Challenges of Future Distribution Systems with a Large Share of Variable Renewable Energy Sources – Review

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***Abstract*—Power distribution systems with a high share of Variable Renewable Energy Sources (VRE) face problems due to the variability, uncertainty, and non-dispatchable nature of VRE. This paper reviews and discusses the pertinent challenges arising for steady state operation of future distribution systems with a large share of weather-dependent renewable energy sources. The substantially increased amount of VRE in future distribution networks transforms them into highly weather-dependent networks with limited real-time observability. Challenges of such networks, like sustained over-voltage, increased power losses in the network, growing stress upon the existing network assets and changing interactions with the upstream grid, are addressed in the paper. Illustrations from past research and practical demonstrations of these challenges are presented to emphasize the severity of the problems.**

I. INTRODUCTION

The share of wind and other renewable energy sources in Denmark and Europe is steadily increasing. The cumulative installed wind capacity in Europe has reached 205 GW in the year 2019 [1]. For example, in Denmark wind power represents 48% of its electricity mix, followed closely by Ireland with 33%, Portugal 27%, and Germany 26% and the UK with 22% . According to the Danish transmission system operator (TSO) - Energinet, 50% of total energy consumption in Denmark in the year 2019 came from renewable energy of which 47% accounted for wind power plants and the rest 3% from solar power [2]. Furthermore, onshore wind power and solar power generation is emerging as the cheapest form of new electricity around the world [3]. As reported by the international renewable energy agency [4], 2019 was the best year for solar power installation in Europe as the amount of solar installations increased by 104 % as compared to the previous year. Over the last few years, a large share of wind power and solar PV has also gained momentum in the distribution system. For example, by the end of 2018, 49% of the EU's cumulative photovoltaic (PV) capacity came from rooftop solar (residential 19%, commercial 30%). In Denmark, the introduction of the feed-in-tariff program in the year 2015 saw a surge in the installations of small wind turbines in the distribution system [2]. Germany and the UK had introduced similar feed-in-tariff programs to promote the uptake of small-scale renewable electricity generation in the years 2000 and 2010 respectively. It is clear that the growing influence of climate change policies and trends in the global uptake of VRE will continue in the years to come, emerging future distribution networks to accommodate large share of VRE.

As underlined in [5], renewable energy installations at lower voltage levels are not a hurdle in network operations whenever their share in the distribution systems is low . However, a substantially increased amount of VRE into distribution networks transforms them into highly weather dependent networks. The variability, uncertainty and non-dispatchable nature of VRE might potentially have an adverse impact on network operation and control, challenging the distribution system operator (DSO) to deal with additional issues like under- and overvoltages, overloading of transformers and feeders, rise in line losses [6]–[11]. Furthermore, the increased variability in the network compels the network assets, such as voltage regulators (VR), on-load tap changers (OLTC), etc., to operate more frequently to maintain power quality in the distribution network [6], [12]–[14]. Such increase in the frequency of operation of network assets deteriorates their lifetime. Older fixed-speed Wind Turbine (WT) connected to the distribution network have presented numerous challenges including regulation of voltage profiles, consumption of reactive power, flicker, harmonics, and increase in fault current level [5], [15]–[17].On one hand, the presence of power electronics inside modern wind turbines has enhanced their energy capture abilities and rendered the problems of harmonic and flicker negligible [18] while on the other hand the increased share of power electronics in the grid has lowered system inertia and short circuit ratio escalating stability problems and making the grid more sensitive to small deviations in the system state [19], [20]. Furthermore, VRE installations connected to the grid via power-electronics have become the new source of harmonic distortions [21]. In addition it is also equally crucial to account for the shortcomings of the distribution network itself. The principal challenge behind integrating a large share of VRE in the network is that the traditional network was initially designed for unidirectional power flow [7], [22]. The additional generation at the distribution level results in a reverse power flow in the network during low load and high generation scenarios, thus being responsible for increased line losses. Moreover, the current lack of infrastructure for real-time observability, monitoring, and control of rooftop PV and small-scale wind installations is an additional challenge for the DSOs. The limited observability of VRE in the distribution network adds on to the existing uncertainties in the network due to a high share of weather-dependent generation.

The trend is clear. The future of energy will depend largely on sustainable and greener sources of energy such as the VRE. Hence, the primary reason behind reviewing the above mentioned challenges for future distribution grid is to ascertain integration of large amounts of VRE into the power systems; in other words, to increase the hosting capacity of the grid, namely the maximum VRE capacity that can be installed in the network without the need of additional network reinforcements [22]. A survey [23], conducted in 2017, underlines that 59% of the power utilities are concerned about the growing distributed generation (DG) sources in relation to the networks' hosting capacity. The same survey predicts $\approx 50\%$ loss of revenue for DSOs with increased share of consumers with the capacity to generate power. In the light of these aspects, it becomes imperative to review the operational steady-state challenges for future distribution systems.

This paper expounds upon the challenges of future distribution systems confronted with the imminent increase of controllable weather-dependent generation sources but with limited observability. Precedents from past academic research and case studies, concerning the large share of RES in the distribution system are used in this review to highlight the severity and importance of the challenges. The attention in this paper is especially directed towards the challenges most relevant for steady-state operation in the distribution network, namely, sustained over-voltages, voltage fluctuations, increased power losses in the network, growing stress upon the network assets and bi-directional interactions with the upstream grid or transmission system.

Section I provides an overview of the challenges of the DSOs with a large share of VRE. An in-depth description of a few relevant concerns for steady-state DSO operations is presented in Section II. Review of research studies, innovations, and tools to overcome the adverse impact of VRE sources and to enhance their contribution in the distribution grid is summarised in Section III. Section III also presents some concluding remarks and directions for future research.

II. CHALLENGES IN FUTURE DISTRIBUTION NETWORKS

Based on a thorough literature review, this section presents and discuss the most relevant challenges DSOs are facing regarding future distributed networks with large share of VRE, namely sustained over-voltage, increased power losses and fluctuations, growing overloading of the existing network assets and the interchanging interactions between the distribution network (DN) and transmission network (TN) in the future.

