Final report Grid Edge Control (GEC)

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Summary

The proliferation of distributed energy resources (DERs) has caused increasing operational issues for distribution systems, including overvoltage, undervoltage, and overloading of cables and transformers. In this project, we aim to develop methodologies and algorithms that make use of the flexibility from DERs to resolve network issues and increase the utilization of the total available grid capacity, without compromising the energy comfort of end-users. Emphasis is put on decentralized and real-time algorithms that work at the premises of end-users and low-voltage grids. Using methods including model-based offline optimization, online feedback optimization, and numerical simulations, the project has made several important contributions. In work #1, we present a real-world study that investigates the heat pump hosting capacity. Our proposed power flow control approach leads to a 100% hosting capacity, while the benchmark approach could accommodate only 51%, translating to 18 more possible connections for the LV feeder. In work #2, we complement current real-time control with a fairness design, ensuring equitable management among end-users. In works #3 and #4, we supply the real-time controller with planning capabilities, making more efficient use of the energy capacities of batteries and EVs. In work #5, we assess the robustness of real-time controllers under different system disturbances and uncertainties. In work #6, we investigate architectures for combined medium- and low-voltage network control, offering insights into their pros and cons. While this project has made important scientific contributions in real-time control, the control strategies are also designed to tackle practical challenges such as the non-availability of accurate grid representations and real-time load measurements. We further identify the necessity for further investigations into the broader systemic impacts of these strategies, especially their role in maintaining system balance and stability in the face of fluctuating renewable inputs.

1. Introduction

Currently the power system (electricity markets and electricity network) is organized top-down. In order to be able to cope with the increasing dynamic behaviour in the edges of the network it is useful to investigate also a decentral, bottom-up control of the system. This is the core of the Grid Edge Control project. In the project it is investigated how GEC can contribute to the optimal usage of the capacity of the medium and low-voltage (MV and LV) networks, how the concept of grid-edge control connects to control concepts on the higher network levels and how it can be integrated in the (inter)national electricity markets and concepts like program responsibility and unbalance markets.

The goal of the project was to investigate the development of methods and algorithms in which decentral and central ICT-architectures work together in order to control the local dynamics in the electricity network. This should result in a optimal usage of the available network capacity.

This document contains the end report of the project Grid Edge Control. Chapter 2 gives a summary of the findings of the report and the main conclusions. Chapter 3 describes the execution of the project.

2. Project

2.1 Introduction

With the ongoing energy transition, distributed energy resources (DERs) including photovoltaics (PVs), electric vehicles (EVs), heat pumps (HPs), and batteries are continuously connected to low-voltage (LV) and medium-voltage (MV) grids. While such electrification of transport and heating in households is seen as an essential part of the energy transition, it also brings increasing operational challenges for distribution system operators (DSOs) in the Netherlands and worldwide. Such challenges include overvoltage, undervoltage, and overloading of transformers and cables.

Cables in distribution grids, especially LV grids, are primarily resistive. Real power therefore flows from nodes with higher voltages to nodes with lower voltages. On a sunny afternoon, PVs are generating large amounts of power while loads can be low. Consequently, power flows from the end of distribution feeders to the beginning of them, causing overvoltage issues at the end of feeders. During peak load hours in the evening, EVs are charging, HPs are on, and PVs are not generating due to low irradiance. Power therefore flows from the beginning of distribution feeders to the end, causing undervoltage problems at the end of feeders. In both cases, large amounts of power are transported through transformers and cables at the beginning of feeders, which can exceed their thermal limits and cause grid security issues. A straightforward solution to these problems is grid expansion by replacing existing cables and transformers with thicker cables and transformers with higher capacities. However, this takes a long time and requires significant investments and well-trained staff for the installation.

2.2 Objective

These DERs, however, should not only be seen as obstacles as they also provide flexibility that can be utilized to resolve these problems. In this context, flexibility reflects the capability of these DERs that their generation and consumption can be modified to a certain extent. For example, PV generation can be temporarily curtailed, EV charging can be planned over the connection time, and HPs can be turned off for a short period without compromising the thermal comfort of end-users. Batteries bridge generation and loads, meaning that they can store energy during generation and release energy during load peaks. The aim of this project Grid Edge Control (GEC) is to develop methodologies and algorithms that make use of the flexibility from DERs to resolve network issues and increase the utilization of the total available grid capacity, without compromising the energy comfort of end-users. Emphasis is put on decentralized algorithms and architectures that work at the premises of end-users and LV grids, shifting from the traditional top-down to a bottom-up paradigm. The algorithms should also be able to be integrated into existing national and international electricity markets.

