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Demand response and dispatchable generation as ancillary services to support the low voltage distribution network operation

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Abstract

The current power systems, namely the low voltage distribution networks, have been suffering considerable changes in recent years. What appeared to be innovation trends nowadays due to technological advances and manufacturing cost reduction has become the new reality in the coming years. Thus, the growing trend of power generation by renewable sources has posed new challenges and new opportunities. Furthermore, the wide installation of "smart meters" and the interest in placing the citizens as core players into the future energy markets and systems operation improves the role of the distribution system operator. In this way, developing new and innovative methodologies to explore the potential mechanisms for providing ancillary services in distribution networks becomes of great importance, namely in low voltage levels. This research paper proposes an innovative methodology to enhance the demand response participation of small consumers and dispatchable distributed renewable energy sources flexibility as ancillary services to mitigate the voltage and congestion issues in low voltage distribution networks. A realistic low voltage distribution network with 236 buses is used to illustrate the application of the proposed model. The results demonstrate a considerable voltage profile and congestion improvements.

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Keywords: Ancillary services; Congestion management; Demand response; Dispatchable generation flexibility; Distribution network; Voltage profile

1. Introduction

According to the conventional electric power systems architecture, the electricity is produced in large power plants and transmitted in high voltage (HV) through the transmission system. The main objective of the distribution systems was to connect the medium voltage (MV) and low voltage (LV) loads, usually locally dispersed. In this way, the voltage and frequency parameters were normally controlled by large generation units by providing ancillary services (AS) directly in the transmission system [1].

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Nowadays, the conventional control and operation framework designed for passive distribution networks is being challenged through the large-scale integration of distributed generators based on renewable energy sources (RES). In this context, the loads can be supplied not only by traditional generation units at the upstream power systems but also by the DER [2–4]. Additionally, distributed energy resources (DER) based on RES are highly volatile and naturally intermittent, depending directly on environmental conditions. In this way, not only new challenges appear, but also opportunities. The wide installation of "smart meters" together with interest in placing the citizens as core players into the future energy markets and systems operation [5] through its power generation or ancillary services (AS) provision is playing an important role in the new era of power systems. On the other hand, the citizens' participation is an important key for the proliferation of smart grids [6]. Also, using the citizens' flexibility in the demand side management can facilitate and increase the use of local RES and enable their participation in demand response (DR) programs [7,8]. Thus, the distribution system operator (DSO) role is strengthened, contributing to the development of a new market environment that will involve interactions between the transmission system operator (TSO) and the DSO. According to the European Commission Regulation 2016/631 [9], the inclusion of distributed renewable energy sources (DRES) in distribution systems (medium and low voltage) adopts the same specifications as those used in transmission systems. The specifications are related to the active power response to over-frequencies and under-frequencies events, support for voltage levels through reactive energy, congestion issues, among others. In this way, developing new and innovative tools to explore the potential mechanisms for providing AS in smart distribution networks becomes of great importance, namely in low voltage levels.

Towards this direction, several works in the specialized literature have been investigating the AS in distribution level [10–18]. The relevance of the DSO's role in AS procurement is also addressed in [10], emphasizing the use of information and communication technology to implement transmission and distribution grid interaction. [11] investigates the transition from hierarchical to open service-based smart systems based on agent technologies, focusing on power quality. Ref. [12] describes a multi-agent system electricity market to create the role of an aggregator. The Aggregator will represent small and medium distributed resources in the market to provide a competitive bidding strategy for energy and AS products. In [13], the potential for demand-side management, specifically interruptible load response on AS, is discussed. Several AS either within the microgrid [14–16] or the allocation of AS among microgrids [17], or the exchange of the AS between the microgrid and the main grid [18], have also been studied in the literature. These AS are for load following and hourly active power ramping [14], fast reserve service provided by dispatchable DRES [15], frequency regulation [14,16], reactive power/voltage control, active loss balancing, and demand interruption [17], and fast and transient exchange of reactive power [18].