A. Voltage stability aspects

Traditional distribution grid design methods assume lower voltage at the remote end of the feeders and a unidirectional power flow. Most of the distribution networks present today are designed with such traditional methods. However, introducing a high share of VRE reverses the power flow in the network making it bidirectional [7], [24].

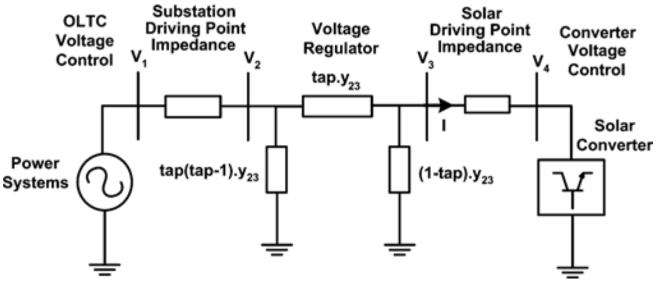

Fig. 1: Equivalent circuit of a radial distribution feeder with voltage regulator [25]

Consider, for example, a radial distribution feeder, as shown in Fig. 1, where a generation source is connected at the remote end of a medium voltage (MV) feeder via, a voltage regulator. The current indicated in Fig. 1 is positive for power flowing from bus with voltage V_1 to V_4 called forward power flow. The vector diagram for forward flow is depicted in Fig. 2 where, the receiving end voltage (V_4) is lower than the sending end voltage (V_1). Although in case of excess generation via the PV system, the direction of power flow reverses as indicated in the reverse power flow vector diagram in Fig. 2. Due to the reverse power flow, voltage at the tail end of the feeder rises.

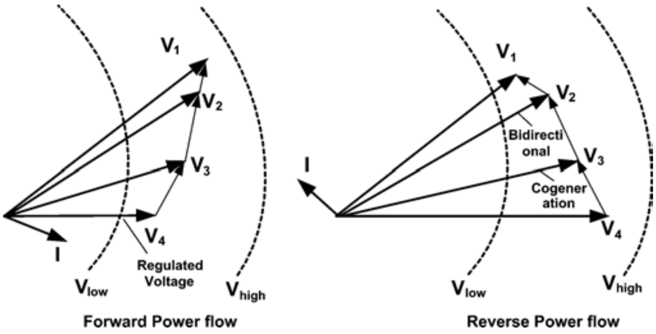

Fig. 2: Vector diagram for the radial system [25]

Besides the reverse power flow aspect, a distribution network with large high-share of VRE becomes also highly weather dependent and hence, the voltages in the network also experience a similar weather dependent variability. Fig. 3 illustrates the voltage and the active power profiles at the secondary side of the TSO/DSO transformer for a distribution network with large share of wind power, described in [26]. The timestamps indicated on the x-axis are with hourly resolution. The convention for power flow used for Fig. 3 is positive for power transfer from TN to DN and negative for reverse power flow, namely from DN to TN. Notice first that based on the power flow convention, the amount of the reverse power flow, namely from DN to TN, is quite significant, i.e. up to 100MW. Notice also that that the voltage fluctuates with the power, with a positive correlation of 0.85, and as it is measured at the secondary side of the TSO/DSO transformer, it decreases with increasing reverse flow, as also depicted in Fig. 2.

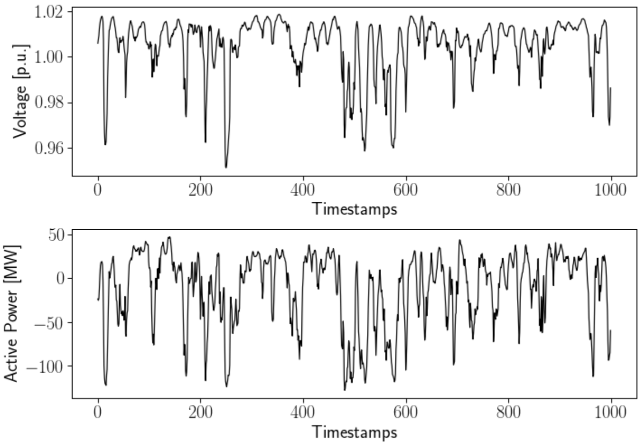

Fig. 3: Voltage and power profile at the secondary side of reference bus (1 hour values) [27]

Various studies conducted on real distribution networks with a high share of VRE highlight over- and under-voltage issues, as one of the most prevalent challenges of future distribution networks [24], [28]–[33]. According to IEEE-1547 standard [34], besides over - and under-voltage issues, the introduction of DG in low-voltage networks challenges the DSOs also in respect to voltage fluctuations and stability. The problem of over-voltage at the remote end of the feeder becomes more prevalent in low loading conditions [15], [29]. Authors in [29] demonstrate this phenomenon through a set of full load and low load scenarios with or without a 3MW wind turbine connected to a rural distribution feeder.

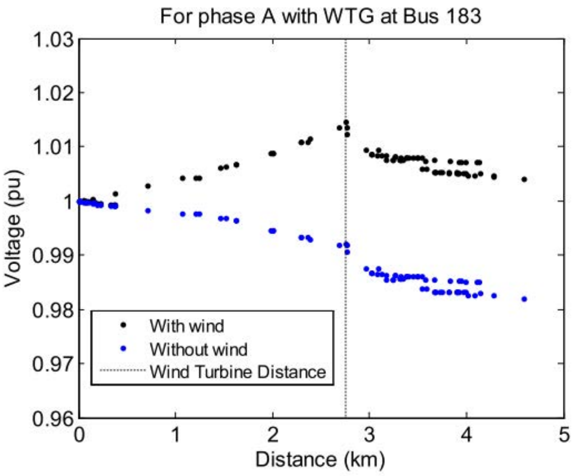

Fig. 4: Voltage along the feeder with 3MW WT connected: Full load scenario [29]

Fig. 4 shows the voltage profiles in the network when a 3MW wind turbine generator (WTG) is connected in the network during full load scenario. Notice that the voltage profiles in the network increase when the WTG is connected, the maximum voltage being however below 1.02 p.u. Fig. 5 depicts the simulation results for a lower load scenario (i.e. 33% of the full load). Notice that the voltage profile increases this time at a higher voltage level, closer to 1.02 p.u. The study in [29] also underlines that, the voltage rise due to connecting WTs depends on the equivalent impedance between the reference bus and WT connection point.

