Demand Response and Electric Vehicles as Services to Provide Support to the Distribution Network Operation

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***Abstract*— Nowadays, the current power systems, particularly the low voltage distribution networks, have undergone significant modifications. The growing trend of power generation by renewable sources and electric vehicles has posed new challenges and new opportunities. Furthermore, the widespread use of "smart meters" and the desire to include citizens as key players in future energy markets and system operations enhances the distribution system operator's role. Therefore, creating new and innovative techniques to investigate the possibility of mechanisms for delivering services in distribution networks, particularly at low voltage levels, becomes crucial. This paper proposes an innovative methodology based on a logic heuristic method for enhancing small customer demand response participation and public and home charging stations for electric vehicles as provided services in low voltage distribution networks to relieve voltage and congestion issues. A realistic low voltage distribution network with 236 buses is employed to demonstrate the proposed model's applicability. The results show significant improvements in the voltage profile and congestion.**

Index Terms--Demand response; congestion management; electric vehicles; distribution network voltage profile, support services

I. INTRODUCTION

The traditional control and operation framework built for passive distribution networks are being challenged by the large-scale integration of distributed generators based on renewable energy sources (RES). Loads can be supplied by traditional generation units at upstream power networks and by distributed energy resources (DER) [1-3]. Furthermore, DERs based on RES are wildly unpredictable and inherently intermittent, as they are directly affected by environmental conditions.

The urban population is responsible for most greenhouse gas emissions, and the United Nations predicts that by 2050, the urban population will represent 70% of the world's total population [4]. Transportation is one of the primary causes of CO2 emissions [5]. It is well recognized that switching from internal combustion engines to electric vehicles offers several environmental and economic benefits. However, as the number of electric vehicles (EV) grows, new infrastructure for EV charging must be developed continuously, resulting in increased energy demand [6]. These charging infrastructures, especially the high charging loads of fast EV charging stations, will cause a burden on the distribution power grid [7]. Additionally, several distribution network operational parameters may deteriorate, such as voltage profile [8-10] and line congestion [11-12].

The widespread deployment of "smart meters," along with a desire to include citizens as fundamental players in future energy markets and system operations [13] through power generation or the provision of demand flexibility, is playing a key role in the new era of power systems. Citizens' participation, on the other hand, is critical for the development of smart grids [14]. Furthermore, citizens' flexibility in demand-side management can also help facilitate and promote local RES usage and their involvement in demand response (DR) initiatives [15, 16]. As a result, the role of the distribution system operator (DSO) is reinforced, supporting the creation of a new market environment, including interactions between the transmission system operator (TSO) and the DSO. Therefore, developing new and innovative techniques to investigate the potential of mechanisms for delivering services in smart distribution networks, particularly at the low voltage level, becomes crucial.

To relieve voltage and congestion issues in the distribution low voltage network (DLVN), this research study proposes a methodology to increase the DR participation of small customers and public and home charging stations for EVs. For this, a logic heuristic model working in conjunction with a tool for electric power system simulation and analysis – MATPOWER [17] was used. A realistic 400V low voltage distribution network with 236 buses, 96 loads (residences), and 4 EV public charging stations were used to show the applicability of the proposed model.

This paper is organized as follows. After this introductory section, Section II introduces the proposed methodology concerning the developed heuristic and its integration with electric power system simulation and analysis tool. Section III depicts the case study used to show the application of the proposed methodology. Section IV presents the results and their discussion. Finally, Section V provides the concluding remarks.

This research has received funding from FEDER funds through the Operational Programme for Competitiveness and Internationalization (COMPETE 2020), National Funds through the FCT Portuguese Foundation for Science and Technology under project UIDB/000760/2020, and from the EU Horizon 2020 research and innovation program under project TradeRES (grant agreement No 864276).

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II. Proposed Methodology

This section presents the adopted methodology used in this work. Demand response is used as a service to support the distribution system operation, namely concerning the voltage and congestion issues. Thus, some assumptions were considered regarding the characteristics of the network, and the AS provided were also considered, namely: i) The distribution network under consideration is radial and has two independent zones with no connections. The same transformer supplies both zones, although through distinct feeders; ii) There is a certain density of distributed generation in the network, which refers to a group of photovoltaic (PV) generation units (non-dispatchable); iii) There is a particular density of loads in the network, referring to EV residential and public charging stations; iv) Service requests can be made on an independently period-by-period basis, and service providers are established and regulated in advance by a shared agreement between the interested parties.

