Open-Source Active Distribution Grid Model with a large share of RES- features and studies

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***Abstract*—Future distribution grids are likely to shift away from a passive grid consuming power to an active grid with a high share of weather dependent renewable generation. Distribution grid operations are greatly interlinked between different voltage level and depend upon the fluctuating load demand along. Thus it is imperative to study and analyze multi-voltage level distribution grids to understand the challenges and opportunities in a distribution grid with a high share of weather-dependent generation. In this research, an open-source multi-voltage level distribution grid model, named the DTU 7k-Bus Active Distribution Grid Model, is presented. The distribution grid model spans across three voltage levels and is modeled on geographical data for network topologies. The generation and load time-series provided with the model is simulated from weather data and derived from measurement data respectively. This work addresses key features of the model, and highlights challenges due to high share of renewables.**

Keywords—active distribution grid model, low voltage network, distributed generation, network characteristics, open-source network model

I. Introduction

Traditional design of a distribution grid serves a unidirectional flow electricity from a transmission network to the consumer end. However, due to increasing interest in low-carbon technologies and encouragement via government subsidies and feed-in tariff programs, the distribution grid has witnessed an increasing number of generation sources connected to the low and middle voltage levels [1]–[3]. Thus, the power flow direction in a traditional distribution grid reverses to flow from low/medium voltage distribution networks to high voltage transmission network in case of high generation or low load demand. The increased reverse power flow conflicts with, and affects adversely with not only the design and network asset settings in the traditional distribution grid, but also the steady state operating conditions in a distribution network [4]–[8]. Furthermore, the interaction of a distribution grid with the transmission grid changes depending on the level of renewable energy penetration. Multiple research works have adderessed the challenges in a traditional distribution network with a large share of renewable energy sources (RES) connected. Authors in [4], [9]–[11] highlight voltage rise and voltage limit violations, while other works such as [6], [12]–[14] focus of active power loss reduction. Increasing the hosting capacity of the distribution network by optimizing the placement of RES in the grid is also a topic of great interest in this field [15], [16]. Since an enormous amount of research has been conducted in this topic, it is difficult to produce an exhaustive list of related research works.

Power electronic converters provide controllable characteristics to the RES connected at low-voltage level. The presence of power electronics can provide unique advantages for the distribution grid to alter its passive role to an active role by providing active and reactive power flexibilities to the transmission network. More recently, active and reactive power flexibility provided by RES connected in the distribution network has emerged as a viable consideration [17]–[19]. Thus, it becomes imperative to study and quantify the impact of a large share of RES in a distribution grid on not only its operating characteristics, but also its interaction with the transmission network. However, the operation of a distribution network depends on the generation as well as the load fluctuations. To study and analyze the impact of RES connected at different voltage levels in the distribution network along with the load demand fluctuations, a multi-voltage distribution grid model derived from real-data is necessary.

Many research works have addressed the design and development of a benchmark power system model. Some of the notable open source models are the benchmark models by CIGRE Task force , IEEE benchmark models for transient and steady state analysis , SciGRID transmission network models, and the more recent SimBench distribution network models [20]–[25]. More examples of distribution/transmission network models are available pertaining to specific systems and problems [26]–[28]. However, often the design of a benchmark power system model only considers one voltage level. This overlooks the impact of assets connected to low-voltage distribution grid, such as EV charging stations, demand response, or the cumulative effect of small-scale user end generators. Moreover, synthetic network topologies form the basis of the distribution network models available so far, which does not encompass the essence of a real densely populated distribution network topology. In addition, a generation or load time-series, derived from meteorological data or real measurement data, does not accompany the network models. Amongst all the network models mentioned only SimBench is a multi-voltage level network with generation and load-time series for about a year [25]. To the best of author's knowledge, a comprehensive network with all the required features mentioned, and a large share of weather-dependent RES, is still a need for the study of future active distribution grids. The aim of this research is to present the DTU 7k-Bus Active Distribution Network Model (DTU-ADN) to fulfill this research gap.

Section I in this paper gives an introduction to the problem statement and a brief literature review of the existing distribution grid models. Section II describes the open source DTU 7k-Bus Active Distribution Network (DTU-ADN) [29] to give an insight into the development process for the model and also an overview of the network model available. Section III presents some of the key features of the DTU-ADN by analyzing the effects of a high share of renewables on the low-voltage side of the distribution network. Finally, section IV provides a brief conclusion.