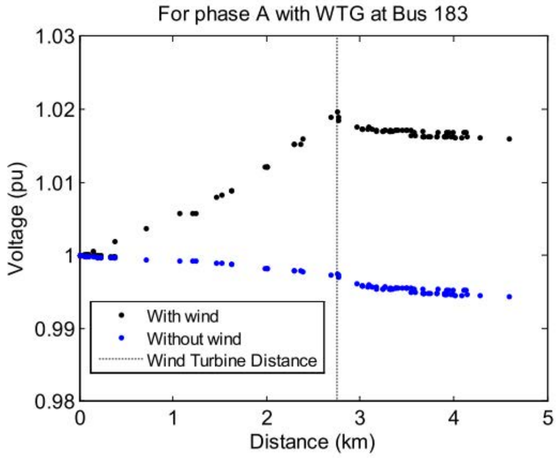

Fig. 5: Voltage along the feeder with 3MW of WT connected: 33% of full load [29]

Similar results are presented in [31] regarding the voltage unbalance factors for a Spanish secondary radial distribution network with installed PV generation sources. Authors in [31] notice that the voltage imbalance in the network increases by increasing the size of PV installation. In [32], it is shown that the voltage imbalance problem in the South African low voltage (LV) distribution network can be reduced by increasing the cable size. However, network reinforcement measures, such as increasing cable sizes, with a very high share of VRE is not an economically viable option for DSOs [15].

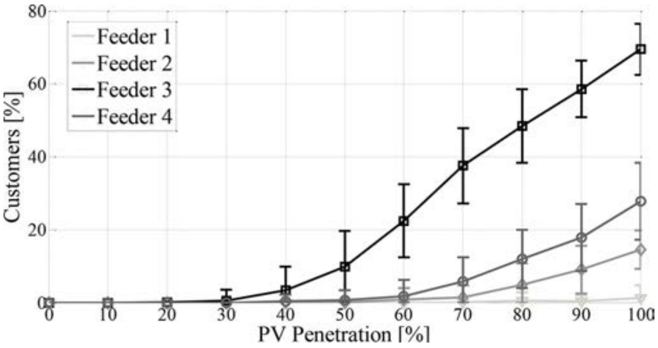

Fig. 6: Percentage of consumers with voltage problems with increasing penetration of PV generation [33]

To further emphasize the conundrum of voltage profiles in LV networks with a high share of VRE, authors in [33] present a probabilistic assessment of the voltage problem with increasing penetration of low-carbon technologies, such as PV generation, on 128 real distribution feeders based in the UK. Fig. 6 indicates that more and more customers will face voltage problems when share of PV generation [%]] increases.

Along with the sustained over-voltages due to VRE, voltage instability and harmonics due to power converters, static VAR compensators, etc. are also a few hurdles that come along with a high share of VRE [8], [21], [35]. Maintaining voltage profile and stability is one of the most important factors determining power transfer capacity and thus, the hosting capacity of a distribution grid according to [36].

B. Line losses and power fluctuations

As mentioned earlier connecting VRE generating sources in the distribution grid can potentially reverse the power flow. Since, active power losses in the network are proportional to current squared, losses in the distribution network increase with increasing reverse power flow. However, these losses depend highly on the power demand and the amount of generation connected in the distribution grid . For instance, authors in [5] report a reduction in the active power losses of $\approx 20\%$ when 3 controllable double fed induction generator (DFIG) WTs of 1.5MW each are connected to a 33kV distribution network in high demand scenario. However, the losses in the network increase when more than 3 WTs of 1.5MW are connected. It is thus noticed that, in general, distribution grid losses increase after a certain threshold of distributed generation penetration is reached.

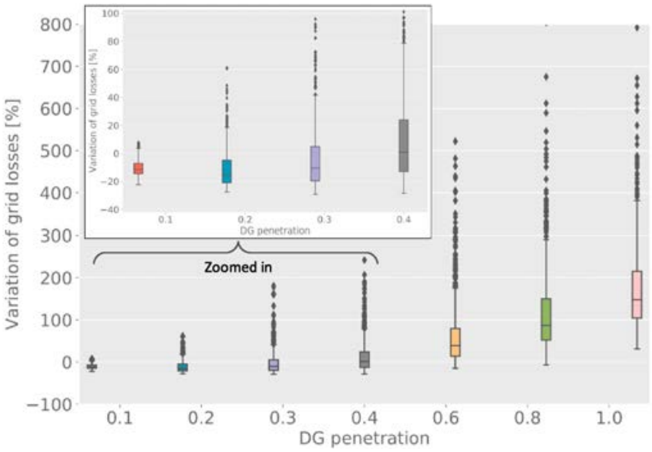

Fig. 7: Loss variation in low voltage grids [37]

Fig. 7 depicts the variation of losses in low voltage grids with increasing DG penetration. It can be observed that the variation of losses up to 60% DG penetration level also contain possibility of loss reduction in the distribution grid. However, the losses increase to as high as 700 % of the base case, for large DG penetration.. A similar increase in the probability and variation of network losses is also evaluated in [38]. Moreover, with a high penetration of VRE sources, which are by nature intermittent and weather-dependent, a higher variation in the expected distribution network losses is anticipated.

According to [39], a significant portion of PV installations in Denmark till the year 2016 are within the range 3-7kW, being rooftop PVs installations. Global solar market predictions [4], [40] also indicate an increase in rooftop PV installations over the coming years. Although, the DSOs are aware of the increased installed capacity of VRE connected in their network, they lack detailed knowledge of the real-time observability and controllability of the weather dependent VRE and consumption installed in their networks. This challenge is exemplified and discussed in [26].