The above-cited literature has not addressed the DR participation of the consumers and the dispatchable DRES flexibility as ancillary services in distribution low voltage networks (DLVN) with high penetration of RES. Also, it does not enhance small consumers' participation in the DLVN operation to mitigate voltage and congestion issues. Comparing with the previous works, this research paper will fill these gaps by proposing a methodology to enhance the DR participation of small consumers and dispatchable DRES flexibility to mitigate the voltage and congestion problems in DLVN. For this, a heuristic working together with a tool for electric power system simulation and analysis — MATPOWER [19] will be used. To demonstrate the application of the proposed model, a realistic 400 V low voltage distribution network with 236 buses and a total of 96 loads (residences) was used.

For this paper, five main sections are considered. After this first introductory section, Section 2 describes the proposed methodology in what concerns the developed heuristic and its integration with electric power system simulation and analysis tool. The case study to show the application of the proposed methodology is shown in Section 3. The results and their discussion are presented in Section 4. Finally, Section 5 presents the most relevant conclusions.

2. Proposed methodology

This section presents the adopted methodology used in this work. Two types of ancillary services have been defined: demand response service (Section 2.1) and generation service (Section 2.2). In addition, some assumptions regarding the characteristics of the network and the AS provided were also considered, namely: (i) The considered distribution network is radial and has two independent zones without interconnections. The same transformer supplies both zones through different feeders; (ii) There is a certain density of distributed generation in the network, referring to a set of photovoltaic generation units (non-dispatchable) and two dispatchable generators, one in each zone; (iii) The request for services (DR or generation) can be made independently, period by period, and service providers are previously defined and regulated by a common agreement between the interested parties.

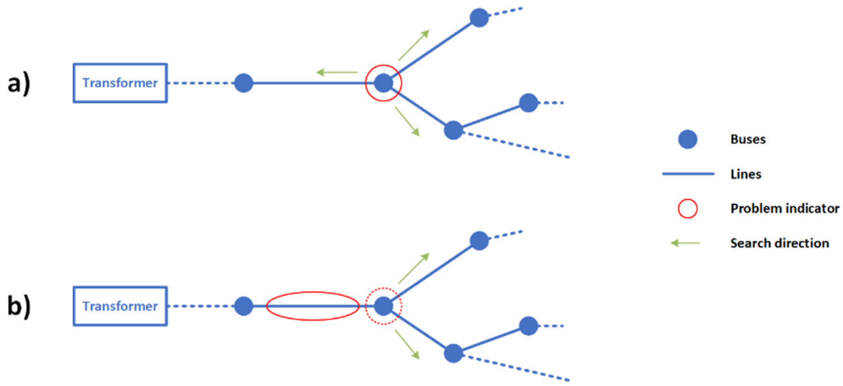

Fig. 1. Search direction – (a) Voltage issues; (b) Congestion issues.

2.1. Demand response service

The DR service consists of mapping the buses and lines that present issues during the network operation, i.e., voltage and congestion problems (by a Power Flow analysis using a tool for electric power system simulation and analysis, e.g., MATPOWER), and then making a service provider search in the surrounding area. After that, through a developed heuristic, the smallest number of necessary providers will be activated to correct the verified issues in the network.

The heuristic considers that the shorter is the distance between the DR service provider and the buses with voltage problems (normally, voltage magnitude values lower than 0.95 p.u. and greater than 1.05 p.u.), the smaller is the amount of energy reduction (kWh) needed. This means that the verified voltage problem must be solved as locally as possible. Furthermore, regarding the congestion issues (violation of line/cable thermal capacity), the demand should be reduced only downstream of the verified congestion line/cable (since we are in the presence of a radial distribution network).

Regarding the voltage issues, when this kind of issue is verified in a bus, a scan is made in all directions searching for DR service providers, as is represented in Fig. 1(a). This search takes place through levels, which gradually expand. The directly connected providers to the bus with voltage problems are activated on the first level. In the next levels, the providers that are connected to the bus with voltage problems are activated through intermediate buses up to N buses apart. The expansion of this search area ends only when all the voltage issues have been solved or any of the stopping criteria have been reached. A line/cable congestion problem is understood as a voltage problem on the bus connected downstream of this line/cable, as shown in Fig. 1(b).