II. DTU 7K-BUS ACTIVE DISTRIBUTION NETWORK MODEL

The DTU-ADN is a multi-voltage level distribution grid model spanning across three voltage levels, namely $60\ kV - 10\ kV - 0.4\ kV$. The network is representative of a distribution network with a large share of weather-dependent generation connected at the lower voltage levels. The DTU-ADN is developed considering the correlations between weather-dependent generation on the load demand.

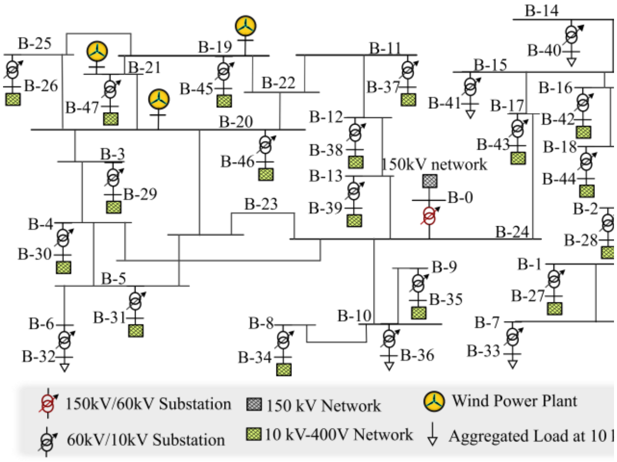


Figure 1:The 60 kV Distribution Network from DTU 7k-Bus Active Distribution Network

A $60kV - 150kV$ step-up transformer connects the DTU-ADN to the transmission network. The network consists of 23 $60kV - 10kV$ substations. The DTU-ADN dataset also contains different $10\ kV - 0.4kV$ networks, modeled from geographical data, which expand 18 out of the 23 $60kV - 10kV$ substations. The $60\ kV$ network topology with $60\ kV - 10\ kV$ substation is depicted in Figure 2. Note that there are three wind power plants (WPPs) with installed capacities $12\ MW, 15\ MW, and\ 15\ MW$ connected to the $60\ kV$ distribution network.

Cumulative installed solar PV and wind capacity across the $60\ kV$ network and all the $10kV - 0.4kV$ networks, amounts to $25\ MW$ and 152 MW respectively. The spectrum of installed solar PV plants extends from small installations at $5\ kW$ up to $3\ MW$. Similarly, the spectrum of installed WPPs extends from 300kW to 15 MW. Figure 2 quantifies and categorizes the RES with an installed capacity of more than 11 kW. It can be seen that the distribution network model contains a large number of small solar PVs along with WPPs with large capacities. According to the Danish grid codes, renewable energy generation sources with installed capacities of more than 11 kW, may participate in the grid operations actively via altering their active and reactive power outputs [30], [31]. Thus, the DTU-ADN provides a basis to study the participation of renewable energy sources to support distribution grid operations.

Load and generation time-series for all the nodes, for approximately a year, are provided along with the network. Unique combinations of load profiles for $10kV - 0.4\ kV$ networks, categorizes them into urban distribution

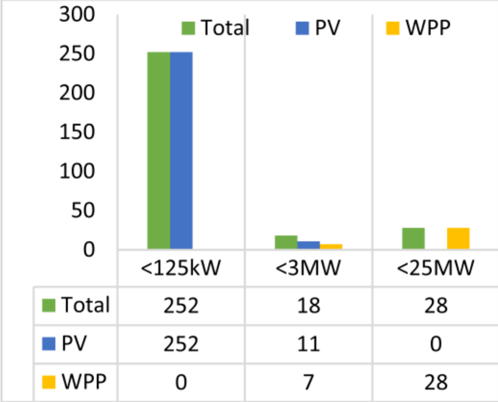


Figure 2: Available Renewable Energy Resources in the DTU-ADN with installed capacity greater than 11 kW

grids with large number of residential customers, or predominantly industrial/ commercial area networks, or rural and agricultural distribution networks. This gives room to conduct specific research studies for different types of load demand from the low voltage networks.