A. Demand Response Service

The DR service consists of mapping the buses and lines that present voltage and congestion problems during network operation (through a Power Flow analysis using a tool for electric power system simulation and analysis, such as MATPOWER [17]), and then doing a service provider search in the local area. The logic heuristic model will activate the minimum number of necessary providers to correct the verified network issues.

In this paper, two types of DR service have been considered: Demand Response with Electric Vehicles and Demand Response without Electric Vehicles. The first one, also called DREV, refers to the adjustment in energy consumption of public and residential charging stations for EV. The second one, called just DR, refers to the adjustment in energy consumption of usual loads of residential consumers. In both types, the heuristic assumes that the shorter is the distance between the DR service provider and the voltage-issue buses (typically, voltage magnitude values lower than 0.95 p.u. and greater than 1.05 p.u.), the less energy reduction (kWh) is required. As a result, the confirmed voltage problem should be addressed locally whenever possible. When it comes to congestion issues (violation of line/cable thermal capacity), the demand should be lowered exclusively downstream of the verified congestion line/cable (since we are in the presence of a radial distribution network).

When a voltage issue occurs in a bus, a search is performed in all directions to find DR service providers, as shown in Fig. 1a). This search progresses via levels that steadily increase in size. On the first level, the directly linked providers to the bus with voltage problems are activated. The providers connected to the bus with voltage issues are activated in the following stages by using intermediary buses up to *N* buses apart. This search area's expansion ends only when all the voltage issues have been resolved or any stopping conditions reached. As indicated in Fig. 1b), a line/cable congestion problem is interpreted as a voltage problem on the bus connected downstream of the line/cable.

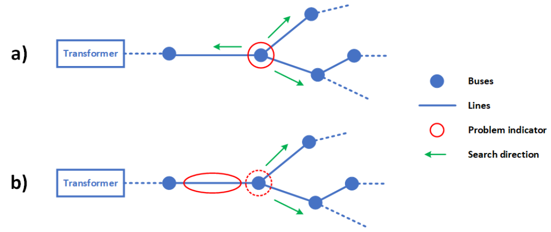

Figure 1. Search direction – (a) Voltage issues; (b) Congestion issues.

The flowchart of the developed logic heuristic model for DR service use is shown in Fig. 2. After loading the input data and initializing the variables, the first step is to conduct a complete network analysis (Power Flow analysis), identifying buses with voltage problems and lines/cables with congestion issues. Then, issues are corrected in order by two iterative cycles, first the voltage problems, then the congestion problems. The steps in each cycle are: Checking for the existence of the problem; updating the search area; activating all service providers available in the search area; doing the network Power Flow analysis; checking if the problem remains.

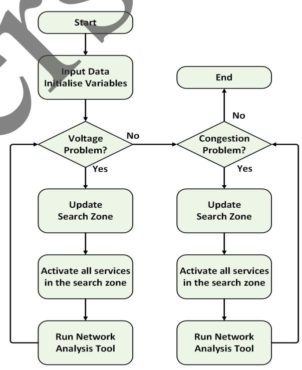

Figure 2. Heuristic flowchart for DR service.

III. Case Study

The proposed methodology is verified using a realistic low voltage distribution network shown in Fig. 3. The network has 236 buses, 235 underground cables, and 96 load points (residential consumers) with a total installed power of 679.65 kVA and is explored radially. The network contains 39 residential consumers with self-use rooftop PV panels (First Solar FS-4120-3 model)[1], corresponding to around 41% of penetration. The modules are connected to a 90% efficiency inverter through cables with 3% of losses. The PV module output power depends on the solar irradiance, temperature, and the module's parameters and can be calculated by (1) to (3):

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

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

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

[1] http://www.firstsolar.com/en-Emea/

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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_{PV}^{0} 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).