Throughout the execution of the project, several specific challenges have been identified and addressed based on the first work packages wherein the scope of the project has been determined. For clarity, we specify these works as work#1 to work#6.

- In work #1, the objective is to investigate the heat pump hosting capacity of a dense urban LV feeder for a social housing company in the Netherlands and provide a solution approach to enable the increasing adoption of heat pumps. Data from the

DSO and the social housing company are combined, including realistic grid topology, load, heat dynamics data, and practical operating characteristics of heat pumps. Recommendations are given to increase the heat pump hosting capacity based on simulation results.

- In work #2, the objective is to develop real-time control algorithms when accurate distribution grid topology and load measurements are not available. Since cables can be buried several decades ago, accurate grid topology and impedance data are not always readily available. Due to privacy concerns and regulatory restrictions, real-time load measurements in residential households are often not available either. These bring challenges to model-based optimization approaches. Another issue for distribution grid management is unfairness, in the sense that costs or burdens are unfairly distributed among end-users to relieve grid issues. This is often caused by the radial structure of distribution grids, where end-users located towards the end of distribution feeders experience more frequent voltage issues and contribute more to solving them. These challenges are addressed leveraging the framework of online feedback optimization (OFO).
- In works #3 and #4, the focus is to address the limitation of OFO as a real-time algorithm, which means that control actions are taken based on only real-time measurements. However, DERs such as EVs and batteries can be planned over a long period to make full use of their limited energy capacity. While work #3 focuses on the simulation of neighbourhood batteries, work #4 extends the simulation to distributed batteries and EVs installed at the premises of end-users.
- In work #5, the goal is to assess the robustness of OFO under a variety of uncertainties and disturbances in distribution grids. These include distribution grid model mismatch, measurement noise, communication delay and failure, topological changes due to network reconfiguration, and generation and load disturbances. The impacts on distribution grid limit satisfaction and balancing service provision are studied. Simulation results will provide guidelines for the practical implementation of OFO.
- In work #6, the main research question to be answered is how MV and LV grids should be operated together. DERs connected to LV grids are also causing operational issues to upstream MV grids. The focus of work #6 is to compare different control architectures for the combined MV-LV network operation.

2.3 Methodology

The main methodology used throughout the project is mathematical optimization. Optimization is the process of building and solving mathematical programs that represent power system problems. In optimization, we seek to minimize or maximize an objective function for given decision variables under a set of constraints. In the power system context, optimal power flow (OPF) is one of the most important problems. OPF pursues a certain objective function subject to power flow relations, and grid and asset limits. The problem is flexible in its formulations. Typical objective functions include minimization of power losses, voltage deviation to reference, generation curtailment, load shedding, reactive power compensation, the number of switching operations, and a combination of those. Decision variables represent for instance on-load tap changer positions, capacitor bank settings, and active and reactive power setpoints of various DERs. Voltage constraints and loading limits of transformers and cables are often considered.

Optimization problems including OPF problems can be solved in different ways. The simplest and the most common way is to leave the solution process to a commercial or open-source solver such as Gurobi, Cplex, and Ipopt. In work #1, a multi-period OPF problem is formulated and solved by Gurobi. The OPF formulation minimizes grid losses while including the end-user's thermal comfort constraints and grid constraints. These problems can be solved efficiently on a standard PC. For potential computational advantages, privacy concerns, and robustness of single-point communication failure, distributed and decentralized optimization techniques have been explored in work #6 to coordinate MV and LV grid operation. In these methods, the original integrated MV-LV optimization problem is decomposed into smaller problems split per area. Mathematical decomposition techniques are explored to achieve solutions of the same quality. Communications at the boundary buses between MV and LV grids are required.

In works #2 to #5, a primal-dual gradient projection algorithm is implemented to solve the OPF problem in an online approach. One of the motivations for the online solution of OPF is that the generation and loads in distribution grids fluctuate rapidly. By the time necessary data are collected and the computation is completed, the grid profiles might already change and the computed solutions become outdated. This online algorithm can make fast control decisions without waiting for the algorithm convergence. Grid measurements including voltage and power flow measurements are incorporated into the algorithm, rendering a closed control loop, and increasing the robustness of the algorithm under different uncertainties and disturbances in distribution grids. While other online algorithms are also possible, this specific algorithm is particularly attractive for real-time distribution grid management due to its distributed implementation. In the implementation, most calculations are carried out locally and include only basic arithmetic operations. Point-to-point communication is also avoided, where broadcasting is sufficient.

