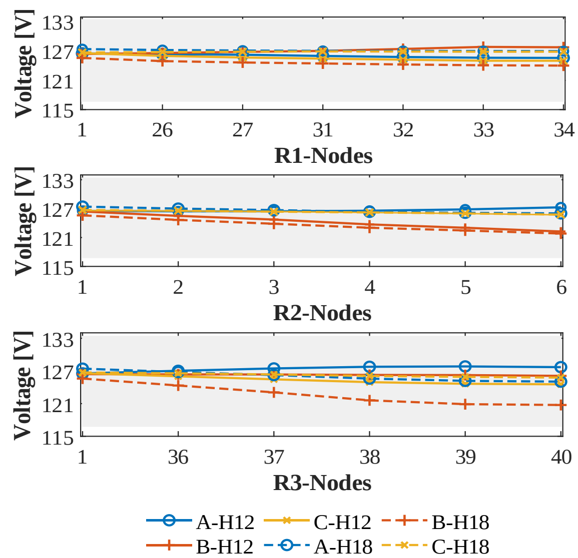
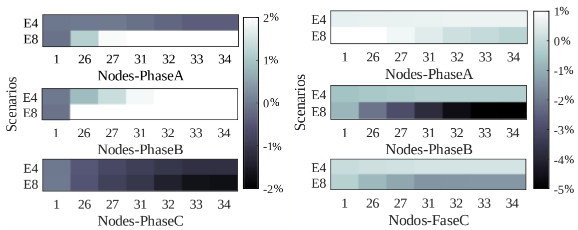


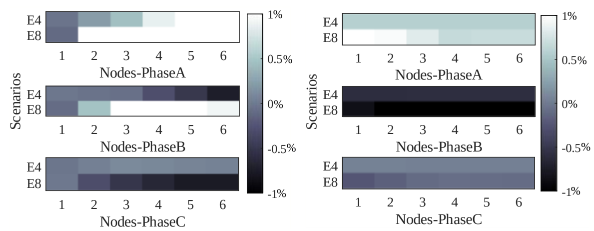
Figure 10. Voltage profile of scenario 8. Source: Authors.

Figures 11, 12, and 13 detail the impacts produced by the simultaneous integration of DER, DR, and BES in the voltage profile of the three main branches in two critical hours of operation. It is possible to appreciate a positive percentage deviation greater than 1% in noon hours in the three branches of the electricity network. Voltages in phases A and B of the branches show an increase of up to 7% compared to the base scenario without integration. This is due to the power injected by PV systems at the level of maximum solar irradiance.



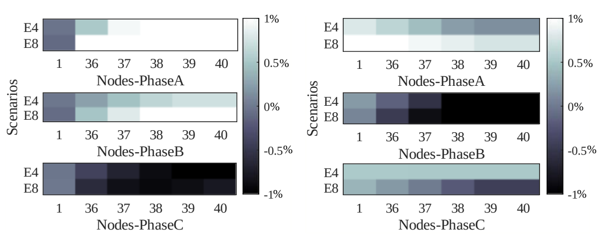
a) 12 hour b) 18 hour

Figure 11. Percentage deviations of the voltage profile in the R1 branch. Source: Authors



a) 12 hour b) 18 hour

Figure 12. Percentage deviations of the voltage profile in the R2 branch. Source: Authors



a) 12 hour b) 18 hour

Figure 13. Percentage deviations of the voltage profile in the R3 branch. Source: Authors

Otherwise, it happens in the voltage values of phase C, where a negative percentage deviation is seen, indicating a maximum decrease of 2% in the voltage along the branches with respect to the base scenario. This may correspond to the low number of PV systems connected to phase C.

However, the percentage deviation in the voltage profile on the three branches at 18 hours differs for each phase. The voltage in phase A shows a maximum positive percentage deviation of 1.5%, corresponding to an increase along the branch. Regarding the voltages in phases B and C, the percentage deviation values for scenario 8 are less than -1% compared to the base scenario, indicating that integrating electric vehicles at night hours is more likely to be done in these two phases.

Generally, it is possible to affirm that the biphasic topology of the electricity grid users contributes to the unbalanced impact produced by integrating the DER, especially electric vehicles, into the voltage profile of the power grid branches.

3.2. Voltage unbalance

The voltage unbalance in the three branches is presented in Figure 14, which highlights the critical four hours of integration of DER (hours 12 and 18), DR (hour 9), and BES strategy (hour 21).

