Network Exchangers for Hosting Capacity Enhancement in Low-Voltage Distribution Networks: An Australian Case Study

Achala Kumarawadu[1], M. Imran Azim[1], Mohsen Khorasany[1], Reza Razzaghi[1], and Julio Braslavsky[2]
[1]Department of Electrical and Computer Systems Engineering, Monash University, Clayton, VIC 3068, Australia
[2]CSIRO, 10 Murray Dwyer Circuit, Mayfield West, Newcastle, NSW, Australia
E-mail: achala.kumarawadu@monash.edu, imran.azim@monash.edu, mohsen.khorasany@monash.edu, reza.razzaghi@monash.edu, julio.braslavsky@csiro.au

***Abstract*—Distribution network operators face growing complexity in managing the growth of distributed energy resources (DERs) due to limited hosting capacity. Costly network upgrades are often considered the conventional solution, which can be prohibitively expensive. Hence, hosting capacity enhancement technologies are gaining interest. This paper evaluates the network exchanger (NEx), a novel grid support technology, using a realistic Australian suburban distribution network. DER uptake projections from the recent integrated system plan report of the Australian Energy Market Operator are used to generate modeling scenarios. Under the step change case in high solar conditions, 23.4% of low-voltage (LV) buses breach statutory limits, and 68% of distribution transformers exceed ratings by 2050. By contrast, only 1.07% of LV buses experience undervoltage events during the evening peak. The NEx is deployed across six LV areas, and results show it eliminates all voltage violations, reduces transformer loading, and reduces curtailment of photovoltaic systems, thereby increasing hosting capacity and deferring costly augmentation.**

***Index Terms*—Hosting Capacity, Photovoltaic, Electric Vehicles, Network Exchanger, Low-Voltage Distribution Network**

I. Introduction

The penetration of distributed energy resources (DERs) in distribution networks (DNs) is rapidly increasing due to government incentives, declining costs, and commitments to international treaties to reduce carbon emissions. Countries like Australia are undergoing a rapid energy transition required to meet net-zero targets. The integrated system plan (ISP), a transition roadmap released by the Australian Energy Market Operator (AEMO), projects the expected penetration of DERs under specific energy-transition scenarios over the coming decades. According to AEMO's 2024 ISP [1], 79% of all residential homes are expected to be equipped with rooftop solar by 2050 under the step change scenario. Similarly, electric vehicles (EVs) are expected to replace today's widely used internal combustion engine (ICE) vehicles. The current levels of rooftop solar and EVs have already created challenges for distribution network operators (DNOs) to maintain network integrity. Uncontrolled bidirectional power flows can cause issues such as voltage violations at the customer end, increased voltage imbalance, transformer and cable overloading, and fairness concerns. Non-compliance with grid codes can result in substantial penalties for DNOs, while prolonged asset overloading may cause catastrophic failures leading to significant financial losses. The term 'hosting capacity' refers to the total capacity of DERs that can be connected to a DN without breaching the prescribed network constraints [2]. The effective use of hosting capacity through DER management, as well as the development of novel technologies to increase that capacity, are active research areas aimed at alleviating pressure on already constrained DNs and avoiding costly infrastructure upgrades.

According to the Australian standard AS 4777.2:2020 for grid-connected inverter-based DERs, all new solar photovoltaic (PV) installations in Australia must be equipped with Volt–Watt and Volt–VAr automatic response modes. These control modes mitigate voltage breaches by curtailing the PV inverter output active power and providing reactive power support based on the line–neutral voltage measured at the terminals. Therefore, this is considered the business-as-usual (BAU) case in the study, while reflecting current compliance rates as observed by AEMO [3]. To improve hosting capacity utilization, Australian DNOs are offering 'flexible exports', also known as dynamic operating envelopes (DOEs), following successful trials [4]. DOEs are time-varying import and export limits computed via iterative or optimization-based approaches [5]. DOEs have demonstrated improved performance over static export limits, which can be overly conservative, and they enable the application of fairness metrics to enhance social welfare across customers. Nevertheless, research into novel technologies that enhance hosting capacity remains critical to minimizing the need for large-scale network upgrades, which are often prohibitively expensive.