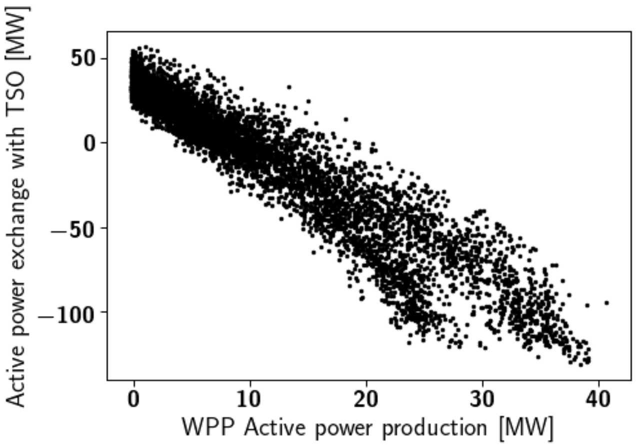

Fig. 8: Power flow between distribution and transmission network [27]

Fig. 8 shows the active power transfer between the distribution network in [26] and the transmission network plotted against the Wind Power Plant (WPP) active power production. The distribution network has 3 WPPs of size 12, 15 and 15 MW respectively. These are the only VRE sources in the network which are measured. Notice that the reverse power flow in the network can get up to 100 MW, as shown in Fig.8 even though the cumulative size of the measured WPPs is only 42MW. This indicates the presence of other generation sources in the network which are not being measured by the DSO. Fig.9 plots the power losses in the same network against the WPP active power production. Notice that there is a strong positive co-relation between the WPP generation and network losses. Furthermore, Fig. 9 indicates that 88% of the total losses in the distribution network over a year come from 37% of the time when wind power generation is high.

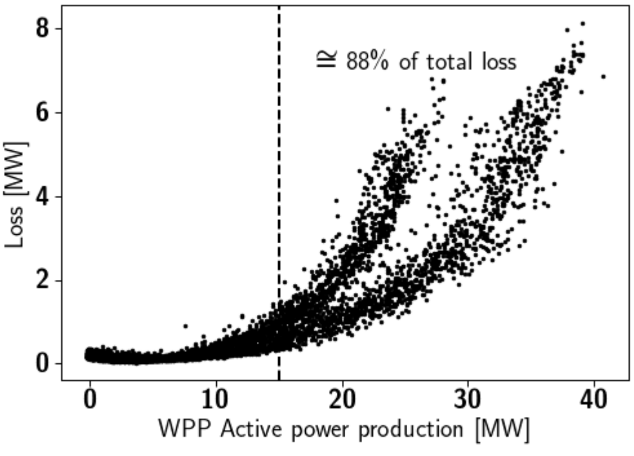

Fig. 9: Wind power plant active power production Vs. Losses in the network [27]

In addition to being non-observable by the DSOs, weather-dependent VRE are also non-dispatchable by their nature. The most common and well-known example highlighting the non-dispatchable nature of weather-dependent VRE is the duck curve [41], which primarily indicates a significant drop in the mid-day load demand curve due to high amount of PV generation. This drop in load during the mid-day forces the bulk power generators to reduce their power output to very low values. Bulk generators, like thermal power plants, take a longer time to start-up, their ramp rates are slow, and are less economical when operated on a stand-by mode. However, when the PV production reduces at the end of the day, the power demand from the TSO suddenly increases, demanding high ramp-up rates. This conundrum can be resolved by curtailing PV power to certain limits which results in spilling readily available green energy. The solution to this problem can be two-faced, one is implementing storage to time-shift the generated power or the second being demand-response. The duck curve also demands a significant increase in the evening ramp-up capacity and flexibility services as illustrated in [41]. Furthermore, the variability and uncertainty of the weather-dependent generation add a high variability to any predictions of the duck curve.

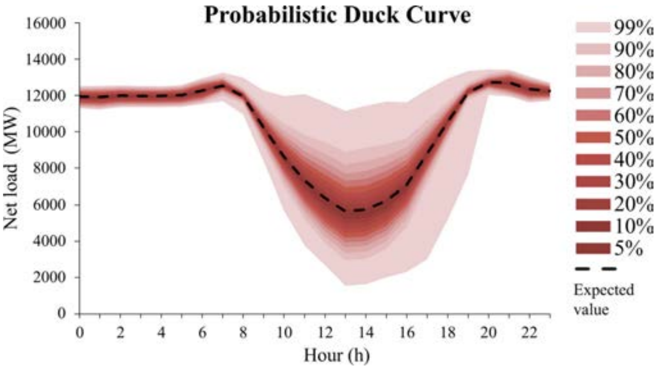

Fig. 10: Probabilistic duck curve [42]

Authors in [42] study the weather and load-demand dependent variability of duck curve and suggest ramp-up capacity using a probabilistic model. The cardinal result of the study is shown in Fig. 10, which depicts a very high variability in the available PV generation for similar hours over the day. Furthermore, the power output profiles for weather-dependent generation also vary over time.

As highlighted in [38], [43], [44], the awareness of the impact of VRE on fluctuations in the power generation and of the line losses is an overriding factor in the future to determine the network efficiency and the additional network reinforcements, if necessary, all these being of highly economically importance for the DSOs.

C. *Overloading of network assets*

The distribution network utilises several control equipment such as automatic OLTCs, VRs, switching capacitors (SC)s, synchronous condensers, and other regulation equipment to maintain voltage levels and power quality in the network. The OLTCs regulate the voltage by changing tap setting of the transformer. Similarly VRs monitor the voltage and load current and change their tap-settings. On the other hand, SCs and synchronous condensors are designed to compensate for the reactive power needs at remote ends, thereby maintaining voltage profiles in the network.