Fig. 2 presents the flowchart of the developed heuristic for DR service use. After loading the input data and the initialization of the variables, the first action is to carry out a complete analysis of the network (Power Flow analysis), identifying the buses with voltage issues and lines/cables with congestion issues. Then, the problems are corrected by two iterative cycles in sequence, i.e., first the voltage problems, followed by the congestion problems. Each cycle consists of the following processes: checking for the problem's existence; updating the search area; activating all service providers available in the search area; running the network Power Flow analysis; checking if the problem persists.

2.2. Dispatchable generation service

The dispatchable generation service also aims to solve network voltage and congestion problems. It consists of activating the dispatchable generating units and working based on adjusting their active and reactive power delivered to the network. The heuristic considers only one generating unit per zone of the network, where each zone corresponds to a region supplied by a single feeder and isolated from the other zones. Additionally, the buses' active power and voltage variables can be modified where this generator is located. So, first, the active power is fixed at zero, and the bus voltage is adjusted so that all voltage problems on the buses that share the same network zone with the generator are solved. Next, the obtained voltage value is fixed, and the generator active power is

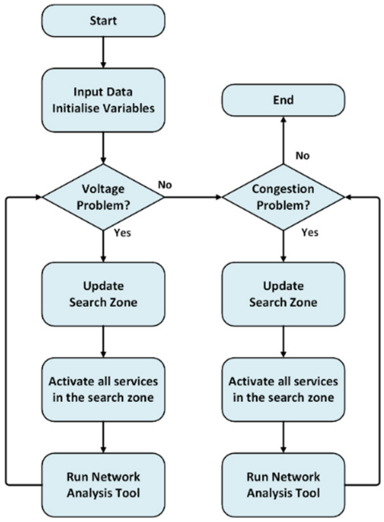

Fig. 2. Heuristic flowchart for DR service.

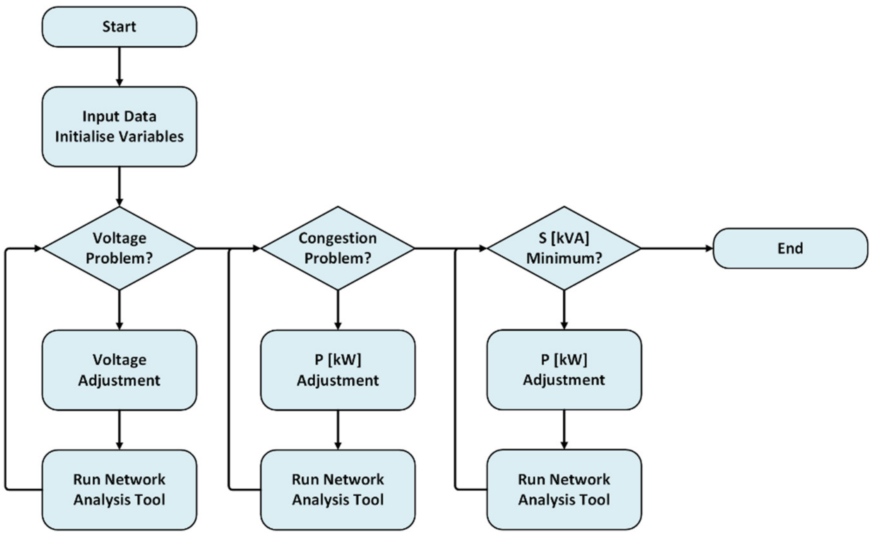

Fig. 3. Heuristic flowchart for dispatchable generation service.

adjusted until all congestion issues are solved. In this way, the generator reaches its operating point with the lowest apparent power value. The flowchart of the developed heuristic for generation service is presented in Fig. 3.