To validate and showcase the performance of our proposed algorithms, simulation studies are conducted based on real or synthetic grids and data. During the project, real Dutch grids and synthetic grids from the Simbench project were used. Various sources of generation and load data are adopted, for instance, the ECO second-scale load dataset and HelioClim PV irradiance data. The simulations are performed on representative days or days with extreme weather conditions. To represent grid states for given control actions, steady-state power flow solvers such as Pandapower and PowerGridModel are used.

2.4 Results

2.4.1 Work package results

First of all, literature research has been conducted towards technical and market aspects, as preparation for the project execution [WP 1]. Secondly, the expected flexibility has been mapped and used for drawing up the future scenario's [WP2]. Based thereon, the current central architecture and de-central architectures have been modelled and KPI's have been identified for simulating and comparing the different architectures and algorithms [WP 3 & 4].

Concretely, several simulations have been conducted based on the approaches that came from the earlier work packages and the works as specified in the 'objectives' chapter. The results of the carried-out simulations and approaches are set out below [WP 5]. Lastly, several publications have been made based on the works that were carried out [WP 6].

2.4.2 Simulation results

In work #1, we proposed a solution approach to enable the increasing adoption of heat pumps in existing dense housing areas. Data from the DSO and a local housing company have been combined to investigate the heat pump hosting capacity on a dense urban LV feeder, including realistic data on grid topology, load and heat dynamics, and practical operating characteristics of heat pumps. Our simulation compares two control strategies: (1) individual peak shaving where heat pumps are kept off when baseloads are high and (2) central optimal power flow control. We show the central optimal power flow control with end-users' thermal comfort constraints and an objective function of minimizing losses can smoothen total grid loading and lead to flat voltage profiles. This renders the approach robust against baseload forecast errors, while the individual peak shaving is more prone to such errors. Moreover, by simulating the strategies on the worst-case scenarios where heat pumps are allocated to end-users at the end of the feeder, we determine the individual peak shaving strategy can slightly increase the heat pump hosting capacity from 49% where no control is imposed to 51%, while the central optimal power flow control allows 100% heat pump connections without causing grid congestion. This translates to the fact that 18 more households can replace their gas heating with heat pumps on the LV feeder.

Based on the simulation results, we provide the following recommendations to improve the hosting capacity. The first strategy is to improve the insulation level of the households. We see that by improving insulation, the feeder can host all heat pump connections using the individual peak shaving strategy. By even better insulating the households, the feeder can handle unmanaged heat pump use due to significantly reduced energy demand. The second recommendation is to use the individual peak shaving strategy. It is determined that this strategy can host 51% heat pump connections with a working forecast and 76% when combined with an accurate baseload forecast. This highlights the importance of an accurate baseload forecast algorithm for the individual peak shaving strategy. An alternative to deploying more advanced forecast algorithms is to allow the use of real-time smart meter measurements. If the peak shaving is insufficient, the last recommendation is to use the central optimal power flow control. Although the DSO must take a more intrusive role in managing heat pumps for end-users, it does not affect the thermal comfort and freedom in demand for end-users. The strategy in the meantime resolves network congestion enabling a higher speed in the transition from gas heating to sustainable heating.

In work #2, we extended the existing online feedback controller design with fairness consideration. Due to the radial structure of distribution grids, end-users located at the end of distribution feeders experience more frequent voltage issues and contribute more to solving them. This results in uneven losses among end-users at different locations. Complementing OFO with fairness considerations alleviates an important barrier to its real-world implementation. Our fairness design is realized by modifying the input-output sensitivities and leveraging the feedback-based implementation to compensate for the modelling inaccuracy. Case studies demonstrated the effectiveness of the fairness-incorporated OFO design to handle distribution grid limits and improve fairness, in both static and dynamic simulations, with balanced and unbalanced grid models, see Figure 1. Considering its fast computation, scalability, robustness, fairness, and the fact that it does not need real-time measurements of non-controllable loads and can make full use of the grid capacity, the fairness-incorporated OFO presents itself to be a promising approach for real-time distribution grid management.