This paper presents a detailed assessment of a novel grid-support technology—the network exchanger (NEx) [6], developed by Third Equation Ltd., on a realistic suburban distribution network in Brisbane, Queensland, demonstrating its potential to enhance hosting capacity in Australian distribution networks. First, the impact of DERs (rooftop PV and EVs) on the representative network is assessed by increasing DER

This work was funded by Cooperative Research Center (CRC) RACE for 2030. This research was supported by an Australian Government Research Training Program (RTP) Scholarship, the Commonwealth Scientific and Industrial Research Organization (CSIRO), Australia, and Third Equation Ltd.

979-8-3315-8138-1

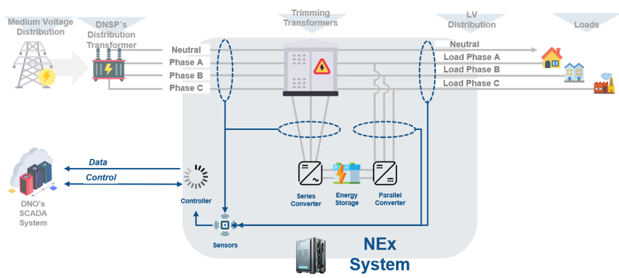

Fig. 1. Overview of the Network Exchanger.

levels in line with AEMO's ISP projections. Secondly, the NEx is evaluated to address the challenges arising from increased DER penetration.

In summary, the main contributions of this paper are

- Assessing the impact of rooftop solar and EVs on a realistic distribution network as per AEMO's ISP projections.
- Evaluating the performance of the NEx by developing a steady-state representation of the technology.

The rest of the paper is structured as follows: Section II provides an overview of the NEx and its modeling. Section III contains the methodology used for the development of DER projections. Section IV contains the results of the case studies conducted.

II. The Network Exchanger

A. Overview and modeling of the technology

The primary goal of the NEx is to enhance the existing hosting capacity of low-voltage (LV) networks through per-phase voltage regulation, current balancing, and power factor correction. Fig. 1 shows a schematic overview of the technology. The NEx consists of two power electronic subsystems: a parallel converter (PConv) and a series converter (SConv), which share a common DC link. The primary goal of the SConv is to achieve per-phase voltage regulation at the connection point by exchanging real power. The SConv is interfaced to the network through individual transformers connected in series to the converter. The PConv is used for three main functions, which are current balancing across phases (due to unbalanced loads and generation), power factor correction at the transformer terminals by providing the necessary reactive power, and maintenance of the DC link voltage by exchanging real power with the grid to ensure energy balance of the system. Real-time sensor measurements are fed to the NEx controller to determine the required converter outputs. Due to the longer simulation time observed with the dynamic NEx model [6], a steady-state version of NEx and its controller is developed. This is achieved using the quasi-dynamic simulation language (QDSL) feature in DIgSILENT PowerFactory [7], which enables users to create load-flow control algorithms. Algorithms for voltage regulation, current balancing, and power factor correction are developed as mathematical expressions within the QDSL model to replicate the NEx's steady-state behavior.