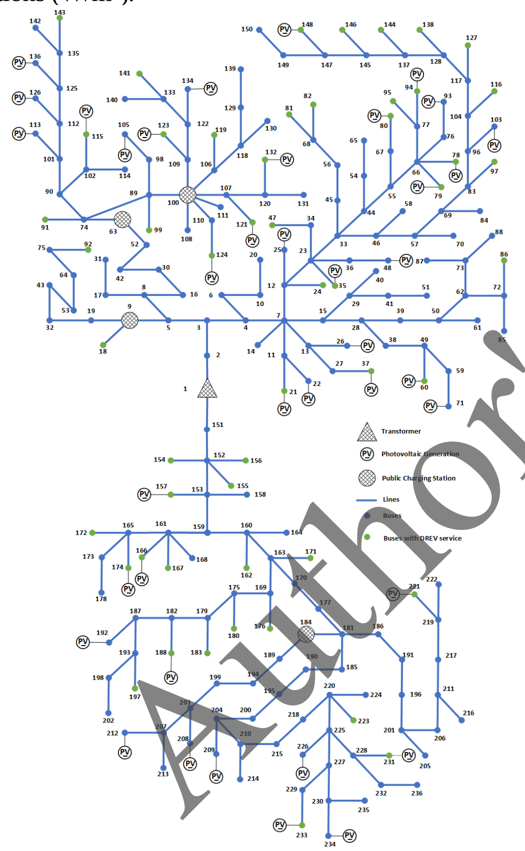

Figure 3. Single line low voltage distribution network.

The network has 51 residence consumers with EV charge stations (corresponding to around 53% of penetration), considering two different rated powers, namely, 3.7 kW and 7.4 kW. The set of public charge stations include two 7.4 kW slow charge stations in buses 63 and 184, respectively, with four and ten places available (29.6 kW and 74 kW of total installed power); and two 22 kW fast-charge stations in buses 9 and 100, both with four places available (88 kW of total installed power each).

The network supply is handled by a 10 kV/420V, 1000 kVA transformer. In terms of solar irradiance and temperature (2 meters high), historical data used came from Basel, Switzerland (47.546944, 7.568918)[2]. The data collection is referred to a period between 21/03/2020 and 18/06/2020 (90 days - spring). Because the acquired data sample is hourly, linear interpolation was applied to convert the sample for every 15 minutes in this case study (8640 of total 15 minutes periods). Furthermore, the loads can be controlled by using demand response programs through direct load control. The controlled value corresponds to 25% of the consumer consumption for conventional loads and 100% of the consumer consumption for public and residential EV charging stations. Three different PV panel rated powers were considered, namely, 0.72 kW, 0.96 kW, and 1.2 kW, corresponding to 6, 8, and 10 modules, respectively. Each PV unit had its profile randomly assigned. The EV residential and public charge profiles were created through simulation using the approach developed in [2]. Two distinct home charge rated powers were considered, namely, 3.7 kW and 7.4 kW.

Three studies were conducted to demonstrate that small consumers and small EV charging stations participating in DR services can mitigate or remove voltage and congestion issues in DLVN. All three cases are compared to a reference case where DR and DREV are not considered (the actual network). Case 1 assumes that only consumers with PV panels can provide both services; case 2 assumes that all loads on the network can provide both services; and case 3 assumes that only consumers with PV panels can provide the DR service, while all loads can provide the DREV service. It is noteworthy that there is no DREV service for public charging stations in case 1 because there is no PV generating at the bus with public charging stations.

IV. RESULTS AND DISCUSSION

The proposed methodology from Section 2 was applied to the previous section's case study. This research work was developed using a computer with a single Intel Core i7-4510U processor and 16 GB of RAM, running Windows 10 21H1 and MATLAB R2017a with MATPOWER 7.1 [17]. In all cases (Case 1, Case 2, Case 3, and reference case), the simulation was conducted for 8640 periods. Table 1 compares the results of all the cases studied. 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 and in the cables which connect bus 1 to bus 151, 152, and 153, consecutively.

The period 460 was used to conduct a more extensive investigation of the reference case due to its atypical behavior (high demand). Fig. 4a) and Fig. 4b) present the voltage magnitude for each bus and the occupation rate for each line/cable, respectively. As can be observed, a group of buses (57 buses) present voltage issues, and 5 line/cable (those closest to the transformer output, respectively 1-2, 2-3, 4-7, 1-151, 151-152) have congestion problems.