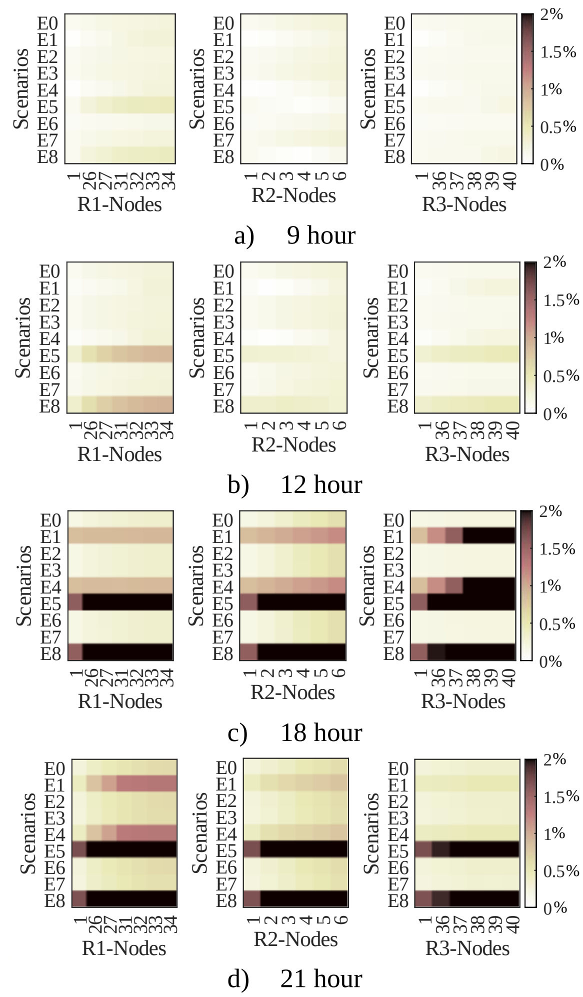


Figure 14. Voltage unbalance in critical hours of integration of DER, RD and EAEE. Source: Authors

It can be seen in Figures 14 a) and 14 b) that the unbalance rate in the three branches is at most 1% for the analyzed operating scenarios. In contrast, in scenarios E5 and E8 in Figure 14b), a difference of 0.6% and 0.2% in the unbalance index of the R1 and R3 branches can be observed with respect to the R2 branch, caused by the power injection of the PV systems in a non-uniform way in these two branches.

At the same time, figures 14 c) and 14 d) show that the integration of 25% electric vehicles (E1 and E4) impacts the rate of voltage unbalance with values between 1.0% and 1.5% in the R1 and R2 branches and greater than 2.0% in the R3 branch. Similarly, integrating 100% electric vehicles (E5 and E8) into the network implies an unbalance index value greater than 2.0% on all branches from the node following the feeder node.

3.3. Transformer loading capability

Figure 15 describes each operating scenario's transformer loading capability throughout the day. It can be seen that the loading values are maintained between 10% and 25% during the day. However, in the 25% DER integration scenarios (E1 and E4), it is possible to differentiate the time slot for integrating PV systems and electric vehicles: the first of hours 8 to 15 and the second of hours 16 to 23.

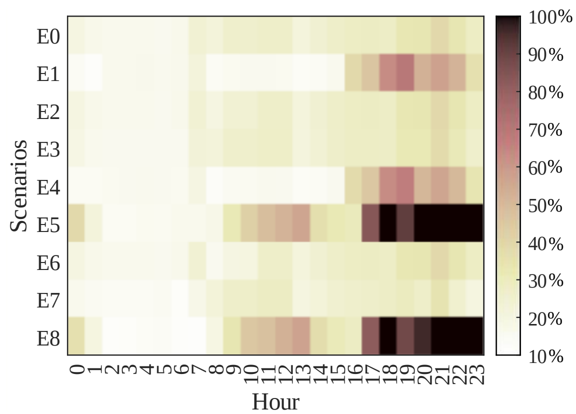


Figure 15. Transformer loading capability for each operating scenario. Source: Authors.

Regarding the deviation between the operating and base scenarios, Figure 16 shows the impact each integration strategy produces on the transformer loading capability.

In the case of DER, it is possible to relate a negative impact on the integration of electric vehicles at night with deviation values below -60%, which implies an increase in the loading capability of the transformer at values greater than 90%, which lead to shortening the life of the device.

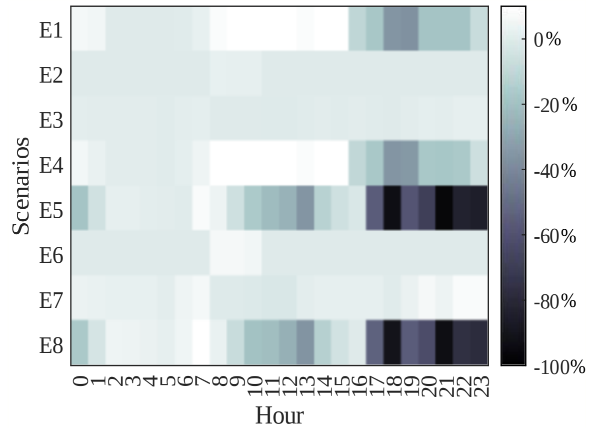


Figure 16. Deviations in the loading capability of the transformer of the electrical network. Source: Authors.