Traditionally the distribution networks have been designed assuming predictable load profiles in the network, having their network assets designed accordingly. However, with increasing installations of DGs, especially VREs, an active distribution network is bound to face additional voltage fluctuations and sustained over-voltages, as illustrated and discussed in Section II-A. Moreover, future distribution networks will also face an increase in electric vehicle charging stations, storage and implementation of demand response techniques. In addition to the presented challenges in focus in this paper, it is important to highlight that the load profiles in future distribution network will be grossly different from the past one, being less predictable due to the large share of VRE. The changing power flows and load profiles in the network thus have an impact on the number of operation instance or frequency of operation of the existing network assets. Furthermore, the capabilities of some of the network assets in maintaining voltage profiles and power quality in the network can be questioning.

The inadequacies of VRs' traditional settings in sensing correct setting in instances of reverse power flow are discussed in greater details in [6]. Furthermore, authors in [45] study the inadequacy of VRs in reverse power flow scenarios on a real distribution network in Sacramento, USA. In addition, [6] also deliberates upon interactions between network assets and DGs which has a potential destabilizing impact on the system voltage. Authors in [12], [13] report the impact of increased PV penetration in the network on operations instances of OLTC. In one of the simulated scenarios, it is shown that the number of operation instances for an OLTC is increased by 150% with a 90% PV penetration as opposed to the base case when no PV are installed. Note that the increase in number of operation instances with increasing PV penetration is due to short-term fluctuations in PV power. A similar study quantifying OLTC operations considering weather-dependent nature of VRE is presented in [14].

D. *Interactions with the upstream grid*

Excessive reverse power flow due to high generation and low demand in the distribution grid leads to a change in the active and reactive power flow between the DN and the upstream grid. Fig. 8 illustrates the reverse power flow problem on a Danish power distribution network, as described in [26]. One aspect of altered interactions with the upstream network is in terms of reactive power flow. Usually VREs connected to the distribution grid operate at unity power factor. This means that, it is only allowed to locally supply active power and not reactive power. The active power demand from upstream synchronous generation reduces, while the reactive power demand remains unaltered. This fact in turn causes the synchronous generators to operate at a lower power factor, thus affecting their efficiency.

Furthermore, when the generation from VRE in the network increases in low loading situations, it overloads the cables, distribution transformers and DSO/DSO interfacing transformer. Overloaded cables behave inductively and demand excessive reactive power from the transmission grid. Fig. 11

illustrates the reactive power exchange between the transmission and distribution networks for a Danish distribution network [26]. The convention of power flow in Fig. 11 is positive from TSO to DSO. Notice from Fig. 11 that the distribution network becomes highly inductive as WPPs generate more active power.

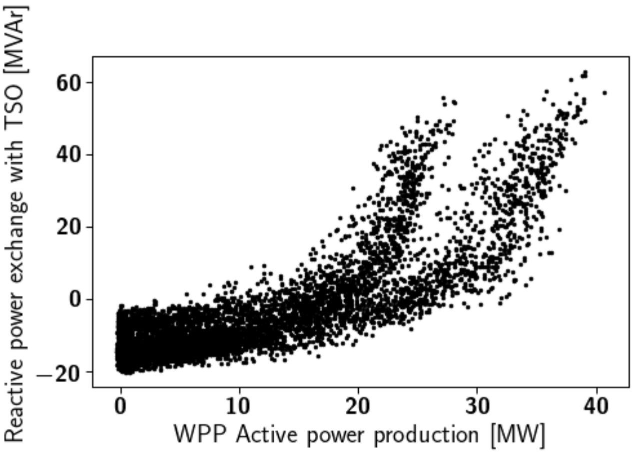

Fig. 11: Reactive power exchange between distribution and transmission grids w.r.t. WPP active power production [27]

Another impact of a high share of VRE in the distribution grid is due to short term variability. Short-term variability changes the active power exchange between transmission and distribution on shorter time scales. This requires the transmission network to increase the flexible reverses and have more and more resources with high ramp up rates. Fig. 12 from [42] shows the variance in active power ramp rate required by the grid due to weather-dependency of PV installations. To maintain the power supply for all loads in the network with increased weather-dependent uncertainty, authors in [46] suggest simulating power flows in the network on a shorter time scale to get a realistic estimate of the system operational costs. It is worth mentioning that simulating the system with higher time resolution decreases the uncertainty in the system due to the fact that the forecast errors are introducing further cost-savings, while increasing the amount of required data and computational load.

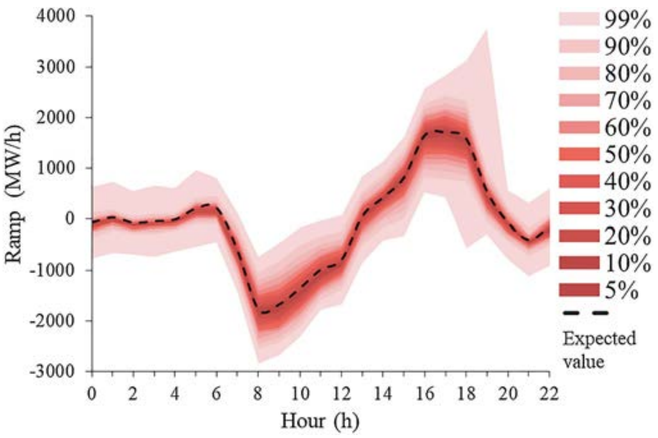

Fig. 12: Probabilistic ramp rate requirements [42]

III. Research opportunities and conclusions

Integrating VRE in distribution networks not only brings challenges to the DSOs but also provides operational, technical and economic opportunities.