[2] www.meteoblue.com

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TABLE I. GENERAL INFORMATION – COMPARISON BETWEEN CASES

Case	Voltage Problem		Congestion Problem		Lower Voltage (V)	Higher Occupancy Rate (%)	Execution Time [s]**	
	Number of periods	Occurrence per period*	Number of periods	Occurrence per period*			With problem (s)	Without problem (s)
Reference	518	16	290	2	0.920	129.913	-	-
1	35	8	7	1	0.939	107.562	10.394	1.428
2	0	-	0	-	0.950	99.995	4.925	1.256
3	0	-	0	-	0.950	99.995	8.091	1.279

* Average value.
** For one single period.

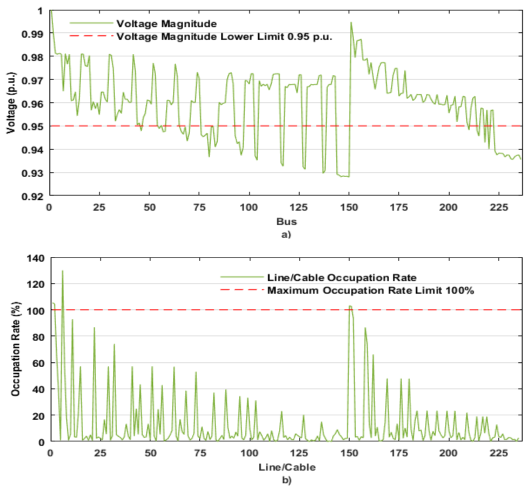

Figure 4. Reference case- (a) Bus voltage magnitude; (b) Line/cable occupation rate.

The obtained bus voltage (blue line) and its improvement (black line) for case 1 are shown in Fig. 5a). The radial feature of the network can also be observed because the voltage declines as the buses move away from the transformer. Applying the limited DR and DREV services, a considerable increase in voltage magnitude up to 2.13% is obtained. Fig. 5b) depicts the occupation rate (blue line) and its change (black line) for case 1. It's worth noting that all consumers who can provide services have been activated. Despite this, not all the network's issues were resolved, indicating that the service is not properly dimensioned. Some possible solutions can arise, for instance, searching for new providers, i.e., increasing the penetration of the services on the network; and increasing the amount of demand reduction by common agreement between the parties. The high percentages of change illustrated by the lines/cables in Fig. 6b) refer to cars being charged that were suddenly turned off.

Fig. 6a) shows the achieved bus voltage (yellow line) and its improvement (black line) for case2. The voltage magnitude follows the expected trend, i.e., the voltage drops progressively on the downstream buses (away from the transformer). However, because the solution suggested for the previous case's problem has been incorporated in this one, all network issues have now been resolved. Furthermore, the high penetration of Demand Response services in the network allows network problems to be treated more locally, preventing them from spreading to the rest of the network. Fig. 7b) presents the line/cable occupation rate and its change for case 2. When comparing Fig. 6b) and Fig. 5b), the peaks of percentage changes (demand decrease) in Fig. 6b) rise radially as one moves away from the transformer.

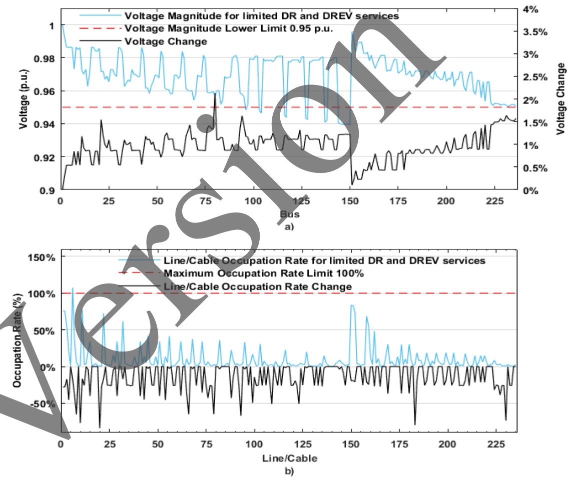

Figure 5. Limited DR and DREV service case – (a) Bus voltage magnitude; (b) Line/cable occupation rate.