Along with the time-series for individual nodes at $10\ kV$ and $0.4\ kV$, the dataset also contains an aggregated time-series at the $60\ kV - 10\ kV$ substation, which makes it feasible to simulate and analyze each of the $10\ kV - 0.4\ kV$ networks individually. This feature, to study $10\ kV - 0.4\ kV$ network individually, is utilized in this research to analyze different distribution networks with varying levels of penetration of weather-dependent generation, energy density, and load profiles.

III. KEY FEATURES OF THE DTU-ADN

This section presents some of the key features of the DTU-ADN by exemplifying the unique characteristics of some of the $10\ kV - 0.4\ kV$ networks. It also highlights the challenges in a distribution network with a large share of RES.

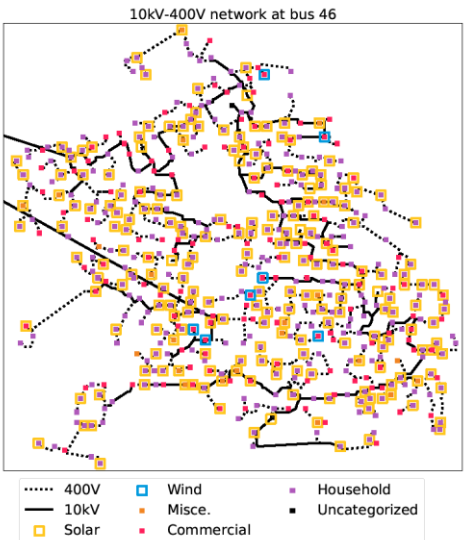
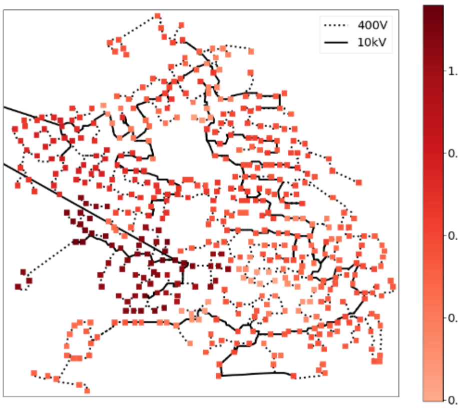
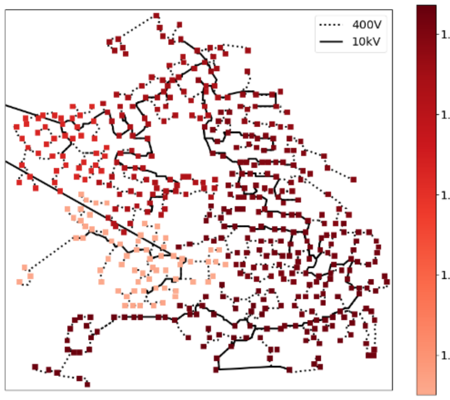


Figure 1: Network topology displaying types of loads and renewable generation connected at each node for the 10 kV-0.4 kV distribution network connected at Bus 46

To begin with, consider the network connection at Bus 46 with 2.75 MW of household and 1.9 MW of commercial/industrial loads. The topology for this low voltage



a)



b)

Figure 2: Voltage profile across the distribution network at Bus 46 for two different time-stamps. a) Demand: 1.84 MW; Generation: 0.042 MW

grid along with the load and RES connections is pictured in Figure 3. The substation at Bus 46 serves 546 connections at $0.4\ kV$ or $10\ kV$ nodes. All individual connection points represent aggregated loads from several customers. The network at Bus 46 has a very high penetration of renewable energy sources with approximately $3.4\ MW$ of solar and $21.5\ MW$ of wind generation connected at $10\ kV$ or $0.4\ kV$. This network also houses a major $15\ MW$ of wind power plant connected at $10\ kV$. Most of the PV installations in this network are less than $125\ kW$, which indicates a major proportion of rooftop solar plants on the consumer end. This assumption also corroborates with the fact that 60 % of the total installed load is household.

RES penetration in this network is about 720 % due to the presence of a large WPPs. The term RES penetration indicates the ratio of installed RES in a network to the installed loads. Similar to a RES power penetration, the energy penetration can be defined as the total energy generated in the distribution network over a given period to the energy demand. The RES energy penetration for this distribution network, stands at 751 %.