AS the DR service, after loading the input data and initializing the variables, the first action taken is to conduct a complete network analysis searching for bus and lines/cables with voltage and congestion issues, respectively. Then, three iterative cycles run in sequence: the first is to solve the bus voltage problems; the second is to solve congestion problems; the third is to adjust the generator to its operating point with the lowest apparent power value. Each cycle consists of the following processes: check stopping criteria; adjustment of the control variable (voltage or active power); run the Power Flow analysis; and check the stopping criterion again.

3. Case study

A realistic low voltage distribution network presented in Fig. 4 is used to demonstrate the proposed methodology. The network has 236 buses, 235 underground cables, and 96 load points (residence consumers), resulting in 679.65

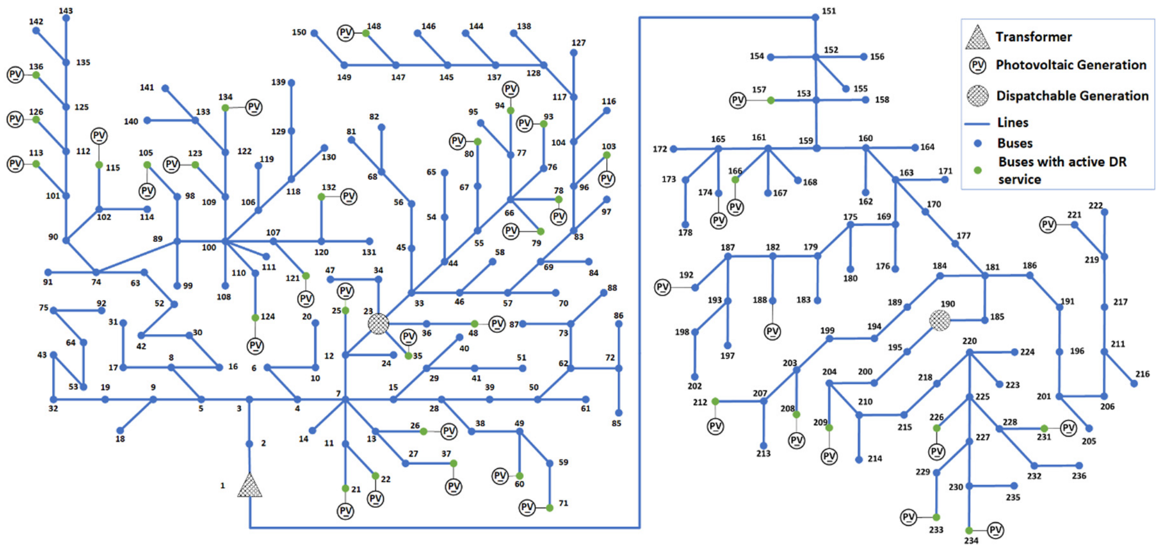

Fig. 4. Single line low voltage distribution network.

kVA of total installed power and explored radially. The network has 39 residence consumers with rooftop PV panels (First Solar FS-4120-3 model)[1] for self-use, considering that the modules are connected to an inverter with 90% efficiency through cables with 3% of losses. The PV module output power depends on the solar irradiance, temperature, and its characteristics and can be calculated by (1) to (3):

$$P_{gen} = n_{inv+c} \times n_{\text{mod}} \times P_{PV} \tag{1}$$

$$P_{PV} = P^0_{PV}\frac{H_{t,\beta}}{H_{ref}}\left[1+\gamma_{P_{mp}}\left(T_C - T_{C,ref}\right)\right] \times n_{SPMP} \tag{2}$$

$$T_C = T_{amb} + H_{t,\beta} \times \left(\frac{T_{NOCT} - T_{NOCT,man}}{H_{NOCT,man}}\right) \times 0.9 \tag{3}$$

where:

P_{gen} is the PV power output [W]; n_{inv+c} is the inverter efficiency plus the cable losses [%]; n_{mod} is the number of PV modules; P_{PV} is the maximum module power as a function of solar irradiance and temperature module [W]; P^0_{PV} is the rated PV power [W]; $H_{t,\beta}$ is the solar irradiance on the PV panel [W/m^2]; ref are the standard conditions (1000 W/m^2 and 25 ºC); $\gamma_{P_{mp}}$ is the temperature coefficient of the maximum power point [%/ºC]; T_C is the equivalent operating temperature [ºC]; n_{SPMP} are the losses in the maximum power point tracking process; T_{amb} is the ambient temperature [ºC]; T_{NOCT} is the operation rated temperature [ºC]; $T_{NOCT,man}$ is the rated temperature under the manufacturing conditions [ºC]; $H_{NOCT,man}$ is the rated irradiance under manufacturing conditions [W/m^2].

A 10 kV/420V, 1000 kVA transformer carries out the network supply. Additionally, two biomass generators (located in buses 23 and 190) with 300 kW (Ettes Power Machinery EZ-300S model)[2] of rated power each are considered as dispatchable DRES. In what concerns the solar irradiance and temperature (2 meters high), historical data was obtained from Basel city in Switzerland (47.546944, 7.568918)[3]. The data collection is referred to a period between 21/03/2020 and 18/06/2020 (90 days - spring). The collected data sample is hourly, so for this case study, linear interpolation was used to convert the sample for every 15 min (8640 of total 15 min periods). Moreover, the loads can be controlled using direct load control and demand response programs. The controlled value corresponds to 25% of the consumer consumption. For this case study, only the consumers with PV panels are available for DR services. Three different PV panel rated powers were considered, namely, 0.72 kW, 0.96 kW,

1 www.firstsolar.com/en-Emea/
2 www.ettespower.com/300kW-Biomass-Engine.html
3 www.meteoblue.com

Table 1. General Information — comparison between cases.

Case	Voltage problem		Congestion problem		Lower voltage (V)	Higher occupation rate (%)	Execution time (s)[b]	
	Number of periods	Occurrence per period[a]	Number of periods	Occurrence per period[a]			With problem (s)	Without problem (s)
Reference	32	6	32	1	0.944	107.990	–	–
1	0	–	0	–	0.950	99.960	4.100	1.160
2	0	–	0	–	0.950	99.960	9.130	1.230

[a]Average value
[b]For one single period

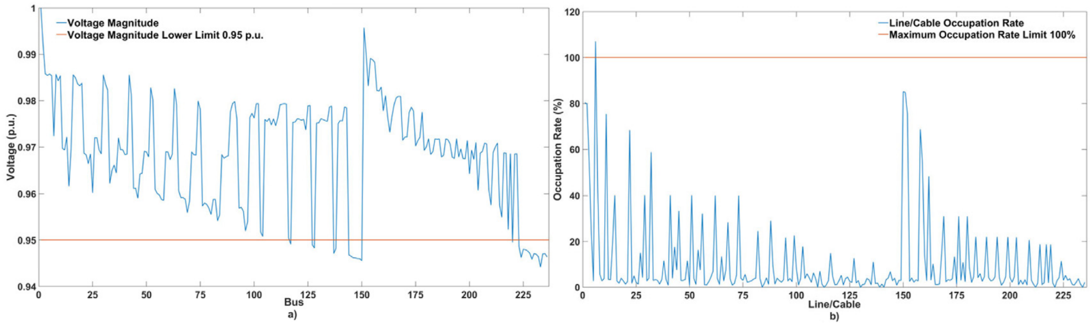

Fig. 5. Reference case - (a) Bus voltage magnitude; (b) Line/cable occupation rate.

and 1.2 kW corresponding to 6, 8, and 10 modules, respectively. Each PV unit had its profile randomly assigned. Two studies were conducted to demonstrate that the small consumers' participation in DR events and the dispatchable DRES flexibility can mitigate or remove the voltage and congestion problems in DLVN: 1) Demand response as ancillary service to mitigate or remove the voltage and congestion issues (Case 1); 2) dispatchable DRES flexibility as ancillary service to mitigate or remove the voltage and congestion issues (Case 2). Both cases are compared with a reference case where DR and dispatchable DRES flexibility are not considered (the actual network).