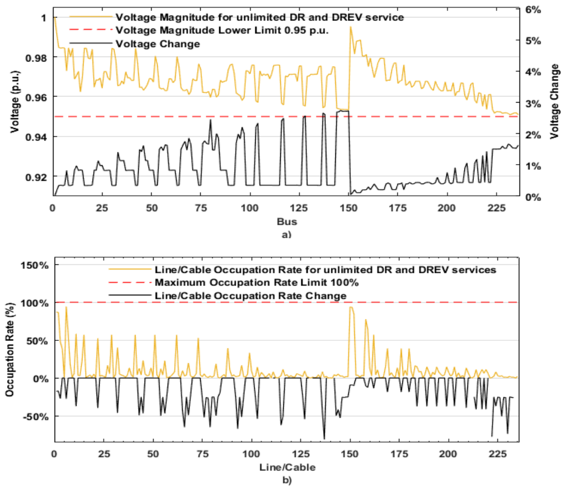

Figure 6. Unlimited DR and DREV service case - (a) Bus voltage magnitude; (b) Line/cable occupation rate.

While Fig. 7a) represents the obtained bus voltage (purple line) and its improvement (black line) compared to the reference case by implementing limited DR and unlimited DREV services (case 3), Fig. 7b) shows the line/cable occupation rate and its change. Even with a more limited approach, all network problems can be solved in this scenario. The percentage improvement achieved is slightly lower than

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in the preceding case (2.48% vs. 2.74%). However, it is sufficient, indicating that this service is well-dimensioned and still not at its maximum limit. Only 20 DR service providers of the 39 available at this period were activated. From the 51 DREV service providers available, 19 are charging EV during this time, and only 6 providers had the DREV service activated.

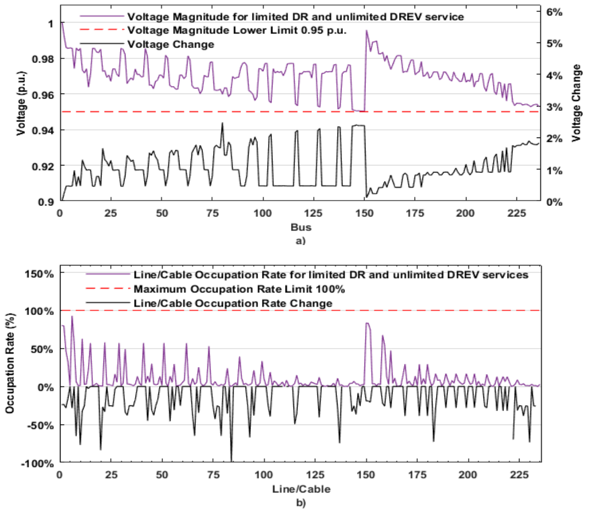

Figure 7. Limited DR and unlimited DREV service case - (a) Bus voltage magnitude; (b) Line/cable occupation rate.

V. Conclusions

This study offered a strategy to mitigate the voltage and congestion problems in distribution low voltage networks through the flexibility of demand response services participation of small consumers and electric vehicles charge stations as provided services. For this, a logic heuristic model working together with MATPOWER, an electric power system simulation, and analysis, is used. Three case studies were considered and compared to a reference case (no demand response services). First, all the network issues were solved using limitless demand response and demand response with electric vehicles service. As a result, they have verified a voltage magnitude improvement of up to around 2.74% and 80% maximum improvement in lines/cables occupation rate. However, on the other hand, there are still voltage and congestion problems in the network for limited demand response and demand response with electric vehicles services, even with all available providers. Next, the case with limited demand response and unlimited demand response with electric vehicles services was revealed to be the most balanced (or better scaled for the investigated network). Even when not all traditional consumers are willing to join a demand response service, the network's problems are solved. Mostly due to the EV charging station's high flexibility. The findings indicate that the proposed methodology can effectively manage distribution low voltage network operational issues, particularly voltage and congestion problems.

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References

[1] B. Canizes, J. Soares, Z. Vale, J. Corchado, “"Optimal Distribution Grid Operation Using DLMP-Based Pricing for Electric Vehicle Charging Infrastructure in a Smart City,” Energies 2019, 12:686. Available: https://doi.org/10.3390/en12040686.