One of the key challenges faced by a distribution network with a large share of renewables is rise in voltage profiles at the end nodes. Traditionally the distribution network was developed for a unidirectional supply; however, due to

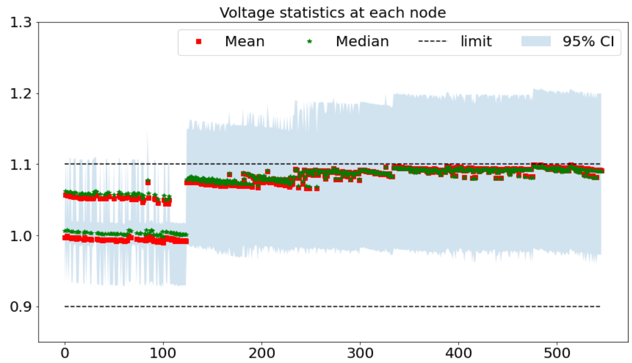


Figure 5: Voltage statistics for all nodes in Network at Bus 46 with 95% confidence intervals (CI) for the voltage distribution. Nodes are arranged in ascending order of distribution line length from the 60 kV/ 10 kV substation

generation sources on the consumer end, the power flow in the distribution network has become bi-directional in nature. Generation at the low voltage nodes increases the voltages at the end of the line, which interferes with the operating characteristics of network assets such as a voltage regulator. This phenomenon can be observed from the difference in the voltage profiles in Figure 4(a) and Figure 4(b). Figure 4(b) depicts a timestamp with high generation in the distribution grid ($32\ MW$) as compared to the load demand, which raises the voltages at the end nodes above the $1.1\ p.u.$ limit. Moreover, Figure 5 shows the voltage distribution statistics for all the available time-stamps in the DTU-ADN dataset. The nodes in Figure 5 are arranged in ascending order of their distribution line length from the $60\ kV - 10\ kV$ substation at Bus 46 in the $60\ kV$ grid (see Figure 1). It is thus, observed that not only do the end nodes in the distribution grid face higher voltages but also that the voltage limits are violated for about 50 % of the total timestamps due to a high share of RES in this distribution grid.

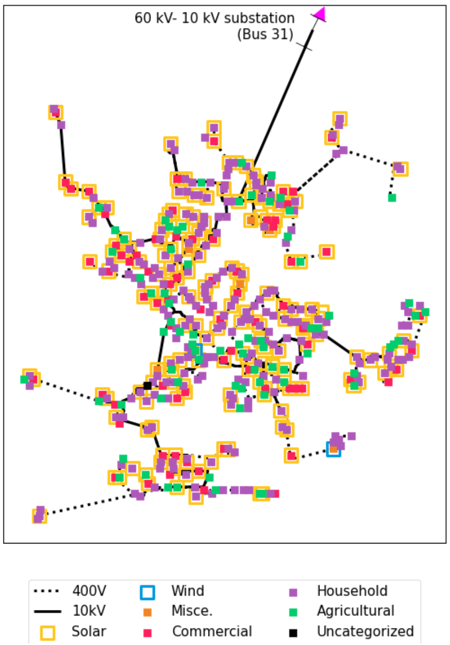


Figure 6: Network topology displaying types of loads and renewable generation connected at each node for the 10 kV- 0.4 kV distribution network connected at Bus 31

The $10\,kV - 0.4\,kV$ network connected at Bus 31, shown in Figure 6, powers 2.3 MW of household, 1.2 MW of agricultural, and 1.4 MW of commercial / industrial loads. About 1.9 MW of solar and 3.4 MW of wind generation is connected in this network, which brings the RES power penetration to 88 %, however, all the RES in this distribution network only generate 40 % of the total energy demand over a year. Since, the RES penetration in network at Bus 31 is lower as compared to the network at Bus 46, only 7 % voltage violations are observed at a few nodes in this network.