One of the obvious advantage of connecting power electronic based VRE to the network is, that it provides significant controllability. The control of active and reactive power from VRE installations is decoupled due to the presence of power electronics. Although, today, these enhanced control capabilities of VRE are not largely utilized in distribution networks. However, some grid codes have started to require better utilization of these control capabilities. For example, the Danish grid codes [47] levy VRE installations to provide reactive power support in the network. In this respect, it should be mentioned that, the capability curves of Type-IV WTs, addressed in IEC 61400-27 [48], [49], reflect that WTs can provide a significant more reactive power output than is allowed as per the grid-codes [50]. In [26], for example, it is shown that the line losses in a real distribution network with large share of Type -IV WTs can be reduced by optimizing reactive power flow in the network, through employing the ability of wind generators to generate as well as absorb reactive power. A comprehensive summary of loss minimization and voltage control techniques in distribution networks with a high share of VRE can be found in [51] and [52] respectively. Another popular, and highly researched technique for maintaining voltage profiles and reducing fluctuations due to VRE in the distribution network is volt-var compensation [53]–[56]. Research studies like [57], [58] focusing on reactive power management from VRE are only a few examples from the vast literature available in this area.

Furthermore, future distribution networks will have a wide array of controllable devices including but not limited to VRE, storage, electric vehicle charging, etc along with advanced compensation devices such as STATCOMs. The control capabilities and flexibility introduced in via such network assets transform the passive traditional distribution network into an active distribution network, which will demand advanced active management techniques [57]. Authors in [15] introduce one such possibility of controlling reactive power from STATCOMs to reduce voltage fluctuations due to WPPs. While authors in [25], [59], [60] present a coordinated control between different sources such as OLTCs, line-compensators, storage, diesel generators along with VRE to address various the challenges put forward by VRE.

In addition to academic research towards enhancing operation of distribution networks with VRE, there has been a significant industrial interest in determining optimal VRE locations, capacity and capability in a distribution network. Homer Energy [61], DER-CAM [62], Ipsys[63], and MI-GRID [64] are few examples of commercial and open-source tools for optimizing the performance of distribution networks with a large share of VRE and other network assets.

Furthermore the substantially increased amount of RES in future distribution networks transforms them into highly weather-dependent networks. There is an acute need for research in this respect, due to the lack of detailed knowledge of weather-dependent RES and consumption in real-time.

All the studies included in this paper thus indicate an immediate and urgent need for more research and deeper understanding amount of impact VREs will have on the power system. It is important to highlight here that, most of the current literature assumes a deterministic generation profile for VRE. Hence, it is also important to evaluate the impacts on the distribution network with stochastic VRE generation profiles. All these research opportunities specifically dealing with the challenges of operation, modeling, and control of distribution networks with significant amount of VRE, are of high relevance for a secure integration of future large scale VRE into the power systems, and they are therefore corner stones for existing and new coming research activities.

REFERENCES

[1] Colin Walsh, "Wind energy in Europe in 2019," Tech. Rep., 2019.

[2] "Energinet." [Online]. Available: https://energinet.dk/

[3] IRENA 2019, "RENEWABLE POWER GENERATION COSTS IN 2018," Tech. Rep., 2019. [Online]. Available: www.irena.org

[4] M. . Schmela, B. Aurélie, C. Naomi, G. P. Mariano, H. Máté, and R. Raffaele, "Global market outlook," Tech. Rep., 2018. [Online]. Available: www.africa-eu-renewables.org

[5] F. R. Arduini, A. L. D. S. Pessoa, M. Oleskovicz, and E. N. Asada, "Analysis of the Integration of Type C Wind Turbines in Distribution Networks," *2019 IEEE Milan PowerTech, PowerTech 2019*, 2019.

[6] R. A. Walling, R. Saint, R. C. Dugan, J. Burke, and L. A. Kojovic, "Summary of distributed resources impact on power delivery systems," *IEEE Transactions on Power Delivery*, vol. 23, no. 3, pp. 1636–1644, 2008.

[7] K. A. Alboaouh and S. Mohagheghi, "Impact of Rooftop Photovoltaics on the Distribution System," *Journal of Renewable Energy*, vol. 2020, pp. 1–23, 2020.

[8] A. S. Huda and R. Živanović, "Large-scale integration of distributed generation into distribution networks: Study objectives, review of models and computational tools," *Renewable and Sustainable Energy Reviews*, vol. 76, no. February, pp. 974–988, 2017.

[9] T. Lund, "Analysis of distribution systems with a high penetration of distributed generation," *Technical University of Denmark*, 2007.

[10] R. Jain, Y. Zhang, and B. M. Hodge, "Investigating the impact of wind turbines on distribution system stability," in *2016 IEEE Power and Energy Society Innovative Smart Grid Technologies Conference, ISGT 2016*, 2016.

[11] W. Deng, Y. J. Huang, L. Zhu, M. Yu, and R. Liao, *Voltage Quality Evaluation of Distribution Network and Countermeasure*. Springer International Publishing, 2020, vol. 902. [Online]. Available: http://link.springer.com/10.1007/978-3-030-12082-5

[12] R. Yan, B. Marais, and T. K. Saha, "Impacts of residential photovoltaic power fluctuation on on-load tap changer operation and a solution using DSTATCOM," *Electric Power Systems Research*, vol. 111, pp. 185–193, 2014. [Online]. Available: http://dx.doi.org/10.1016/j.epsr.2014.02.020

[13] Y. Xue, I. Sharma, T. Kuruganti, J. Nutaro, J. Dong, M. Olama, and D. Fugate, "Voltage impact analyses of solar photovoltaics on distribution load tap changer operations," *2017 North American Power Symposium, NAPS 2017*, 2017.

[14] 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. [Online]. Available: http://dx.doi.org/10.1016/j.egypro.2016.11.249

[15] M. Rahimi and H. Assari, "Addressing and assessing the issues related to connection of the wind turbine generators to the distribution grid," *International Journal of Electrical Power and Energy Systems*, vol. 86, pp. 138–153, 2017. [Online]. Available: http://dx.doi.org/10.1016/j.ijepes.2016.10.007

[16] P. Sørensen, N. A. Cutululis, T. Lund, A. D. Hansen, T. Sørensen, J. Hjerrild, M. H. Donovan, L. Christensen, and H. K. Nielsen, "Power quality issues on wind power installations in Denmark," *2007 IEEE Power Engineering Society General Meeting, PES*, pp. 1–6, 2007.