4. Results and discussion

The proposed methodology presented in Section 2 was applied to the case study from the previous section. This research work was developed on a machine with a single Intel Xeon E5-2620 v2 processor and 16 GB of RAM running Windows 10 Pro and MATLAB R2016a with MATPOWER 7.1 [19]. In both cases (Case 1, Case 2, and reference case), the simulation was carried out for the 8640 periods. Table 1 presents a result comparison between both considered cases. The observed voltage problems generally occurred in both network areas, in a set of buses away from the main transformer. The congestion problems occur mainly in the cable which connects bus 4 to bus 7.

Due to its atypical behavior (high demand), the period 4977 was used to carry out a more detailed analysis. Fig. 5(a) and Fig. 5(b) present the voltage magnitude for each bus and the occupation rate for each line/cable, respectively. As can be seen, a set of buses present voltage issues (26 buses), and 1 line/cable (the line between bus 4 and bus 7) presents congestion problems.

The obtained bus voltage (green line) and its improvement (purple line) through the implementation of the DR service are shown in Fig. 6(a). It is also possible to observe the radial characteristic of the network since the voltage drops as the buses move away from the transformer. Applying the DR service, a considerable improvement in the voltage magnitude up to around 0.7% is obtained. Fig. 6(b) depicts the occupation rate (green line) and its change (purple line) by using the DR service. It is noteworthy that almost all consumers able to provide the DR service are activated, except for those located on buses 174, 188, 192, and 221 (35 of 39 are activated). This denotes that the service is well dimensioned but working at the limit. This means that facing a worse situation, the possibility to solve the occurred issues will be compromised. However, some possible solutions can arise, for

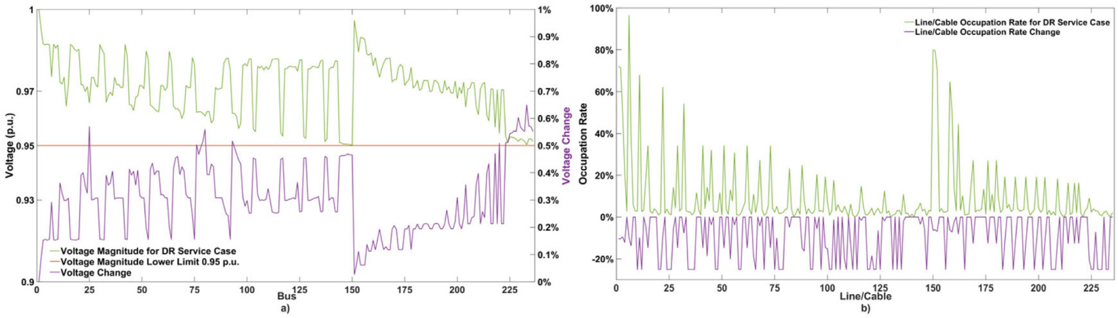

Fig. 6. Demand response service case – (a) Bus voltage magnitude; (b) Line/cable occupation rate.

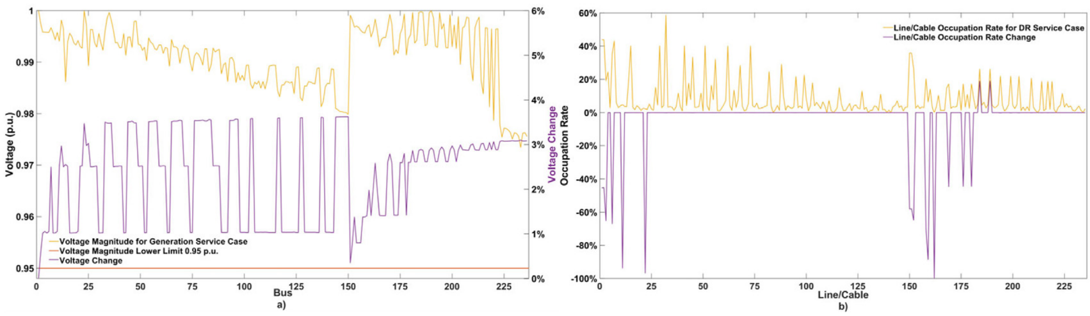

Fig. 7. Dispatchable generation service case - (a) Bus voltage magnitude; (b) Line/cable occupation rate.