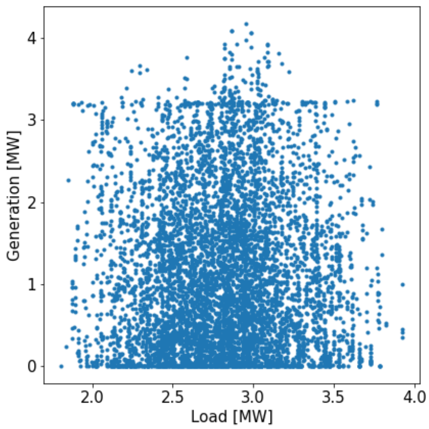


Figure 7: Scatter plot of aggregated load demand [MW] Vs. renewable generation at Bus 31

A scatter plot of the renewable generation in the distribution network at Bus 31 and its load demand is shown in Figure 7 highlighting the fact that renewable generation does not correlate with the load demand in addition to being inherently non-dispatchable. However, this is not the case with active power losses in the network. It is observed that the active power losses in the network decrease up to a certain level of distributed generation in the network as the load demand is satisfied locally by distributed RES. However, a high level of distributed generation increases the reverse power flow and also the distribution line losses. The positive correlation between renewable generation and line losses in the distribution network can be observed in Figure 8 for the network at Bus 31. A similar phenomenon is more strikingly

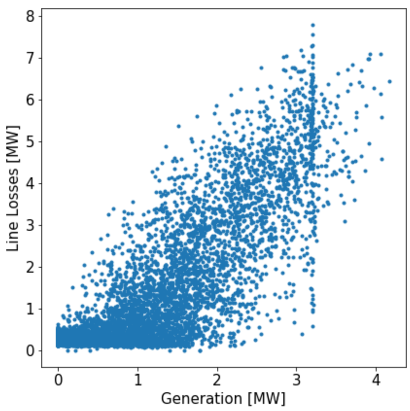


Figure 8: Renewable generation [MW] Vs. Active Power Losses [MW] in the distribution network for network at Bus 31

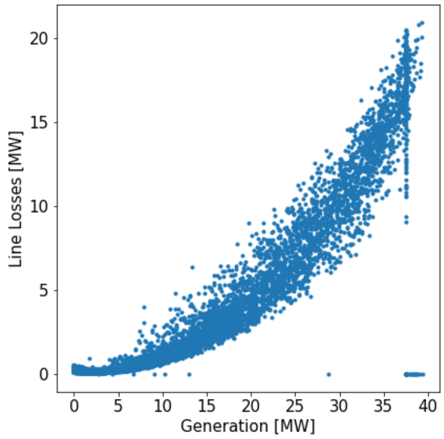


Figure 9: Renewable generation [MW] Vs. Active Power Losses [MW] in the distribution network for network at Bus 46

observed for the network at Bus 46, which has a much higher penetration of RES, as illustrated in Figure. 9

A high amount of generation connected at the low voltage grid, not only affects the voltage profiles and power losses in the network, but also reactive power demand from the connecting substation. As the reverse power flow in the low voltage distribution network increases, the reactive power flow is also altered as pictured in Figure 10. Thus, the low voltage distribution network, in this case, demands higher reactive power from the medium voltage network. The scatter

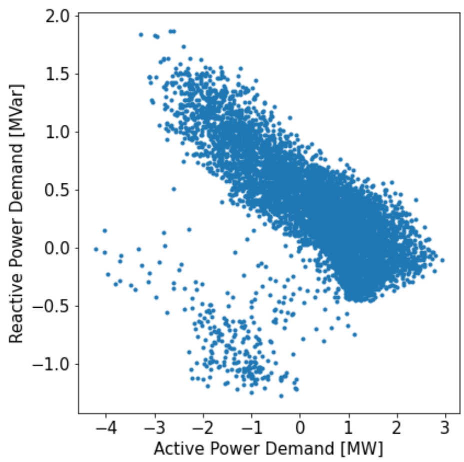


Figure 10: Active Vs. Reactive Power Flow at Bus 31

plot in Figure 10 confirms that the interactions of low-medium voltage distribution grid with the high-voltage transmission grid is also altered.

IV. Conclusion

Future distribution networks are likely to host a large quantity of weather-dependent renewable generation. However, the present distribution grid is designed for a unidirectional flow of power and will thus face operational challenges adapting to a new distribution network with a large share of renewable energy sources. The operation of a low-voltage distribution network is correlated with the operation of the medium-voltage network. It is therefore important to study and analyze the operating conditions in the low voltage-medium voltage network via co-simulating them. This paper presents an open source multi-voltage level distribution network with a large share of RES, named as the DTU 7k-Bus Active Distribution Grid Model (DTU-ADN).