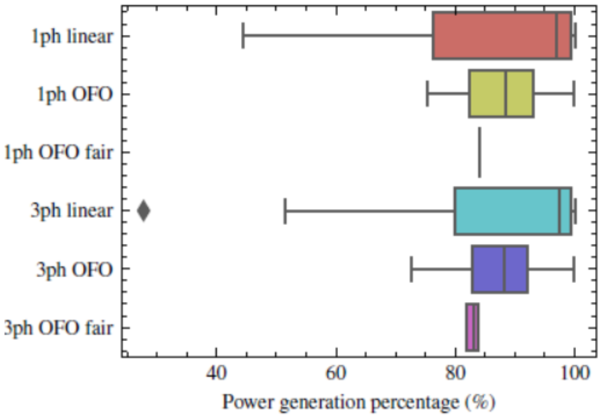

Figure 1: Distribution of active power generation percentages with different methods under single-phase and three-phase grid representations. Our proposed design shown in "1ph OFO fair" and "3ph OFO fair" leads to similar power generation percentages among end-users at different locations, which is considered fairer.

In works #3 and #4, a multi-timescale coordinated control approach was developed to address the limitation of OFO that it is only based on real-time information and does not have planning capabilities. For DERs such as batteries and EVs, a naïve application of OFO will leave their planning capabilities behind and result in an inefficient use of their energy capacity. Case studies based on a 96-bus LV grid are conducted to test the effectiveness of the proposed multi-timescale approach. In work #3, the simulation is on neighbourhood batteries. The proposed approach not only successfully manages voltage and loading issues, Figure 2 shows that the approach leads to higher PV energy harvest, which is due to its more efficient use of the existing grid capacity. In work #4, the simulation is extended to distributed battery storage units and EVs installed in individual households. Simulation results suggest satisfaction of EV demand and also slightly higher PV energy harvest. The overall approach does not require precise grid topologies or intrusive load metering, has minimum computation and communication requirements, and guarantees compliance with grid limits. These characteristics make it highly applicable to managing distribution grids.

In work #5, the focus is to examine the effectiveness and robustness of OFO under a variety of uncertainties and disturbances in distribution grids. These include inaccurate grid models, measurement noise, communication delay and failure, network reconfiguration, and generation and load fluctuations. Simulations are conducted on a 10kV 136-bus MV grid. Results suggest that OFO controllers are sufficiently robust to those disturbances except systematic communication delay. Even under a fixed delay of 1 iteration, meaning that the active and reactive power setpoints are calculated using dual variables of the previous iteration, the algorithm can diverge and become unstable. This finding provides important guidelines for the real-world implementation of OFO. Under systematic communication delays, a slower update rate is recommended to avoid asynchronous primal and dual variable updates.

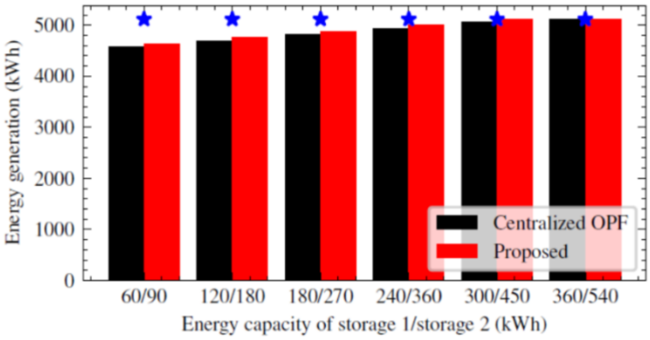

Figure 2: PV energy harvest using centralized OPF as an ideal benchmark and our proposed approach. Blue stars represent the maximum generation potential. The results indicate that the proposed approach leads to more PV energy harvest, because it can make full use of the grid capacity.

In work #6, the research focuses on the combined MV-LV network operation, making contributions to comparing control architectures and simulating the practical performance of different approaches for implementing the decentralized architecture. Based on a case study with 1 MV feeder and 3 LV networks, it is shown that the sequential, integrated, and decentralized architectures can all solve network issues, while the integrated and decentralized architecture can reduce generation curtailment by 5.7%. For implementing the decentralized architecture, several mathematical decomposition algorithms are compared.

These results provide guidelines for deploying suitable architectures for combined MV-LV network management for DSOs.