Table 2. Generator operation information.

Generator ID	Bus	Voltage output (p.u.)	P (kW)	Q (kVar)	S (kVA)	Power factor
1	23	1.00	132.00	100.25	165.75	0.80
2	190	1.00	90.00	47.82	101.92	0.88

instance, searching for new providers, i.e., increasing the penetration of the service on the network; and increasing the amount of demand reduction by common agreement between the parties. The occupation change rate is relatively homogeneous, alternating between two levels (0% and −25%). This makes sense since almost all available loads reduce their consumption and are relatively evenly distributed across the network.

Fig. 7(a) presents the obtained bus voltage (yellow line) and its improvement (purple line) compared to the reference case through the implementation of the generation service. The voltage magnitude follows the expected trend, i.e., on the buses where the dispatchable generating units are connected, the voltage is adjusted to 1 p.u. On the downstream buses (away from the transformer), the voltage gradually drops. Fig. 7(b) presents the line/cable occupation rate and its change using generation service. It can be seen through this figure that the lines/cables 22 (from bus 12 to bus 23) and 162 (from bus 160 to bus 163) the occupation rates have a strong decrease, i.e., 94.14% and 98.87%, respectively. These two lines/cables, as can be seen in Fig. 4, are feeding considerable large areas, meaning that the downstream loads are being mostly supplied by the dispatchable generators (generation service). Additionally, in critical situations, such as total or partial disconnection of these areas from the main grid, the areas could be temporarily supplied by these generators. Indeed, all technical and operational requirements should be approved in advance for this type of situation.

In addition, Table 2 shows some operational parameters of the generation units that are providing the generation service, such as the active power, reactive power, apparent power, voltage magnitude, and the power factor. The active power was adjusted to eliminate the network congestion issues and keep the generator running at the minimum value of S [kVA]. Even so, the power factor obtained is still within the expected range.

5. Conclusions

This research paper presented a methodology to mitigate the voltage and congestion problems in distribution low voltage networks through the flexibility of dispatchable distributed renewable energy sources and demand response services participation of small consumers as ancillary services. For this, a heuristic working together with MATPOWER, an electric power system simulation, and analysis, is used. A realistic low voltage distribution network was used to test the proposed model and compare it with a reference case (no demand response needer dispatchable distributed renewable energy sources flexibility ancillary services available) to demonstrate the advantage of the former. Using the demand response service, it was verified that it achieved a voltage magnitude improvement up to around 0.7% and 25% maximum improvement in lines/cables occupation rate. For the dispatchable generation service, it is observed an expected trend on voltage magnitude behavior, i.e., the voltage gradually drops from 1 p.u. (the buses where the dispatchable generating units are connected) but within the lower limits. While for the lines/cables occupation rate it is obtained strong reductions, namely in lines/cables 22 (bus 12 to bus 23) and 162 (bus 160 to bus 163), with 94.14% and 98.87%, respectively. The results suggest that the proposed methodology can be used as an efficient approach to deal with distribution low voltage network operational issues, namely in what concerns the voltage and congestion problems.

CRediT authorship contribution statement

Bruno Canizes: Conceptualization, Investigation, Formal analysis, Validation, Writing – original draft, Data curation. **Vitor Silveira:** Conceptualization, Investigation, Formal analysis, Validation, Writing – original draft , Data curation. **Zita Vale:** Conceptualization, Supervision, Writing – review & editing, Project administration, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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