[17] H. S. Brorazeado, P. A. Rosas, E. A. Feitosa, and M. S. Miranda, "Behavior of wind turbines under Brazilian wind conditions and their interaction with the grid," *Proceedings of International Conference on Harmonics and Quality of Power, ICHQP*, vol. 2, pp. 906–910, 1998.

[18] I. Colak, G. Fulli, S. Bayhan, S. Chondrogiannis, and S. Demirbas, "Critical aspects of wind energy systems in smart grid applications," *Renewable and Sustainable Energy Reviews*, vol. 52, pp. 155–171, 2015.

[19] S. C. Johnson, J. D. Rhodes, and M. E. Webber, "Understanding the impact of non-synchronous wind and solar generation on grid stability and identifying mitigation pathways," *Applied Energy*, vol. 262, no. December 2019, p. 114492, 2020. [Online]. Available: https://doi.org/10.1016/j.apenergy.2020.114492

[20] B. Hartmann, I. Vokony, and I. Táczi, "Effects of decreasing synchronous inertia on power system dynamics—Overview of recent experiences and marketisation of services," *International Transactions on Electrical Energy Systems*, vol. 29, no. 12, pp. 1–14, 2019.

[21] C. A. Pereira, J. A. Lopes, and M. A. 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.

[22] S. M. Ismael, S. H. Abdel Aleem, A. Y. Abdelaziz, and A. F. Zobaa, "State-of-the-art of hosting capacity in modern power systems with distributed generation," 2019.

[23] Accenture, "Power Surge Ahead: How Distribution Utilities Get Smart With Distributed Generation," Tech. Rep., 2017. [Online]. Available: https://www.accenture.com/

[24] K. M. Muttaqi, A. D. Le, M. Negnevitsky, and G. Ledwich, "A novel tuning method for advanced line drop compensator and its application to response coordination of distributed generation with voltage regulating devices," *IEEE Transactions on Industry Applications*, vol. 2016, no. 2, pp. 1842–1854, 2016.

[25] 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 Transactions on Power Systems*, vol. 29, no. 1, pp. 182–192, 2014.

[26] K. Das, E. N. Martinez, M. Altin, A. D. Hansen, P. E. Sorensen, G. W. Thybo, M. Rangard, and K. M. Skytte, "Facing the challenges of distribution systems operation with high wind power penetration," *2017 IEEE Manchester PowerTech, Powertech 2017*, 2017.

[27] F.-p. n. 2016-1-12433, "Technical methodology for minimization of network losses," Tech. Rep. 2016, 2018.

[28] Electric Power Research Institute (EPRI), "APS Solar Partner Program : Research Highlights 2017 Electric Power Research Institute," 2017.

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

[30] A. Gonzalez, J. A. Saavedra, J. Tello-Guijarro, D. Trebolle, and M. Casas, "PRICE-GDI: A pilot experience for the integration of Distributed Generation in active distribution systems," *Proceedings - 2015 International Symposium on Smart Electric Distribution Systems and Technologies, EDST 2015*, pp. 183–188, 2015.

[31] F. J. Ruiz-Rodriguez, J. C. Hernández, and F. Jurado, "Voltage unbalance assessment in secondary radial distribution networks with single-phase photovoltaic systems," *International Journal of Electrical Power and Energy Systems*, vol. 64, pp. 646–654, 2015. [Online]. Available: http://dx.doi.org/10.1016/j.ijepes.2014.07.071

[32] Z. Goqo, S. Sewchurran, I. E. Davidson, and O. Ojo, "An assessment of voltage rise phenomenon on existing eThekwini Electricity low-voltage distribution network," *Proceedings - 2017 IEEE PES-IAS PowerAfrica Conference: Harnessing Energy, Information and Communications Technology (ICT) for Affordable Electrification of Africa, PowerAfrica 2017*, pp. 231–235, 2017.

[33] A. Navarro-Espinosa and L. F. Ochoa, "Probabilistic Impact Assessment of Low Carbon Technologies in LV Distribution Systems," *IEEE Transactions on Power Systems*, vol. 31, no. 3, pp. 2192–2203, 2016.

[34] F. Der, "IEEE Standard 1547 TM Power Quality Considerations for Distributed Energy Resources," pp. 1–15, 2017.

[35] J. H. Liu and C. C. Chu, "Long-Term Voltage Instability Detections of Multiple Fixed-Speed Induction Generators in Distribution Networks Using Synchrophasors," *IEEE Transactions on Smart Grid*, vol. 6, no. 4, pp. 2069–2079, 2015.

[36] L. Aolaritei, S. Bolognani, and F. Dörfler, "A distributed voltage stability margin for power distribution networks," *IFAC-PapersOnLine*, vol. 50, no. 1, pp. 13 240–13 245, 2017.

[37] 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," *Applied Energy*, vol. 242, no. November 2018, pp. 674–683, 2019. [Online]. Available: https://doi.org/10.1016/j.apenergy.2019.03.090

[38] M. Delfanti, D. Falabretti, and M. Merlo, "Dispersed generation impact on distribution network losses," *Electric Power Systems Research*, vol. 97, pp. 10–18, 2013.

[39] A. Peter;, “National Survey Report of PV Power Applications in Denmark,” PA Energy Ltd. Denmark, Tech. Rep. August, 2016.

[40] IEA-Pvp, “Snapshot of Global PV Markets 2020,” *Www.Iea-Pvps.Org*, pp. 1–16, 2020. [Online]. Available: http://www.iea-pvps.org/fileadmin/dam/public/report/technical/PVPS_report_-_A_Snapshot_of_Global_PV_-_1992-2014.pdf

[41] P. Denholm, M. O’Connell, G. Brinkman, and J. Jorgenson, “Overgeneration from Solar Energy in California: A Field Guide to the Duck Chart (NREL/TP-6A20-65023),” *Technical Report*, no. November, p. 46, 2015. [Online]. Available: http://www.nrel.gov/docs/fy16osti/65453.pdf

[42] Q. Hou, N. Zhang, E. Du, M. Miao, F. Peng, and C. Kang, “Probabilistic duck curve in high PV penetration power system: Concept, modeling, and empirical analysis in China,” *Applied Energy*, vol. 242, no. March, pp. 205–215, 2019. [Online]. Available: https://doi.org/10.1016/j.apenergy.2019.03.067

[43] P. Janik, G. Kosobudzki, and H. Schwarz, “Influence of increasing numbers of RE-inverters on the power quality in the distribution grids: A PQ case study of a representative wind turbine and photovoltaic system,” *Frontiers in Energy*, vol. 11, no. 2, pp. 155–167, 2017.