The DTU-ADN spans across three voltage levels, namely 60kV-10kV-0.4kV. The 10kV-0.4kV networks shown in this paper exemplify some of the features and attributes of a low voltage-medium voltage distribution network with a large share of RES. The DTU-ADN provides 17 such 10kV-0.4kV distribution networks with a variety of load profile combinations and RES penetration.

The motive behind developing a multi-voltage distribution network with data derived from geographical topologies and measurement data is to study the challenges in the future distribution network with a large share of RES. Some of these challenges, namely voltage profiles, higher active power losses, and altered reactive power flow, are presented in this study via the DTU 7k-Bus Active Distribution Network.

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REFERENCES

[1] Energistyrelsen, "Analyseforudsætninger til energinet," 2019.

[2] A. Peter;, "National Survey Report of PV Power Applications in Denmark," 2016.

[3] IRENA 2019, "RENEWABLE POWER GENERATION COSTS IN 2018," International Renewable Energy Agency, Abu Dhabi, 2019.

[4] A. Allen and A. Allen, "Voltage Impacts of Utility-Scale Distributed Wind Voltage Impacts of Utility- Scale Distributed Wind," no. September, 2014.

[5] A. Baviskar, A. D. Hansen, K. Das, and M. Koivisto, "Challenges of Future Distribution Systems with a Large Share of Variable Renewable Energy Sources – Review," *19th Wind Integr. Work. 2020*, no. November, 2020.

[6] K. Das, M. Altin, and A. D. Hansen, "Technical methodology for minimization of network losses," 2016-1-12433, ForskEL-project nr., Eniig Forsyning A/S, DTU Wind Energy, Dansk Energi, 2018.

[7] K. Das *et al.*, "Facing the challenges of distribution systems operation with high wind power penetration," *2017 IEEE Manchester PowerTech, Powertech 2017*, 2017, doi: 10.1109/PTC.2017.7981136.

[8] Y. P. Agalgaonkar, B. C. Pal, and R. A. Jabr, "Distribution voltage control considering the impact of PV generation on tap changers and autonomous regulators," *IEEE Trans. Power Syst.*, vol. 29, no. 1, pp. 182–192, 2014, doi: 10.1109/TPWRS.2013.2279721.

[9] W. Deng, Y. J. Huang, L. Zhu, M. Yu, and R. Liao, *Voltage Quality Evaluation of Distribution Network and Countermeasure*, vol. 902. Springer International Publishing, 2020.

[10] Y. Xue *et al.*, "Voltage impact analyses of solar photovoltaics on distribution load tap changer operations," *2017 North Am. Power Symp. NAPS 2017*, 2017, doi: 10.1109/NAPS.2017.8107252.

[11] C. Y. Lau, C. K. Gan, Z. Salam, and M. F. Sulaima, "Impact of Solar Photovoltaic System on Transformer Tap Changer in Low Voltage Distribution Networks," *Energy Procedia*, vol. 103, no. April, pp. 58–63, 2016, doi: 10.1016/j.egypro.2016.11.249.

[12] C. Ma, J. Dasenbrock, J. C. Töbermann, and M. Braun, "A novel indicator for evaluation of the impact of distributed generations on the energy losses of low voltage distribution grids," *Appl. Energy*, vol. 242, no. November 2018, pp. 674–683, 2019, doi: 10.1016/j.apenergy.2019.03.090.

[13] M. Delfanti, D. Falabretti, and M. Merlo, "Dispersed generation impact on distribution network losses," *Electr. Power Syst. Res.*, vol. 97, pp. 10–18, 2013, doi: 10.1016/j.epsr.2012.11.018.

[14] A. Soroudi, A. Rabiee, and A. Keane, "Distribution networks' energy losses versus hosting capacity of wind power in the presence of demand flexibility," *Renew. Energy*, vol. 102, pp. 316–325, 2017, doi: 10.1016/j.renene.2016.10.051.

[15] S. M. Ismael, S. H. E. Abdel Aleem, A. Y. Abdelaziz, and A. F. Zobaa, "State-of-the-art of hosting capacity in modern power systems with distributed generation," *Renewable Energy*. 2019, doi: 10.1016/j.renene.2018.07.008.