[2] B. Canizes, J. Soares, A. Costa, T. Pinto, F. Lezama, et al., “Electric Vehicles’ User Charging Behaviour Simulator for a Smart City,” Energies 2019, 12:1470. Available: https://doi.org/10.3390/en12081470.

[3] B. Canizes, J. Soares, F. Lezama, C. Silva, Z. Vale, et al., “Optimal expansion planning considering storage investment and seasonal effect of demand and renewable generation,” Renew Energy 2019, 138:937–54. Available: https://doi.org/10.1016/j.renene.2019.02.006.

[4] A. Paaso, D. Kushner, S. Bahramirad, A. Khodaei, “Grid Modernization Is Paving the Way for Building Smarter Cities [Technology Leaders],” IEEE Electr. Mag. 2018, 6, 6–108. Available: doi:10.1109/MELE.2018.2816848.

[5] L. E. Erickson, J. Robinson, G. Brase, J. Cutsor, “Solar Powered Charging Infrastructure for Electric Vehicles: A Sustainable Development,” CRC Press: Boca Raton, FL, USA, 2016.

[6] M. M. Alam, S. Mekhilef, M. Seyedmahmoudian, B. Horan, “Dynamic Charging of Electric Vehicle with Negligible Power Transfer Fluctuation,” Energies 2017, 10, 1–20. Available: doi:10.3390/en10050701.

[7] S. Rahman, G. B. Shrestha, “An investigation into the impact of electric vehicle load on the electric utility distribution system,” IEEE Trans. Power Deliv. 1993. Available: doi:10.1109/61.216865.

[8] C. H. Dharmakeerthi, N. Mithulananthan, T. K. Saha, “Impact of electric vehicle fast charging on power system voltage stability,” Int. J. Electr. Power Energy Syst. 2014. Available: doi:10.1016/j.ijepes.2013.12.005.

[9] A. Ul-Haq, C. Cecati, K. Strunz, E. Abbasi, “Impact of Electric Vehicle Charging on Voltage Unbalance in an Urban Distribution Network,” Intell. Ind. Syst. 2015, 1, 51–60. Available: doi:10.1007/s40903-015-0005-x.

[10] J. Hoog, V. Muenzel, D. C. Jayasuriya, T. Alpcan, M. Brazil, et al., “The importance of spatial distribution when analysing the impact of electric vehicles on voltage stability in distribution networks,” Energy Syst. 2014. Available: doi:10.1007/s12667-014-0122-8.

[11] W. Liu, Q. Wu, F. Wen, J. Ostergaard, “Day-ahead congestion management in distribution systems through household demand response and distribution congestion prices,” IEEE Trans. Smart Grid 2014. Available: doi:10.1109/TSG.2014.2336093.

[12] S. Huang, Q. Wu, S. S. Oren, R. Li, Z. Liu, “Distribution Locational Marginal Pricing Through Quadratic Programming for Congestion Management in Distribution Networks,” IEEE Trans. Power Syst. 2015. Available: doi:10.1109/TPWRS.2014.2359977.

[13] European Commission, “Clean energy for all Europeans,” Euroheat and Power 2019. Available: https://doi.org/10.2833/9937.

[14] G. Schweiger, L. V. Eckerstorfer, I. Hafner, A. Fleischhacker, J. Radl, et al., “Active consumer participation in smart energy systems,” Energy Build 2020, 227:110359. Available: https://doi.org/10.1016/j.enbuild.2020.110359.

[15] Y. Zhang, P. E. Campana, Y. Yang, B. Stridh, A. Lundblad, et al., “Energy flexibility from the consumer: Integrating local electricity and heat supplies in a building,” Appl Energy 2018, 223:430–42. Available: https://doi.org/10.1016/j.apenergy.2018.04.041.

[16] M. Afzalan, F. Jazizadeh, “Residential loads flexibility potential for demand response using energy consumption patterns and user segments,” Appl Energy 2019, 254:113693. Available: https://doi.org/10.1016/j.apenergy.2019.113693.

[17] R. D. Zimmerman, C. E. Murillo-Sanchez, “MATPOWER (Version 7.1),” [Software] 2020. Available: https://matpower.org

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