2.4.3 Key Performance Indicators

KPI	**Description**
TRL at start of project	1
TRL at end of project	4
Follow-up	Integration of results in Network operators’ operations and roadmaps; follow-up research
Amount of expected peer-reviewed publications	5 (including peer-reviewed thesis)
Amount of peer-reviewed publications	10 See page 13 for the list of publications and DOI’s
Patent requests	0
Amount of licences	0
Amount of prototypes	0
Amount of demonstrators	0
Amount of spin-offs	0
New or improved products/ processes/ services	0
Impact	See public summary

2.5 Scientific contribution

This project GEC has so far made important contributions in real-time control for distribution systems. In work #2, we identified the unfairness issue in distribution grid management. Due to their different locations in the grid, end-users contribute unequally. Specifically, end-users located towards the end of distribution feeders often receive higher losses. The proposed OFO design in work #2 addressed this unfairness issue, alleviating an important barrier to the real-world implementation of OFO as a real-time controller for distribution grid management. This work combines social science and engineering. Its scientific contribution has been recognized and it has been published in a well-known journal *IEEE Transactions on Smart Grid*.

In works #3 and #4, another barrier of OFO has been identified and resolved. Despite its excellent performance, OFO has so far mostly been applied to DERs such as PVs. For DERs such as batteries and EVs, they can not only be controlled in real time but also be planned over a longer period to schedule their energy capacity. These works developed the concept of multi-timescale optimization, which integrates offline optimization with online optimization. The performance of this design has been verified in simulation case studies. These works are currently submitted and under review.

2.6 Application perspective

Despite a research-focused project, we also aim to solve real-world problems that are happening in our distribution systems. In work #1, we collaborated with a local DSO and a social housing company to investigate the heat pump hosting capacity on a real dense urban LV feeder. Results informed them how many more heat pumps can be installed with different control methods without compromising grid safety. In works #2 to #4, we developed methodologies that address several limitations for real-time distribution grid management. These include inaccurate grid models, lack of load measurements, and unfairness. These have significantly increased the applicability of our developed methodologies for real-time distribution grid management. In work #5, we assessed the robustness of the developed methodologies under various uncertainties and disturbances in real-world scenarios, which will inform DSOs about the deployment of the developed control strategies. In work #6, we focused on different architectures for combined MV-LV network operation and quantified the benefits and losses of different architectures. This could help DSOs make well-informed decisions over architectures to manage a large area of networks of different voltage levels.

2.7 Outlook

During the implementation of the project, we have focused on real-time control and control strategies on the premises of end-users and low-voltage grids. These are recognized as the edges of grids. The development of control strategies at the grid edge is important for a bottom-up control architecture for future power systems with high amounts of renewable energy resources. In work #5, we have also considered balancing service provision in the form of tracking active power setpoints from grids of higher voltage levels. By following such setpoints, MV and LV grids can provide balancing services for high-voltage gris and transmission system operators. However, to what extent those services can help system balancing, and what kind of impact real-time control occurring in grid edge has on system balancing are still open research questions and deserve further exploration.

2.8 Conclusion

This project contributes significantly to the field of distribution grid management by demonstrating the efficacy of decentralized and real-time control strategies in enhancing the hosting capacity of DERs and ensuring the safe and equitable operation of distribution grids. The findings emphasize the transformative potential of real-time control in distribution systems, particularly in grids with high renewable energy penetration. The research underlines the need for a paradigm shift in grid management, moving towards more autonomous and decentralized systems. Looking forward, we identify the necessity for further investigations into the broader systemic impacts of these strategies, especially their role in maintaining system balance and stability in the face of fluctuating renewable inputs. The project paves the way for future explorations in Grid Edge Control, highlighting its critical importance in the transition towards more sustainable and resilient power systems. In all, the goals of the project have been reached and the project has been successfully completed.

3. Project execution

3.1 Issues and changes

No large issues have been encountered during the execution of project. The most important challenge was to find a suitable candidate. As is encountered in more projects it takes a significant period to find and select the right PhD candidate. Because of the start of the Covid pandemic it took even more time than normal. Fortunately, we were able to find a good candidate in the end. Also due to the knowledge and other skills of the candidate we were able to finalize the project almost in time and to deliver most of the results before the official end date of the project.

3.2 Changes in the projectplan

The start date of the project has been changed from 1-9-2019 to 1-9-2020, because of the issues with finding a suitable PhD candidate, as mentioned in section 3.1. The end date of the project was therefore changed from 31-8-2023 to 12-11-2023. Because of the delayed start WP5 was not completely finalized (comparison between different architectures). These changes have alle been communicated with TKI during the project.