For PV systems, the positive impact produced by these is reflected in a reduction of the transformer loading capability by up to 13%. However, PV systems negatively impact loading capability in 100% penetration scenarios (E5 and E8) with deviations above -35%.

In terms of the individual application of the DR scheme, it is possible to detail the time slot of 8-10 am in scenarios E2 and E6, where the deviation values are greater than 2.0%, producing a positive impact, and, therefore, a decrease in the loading capability of the transformer.

Likewise, integrating the BES strategy in residential customers produces the same effect as the application of the DR scheme, a positive impact with deviations greater than 1.0% in E3 and E7 scenarios.

It should be noted that, although in the simultaneous integration of the three strategies, the penetration of electric vehicles at night predominates with a negative impact compared to the other strategies, in scenarios E4 and E8, between hours 20 to 22 can be seen an improvement in the loading capability of the transformer up to 7% compared to those scenarios where there is only integration of DER (E1 and E5).

3.4. Power losses

Figure 17 presents the overall power losses of the grid for the operation scenarios analyzed over a day. This shows the exact behavior of the transformer loading capability, in which the slots of the integration of PV systems are between hours 8 and 16, and electric vehicles are between hours 17 and 23.
Due to the power injection of PV systems, losses increase up to 1500 W; the same happens with the connection of

electric vehicles, which produces losses exceeding 3000 W in hours of critical integration.

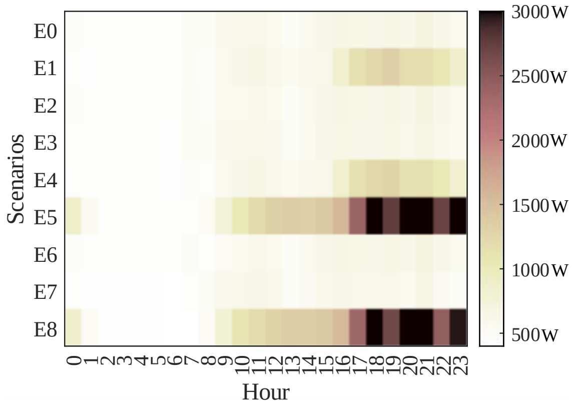


Figure 17. Power losses for each operating scenario. Source: Authors.

Figure 18 details the percentage deviations in terms of active power losses of the power grid. This shows the negative impact of DER integration, especially on electric vehicles. The negative impact on 25% penetration levels is between -50% and -100%, while the percentage deviation for 100% penetration scenarios is less than -250%. For PV systems, the severity of the impact varies depending on the penetration level: in 25%, the impact is negative with percentage deviation values greater than -10%, and in 100% penetration, the impact is negative with values less than -30%.

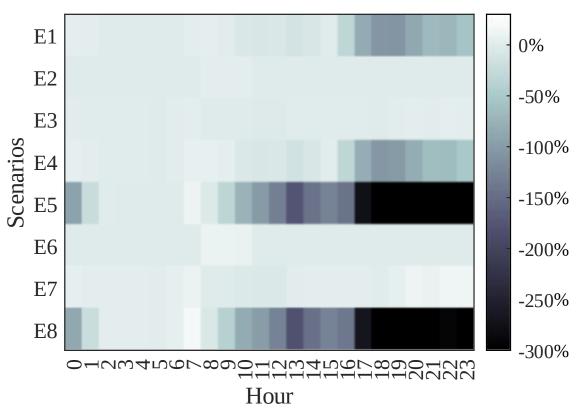


Figure 18. Percentage deviations in the power losses of the electrical network. Source: Authors

4. Conclusions

This study aims to analyze the impacts on electrical parameters of individual and simultaneous integration of distributed energy resources (DER), a demand response scheme (DR), and energy saving strategies in buildings (BES strategies).

Regarding the impact on the voltage profile, it is possible to observe that this is positively affected by the increase of generation on-site by PV systems and is negatively affected by the rise in demand for the connection of electric vehicles at night.

Similarly, the voltage unbalance has positive and negative effects when integrating PV systems and electric vehicles. However, assuming that the DER is connected at the end-user points of the network, it is possible to state that the topology of the users influences the potential increase or decrease of the imbalance index once the DER is integrated.

However, it is possible to assess the impact of the simultaneous integration of the three initiatives implemented in analyzing the transformer loading capability and power losses. The negative impact on the parameters is more severe with a high level of DER penetration; however, in the hours of simultaneous integration of DER, RD, and BES strategy, the negative impact has an improvement of up to 40%. It is, therefore, necessary to consider the appropriate coordination of initiatives to take full advantage of the positive effects of simultaneous integration on the electrical parameters of the network.

It is also advisable to set limits for integrating DER, especially electric vehicles, into low-voltage distribution networks to avoid overloading the transformer and conductors.

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