[44] A. Soroudi, A. Rabiee, and A. Keane, “Distribution networks’ energy losses versus hosting capacity of wind power in the presence of demand flexibility,” *Renewable Energy*, vol. 102, pp. 316–325, 2017. [Online]. Available: http://dx.doi.org/10.1016/j.renene.2016.10.051

[45] A. Nagarajan, M. Coddington, D. Brown, S. Hassan, L. Franciosa, and E. Sison-Lebrilla, “Studies on the Effects of High Renewable Penetrations on Driving Point Impedance and Voltage Regulator Performance: National Renewable Energy Laboratory/ Sacramento Municipal Utility District Load Tap Changer Driving Point Impedance Project,” no. January 2018, 2018. [Online]. Available: www.nrel.gov/publications.

[46] J. P. Deane, G. Drayton, and B. P. Ó Gallachóir, “The impact of sub-hourly modelling in power systems with significant levels of renewable generation,” *Applied Energy*, vol. 113, pp. 152–158, 2014. [Online]. Available: http://dx.doi.org/10.1016/j.apenergy.2013.07.027

[47] Danksk Energi, “Guide for connection of power- generating plants to the medi- um and high-voltage grid ¿1kV,” no. April, 2019.

[48] W. Turbines—Part, “27-1: Electrical Simulation Models-Wind Turbines,” *IEC Standard*, vol. 61, pp. 400–27, 2015.

[49] K. Das, A. D. Hansen, and P. E. Sørensen, “Understanding IEC standard wind turbine models using SimPowerSystems,” *Wind Engineering*, 2016.

[50] M. Sarkar, T. Souxes, A. D. Hansen, P. E. Sorensen, and C. D. Vournas, “Enhanced Wind Power Plant Control Strategy during Stressed Voltage Conditions,” *IEEE Access*, vol. 8, pp. 120 025–120 035, 2020.

[51] S. Kalambe and G. Agnihotri, “Loss minimization techniques used in distribution network: Bibliographical survey,” *Renewable and Sustainable Energy Reviews*, vol. 29, pp. 184–200, 2014. [Online]. Available: http://dx.doi.org/10.1016/j.rser.2013.08.075

[52] J. Dong, Y. Xue, M. Olama, T. Kuruganti, J. Nutaro, and C. Winstead, “Distribution Voltage Control: Current Status and Future Trends,” *2018 9th IEEE International Symposium on Power Electronics for Distributed Generation Systems, PEDG 2018*, 2018.

[53] G. C. Lampley, “Volt/VAR control at progress energy carolinas past, present and future,” *IEEE PES General Meeting, PES 2010*, pp. 33–35, 2010.

[54] S. Genc and M. Baggu, “Look ahead Volt/VAR control: A comparison of integrated and coordinated methods,” *Proceedings of the IEEE Power Engineering Society Transmission and Distribution Conference*, pp. 1–5, 2014.

[55] R. R. Biazzi, D. P. Bernardon, P. Marcolin, A. P. De Mello, and R. G. Bento, “Coordinated Volt/Var Control for Distribution System based on Heuristic Algorithm,” *2019 IEEE PES Conference on Innovative Smart Grid Technologies, ISGT Latin America 2019*, pp. 2–7, 2019.

[56] E. Gupta, C. Nickell, R. Moghe, H. Chun, and D. Tholomier, “Using Secondary VAr Controllers to Enhance Integrated Volt-VAr Optimization Benefits,” *2019 IEEE Canadian Conference of Electrical and Computer Engineering, CCECE 2019*, 2019.

[57] J. Zhao, C. Wang, B. Zhao, F. Lin, Q. Zhou, and Y. Wang, “A review of active management for distribution networks: Current status and future development trends,” *Electric Power Components and Systems*, vol. 42, no. 3-4, pp. 280–293, 2014.

[58] U. Jamil, N. Qayyum, A. Mahmood, and A. Amin, “Control Grid Strategies for Reduction of Real and Reactive Line Losses in Radial Power Distribution System,” *1st International Conference on Electrical, Communication and Computer Engineering, ICECCE 2019*, no. January 2020, pp. 1–5, 2019.

[59] H. Ji, C. Wang, P. Li, G. Song, H. Yu, and J. Wu, “Quantified analysis method for operational flexibility of active distribution networks with high penetration of distributed generators,” *Applied Energy*, vol. 239, no. October 2018, pp. 706–714, 2019. [Online]. Available: https://doi.org/10.1016/j.apenergy.2019.02.008

[60] X. Hua, T. Lulu, Z. Ning, Z. Jian, and S. Qian, “Coordinated optimal dispatch for active distribution network under multi-time scales,” *Proceedings of the 13th IEEE Conference on Industrial Electronics and Applications, ICIEA 2018*, pp. 695–699, 2018.

[61] “Homer Energy.” [Online]. Available: https://www.homerenergy.com/

[62] “The Distributed Energy Resources Customer Adaptation Model: DER-CAM.” [Online]. Available: https://gridintegration.lbl.gov/der-cam

[63] H. Bindner, O. Gehrke, and P. Lundsager, “IPSYS–A tool for performance assessment and supervisory controller development of integrated power systems with distributed renewable energy,” *Risø National* . . . , 2004. [Online]. Available: http://solar.org.au/papers/04papers/Bind.pdf

[64] “MIGRID: Smart Micro-grids.” [Online]. Available: https://www.migrid.ma/about/