[16] C. A. N. Pereira, J. A. P. Lopes, and M. A. C. C. Matos, "Assessment of the distributed generation hosting capacity incorporating harmonic distortion limits," in *2018 International Conference on Smart Energy Systems and Technologies, SEST 2018 - Proceedings*, 2018, doi: 10.1109/SEST.2018.8495843.

[17] F. Capitanescu, "TSO–DSO interaction: Active distribution network power chart for TSO ancillary services provision," *Electr. Power Syst. Res.*, vol. 163, no. March, pp. 226–230, 2018, doi: 10.1016/j.epsr.2018.06.009.

[18] S. Stanković, L. Söder, Z. Hagemann, and C. Rehtanz, "Reactive Power Support Adequacy at the DSO/TSO Interface," *Electr. Power Syst. Res.*, vol. 190, 2021, doi: 10.1016/j.epsr.2020.106661.

[19] A. O. Rousis, D. Tzelepis, Y. Pipelzadeh, G. Strbac, C. D. Booth, and T. C. Green, "Provision of Voltage Ancillary Services Through Enhanced TSO-DSO Interaction and Aggregated Distributed Energy Resources," *IEEE Trans. Sustain. Energy*, vol. 12, no. 2, pp. 897–908, 2020, doi: 10.1109/tste.2020.3024278.

[20] K. Strunz, C. Abbey, C. Andrieu, R. C. Campbell, and R. Fletcher, *Benchmark Systems for Network Integration of Renewable and Distributed Energy Resources*, no. July. 2009.

[21] K. Strunz, R. H. Fletcher, R. Campbell, and F. Gao, "Developing benchmark models for low-voltage distribution feeders," *2009 IEEE Power Energy Soc. Gen. Meet. PES '09*, no. July, pp. 1–3, 2009, doi: 10.1109/PES.2009.5260227.

[22] C. Matke, W. Medjroubi, and D. Kleinhans, "SciGRID - An Open Source Reference Model for the European Transmission Network (v0.2)," no. November, 2016, doi: 10.13140/RG.2.2.14596.12161.

[23] D. Sarajlić and C. Rehtanz, "Low Voltage Benchmark Distribution Network Models Based on Publicly Available Data," *Proc. 2019 IEEE PES Innov. Smart Grid Technol. Eur. ISGT-Europe 2019*, pp. 1–5, 2019, doi:

10.1109/ISGTEurope.2019.8905726.

[24] S. Meinecke, N. Bornhorst, and M. Braun, “Power System Benchmark Generation Methodology,” no. February, 2019.

[25] C. Spalthoff *et al.*, “SimBench : Open source time series of power load , storage and genera- tion for the simulation of electrical distribution grids,” no. September, pp. 447–452, 2019.

[26] J. Amme, G. Pleßmann, J. Bühler, L. Hülk, E. Kötter, and P. Schwaegerl, “The eGo grid model: An open-source and open-data based synthetic medium-voltage grid model for distribution power supply systems,” *J. Phys. Conf. Ser.*, vol. 977, no. 1, 2018, doi: 10.1088/1742-6596/977/1/012007.

[27] M. Sarstedt, G. Steffen, C. Blaufus, and L. Hofmann, “Modelling of Integrated Transmission and distribution grids based on synthetic distribution grid models,” *IEEE Milan Power*, 2019.

[28] J. Kays, A. Seack, T. Smirek, F. Westkamp, and C. Rehtanz, “The generation of distribution grid models on the basis of public available data,” *IEEE Trans. Power Syst.*, vol. 32, no. 3, pp. 2346–2353, 2017, doi: 10.1109/TPWRS.2016.2609850.

[29] A. Baviskar, A. D. Hansen, K. Das, and M. Koivisto, “DTU 7k Bus Active Distribution Network,” *Dataset*. 2021, doi: 10.11583/DTU.c.5389910.

[30] Energinet.dk, “Technical regulation 3.2.2 for PV power plants above 11 kW,” pp. 1–108, 2016.

[31] “Guide for connection of pow- er-generating plants to the low-voltage grid (≤ 1 kV),” no. December, pp. 1–97, 2019.