3.3 Changes in budget

The TU/e spent less hours than expected in the project plan because of the delayed start of the PhD candidate. Most results were obtained nevertheless.

Enexis en Liander spent less hours than expected on the project. The main contributions of the network operators to the project were sharing knowledge and data, guiding the PhD student and research to maximize impact, reflection and feedback on the results and knowledge dissemination. As the PhD candidate was quite independent and pro-active, less time of the participants from the network operators was needed. Another factor that plays a role is that most participants at network operators are often not used to registration of hours, which means it is possible that some hours weren’t registered

3.4 Knowledge dissimination

The knowledge that has been obtained during the project is disseminated in several ways. The PhD student collaborated with Alliander in the Parteon project. In this project a large number of households obtained a heatpump which resulted in overloading of the network. Results of the GEC project were used to control the heatpumps in such a way that overloading could be avoided and more households could install a heatpump. The collaboration with the Parteon project shows the relevance and applicability of the results of the project.

During the regular progress meetings knowledge has been shared between the different project partners. The network operators have integrated the results in their strategies and research roadmaps. The knowledge that was obtained was implicitly also used in many discussions in the last years with all kind of stakeholders in different working groups and projects, both in the Netherlands and internationally.

Presentation on the progress and the results have been given in meetings with other PhD students and staff of the Electrical Energy Systems group and also in the 4th power grid model meet-up at Enexis. Several master and bachelor graduation and internship projects have been supervised. This also gave the opportunity for knowledge dissemination.

The main part of the knowledge dissemination was however done through a number of scientific publications. They are listed below. In chapter 2 we refer to the following 6 publications as Work #1 – Work #6 in the same order.

1. S. Zhan, T. Gu, W. van den Akker, W. Brus, A. van der Molen, and J. Morren, “Towards congestion management in distribution networks: a Dutch case study on increasing heat pump hosting capacity,” IET APSCOM, 2022.
2. S. Zhan, J. Morren, W. van den Akker, A. van der Molen, N. G. Paterakis, and J. G. Slootweg, “Fairness-incorporated online feedback optimization for real-time distribution grid management,” IEEE Trans. Smart Grid, 2023, doi: 10.1109/TSG.2023.3315481.
3. S. Zhan, J. Morren, W. van den Akker, A. van der Molen, N. G. Paterakis, and J. G. Slootweg, “Multi-timescale Coordinated Operation of Battery Storage in Distribution Grids via Profile Steering and Online Feedback Optimization,” submitted to IEEE Trans. Power Syst., pp. 1–10, 2023.
4. S. Zhan, J. Morren, A. Van Der Molen, N. G. Paterakis, and J. G. Slootweg, “Multi-timescale Coordinated Distributed Energy Resource Control Combining Local and Online Feedback Optimization,” submitted to PSCC 2024, 2023.
5. S. Zhan, J. Morren, W. van den Akker, A. van der Molen, N. G. Paterakis, and J. G. Slootweg, “Robustness assessment of online feedback optimization for congestion management and balancing service provision in distribution grids,” *under preparation*, 2023.
6. S. Zhan, J. Morren, W. van den Akker, A. van der Molen, N. G. Paterakis, and J. G. Slootweg, “Combined MV-LV power grid operation: comparing sequential, integrated, and decentralized control architectures,” IEEE SEST, 2022.

Besides these publications, some more papers have been published:

7. S. Zhan et al., “Review of recent developments in technical control approaches for voltage and congestion management in distribution networks,” IEEE PowerTech, 2023.
8. H. Zhang, S. Zhan, J. K. Koen, and N. G. Paterakis, “Hybrid local electricity market designs with distributed and hierarchical structures,” IEEE PowerTech, 2023.
9. S. Zhan, P. Hou, G. Yang, and J. Hu, “Distributionally robust chance-constrained flexibility planning for integrated energy system,” Int. J. Electr. Power Energy Syst., vol. 135, p. 107417, Feb. 2022, doi: 10.1016/J.IJEPES.2021.107417.
10. J. Li et al., “Coordinated planning of HVDCs and power-to-hydrogen supply chains for interregional renewable energy utilization,” IEEE Trans. Sustain. Energy, vol. 3029, no. 26, 2022, doi: 10.1109/TSTE.2022.3175855.