B. Modeling of the Series Converter of NEx

The SConv is primarily responsible for the voltage regulation in the LV area. Note that the SConv can independently regulate the voltage of each phase. In the developed steady-state model, this is achieved by controlling an AC voltage source for each phase within the QDSL framework. The QDSL model computes the magnitude and angle of each AC voltage source based on the control logic output. The generated voltage signal of the SConv is injected through a series transformer. The target or optimal voltage is a parameter that the operator must set based on network conditions. The required voltage magnitude output of each SConv at each control iteration can be expressed as shown in (1).

$$V^{\phi}_{SC,iter} = (V^{\phi}_{target} - V^{\phi}_{tr,iter}) \times \frac{N_{prim}}{N_{sec}} \quad \forall\, \phi \in \{a,b,c\} \tag{1}$$

Here, $V^{\phi}_{SC,iter}$ represents the voltage output of the modeled SConv of phase ϕ, V^{ϕ}_{target} represents the user-defined target voltage of phase ϕ, $V^{\phi}_{tr,iter}$ represents the voltage observed on phase ϕ of the transformer secondary terminal, N_{prim} and N_{sec} represents the number of primary and secondary windings of the series connected transformer. The voltage that can be generated at the SConv terminals is limited by NEx's actual capabilities, which are defined as 1.1 p.u. The phase angle output of each voltage source (θ^{ϕ}_{SC}) is fixed at the phase angle observed at the transformer secondary terminal of the respective phase (θ^{ϕ}_{DT}). The algorithm for controlling SConv of NEx in the QDSL modeling framework is shown in Algorithm 1. The optimal target voltage must be provided to resolve voltage events in the network. This could be achieved either by running a series of unbalanced power flows or by incorporating sensor data from customer smart meters together with an algorithm to decide the operating point. In this model, the target voltages were initially set at the nominal voltage (230 V). Line-neutral voltage measurements from the LV area for each phase (V^{ϕ}_{cust}) are fed to the QDSL model. If the maximum or minimum voltage observed in the LV network of any phase exceeds the regulatory standards, an increment or decrement of 2 V is applied to the target voltage of that phase until the voltage issue is resolved or the technical capability of the SConv is reached.

C. Modeling of the Parallel Converter of NEx

The PConv serves three main functions of the NEx: current balancing, power factor correction, and maintaining the DC link voltage. Similar to the SConv, the PConv is modeled as a controlled-voltage source in DIgSILENT PowerFactory [7] to emulate NEx's behavior. The objective of current balancing is to match the real components of current in each phase so that each phase draws equal current. The real and imaginary components of the load current with reference to the PConv connection point voltage in each phase can be expressed as shown in (2a) and (2b).

$$I^{\phi}_{real} = I^{\phi} \times cos(\theta^{\phi}_{iv}) \quad \forall\, \phi \in \{a,b,c\}, \tag{2a}$$

$$I^{\phi}_{imag} = I^{\phi} \times sin(\theta^{\phi}_{iv}) \quad \forall\, \phi \in \{a,b,c\}. \tag{2b}$$

979-8-3315-8138-1

Algorithm 1 Series Converter Model

Inputs: $SConv\_enable \in \{0, 1\}$; $V^{\phi}_{target}, V^{\phi}_{tr}, V^{\phi}_{cust}, \theta^{\phi}_{DT}$
Outputs: $V^{\phi}_{SC}, \theta^{\phi}_{SC}$

Initialize $V^{\phi}_{target} \leftarrow 1.0,\ \forall \phi \in \{a, b, c\}$
Initialize iteration counter $iter \leftarrow 0$
if $iter < maximum\ iterations$ **then**
  if $SConv\_enable$ **then**
    for all $\phi \in \{a, b, c\}$ **do**
      if $\big(\exists i : V^{\phi}_{cust,i} > 1.1\big) \land \big(\forall i : V^{\phi}_{cust,i} > 0.94\big) \land (iter > 0)$ **then**
        $V^{\phi}_{target} \leftarrow V^{\phi}_{target} - 2$
      end if
      if $\big(\exists i : V^{\phi}_{cust,i} < 0.94\big) \land \big(\forall i : V^{\phi}_{cust,i} < 1.1\big) \land (iter > 0)$ **then**
        $V^{\phi}_{target} \leftarrow V^{\phi}_{target} + 2$
      end if
      Calculate required SConv voltage for each phase using (1)
      if $V^{\phi}_{SC} > 1.1$ **then**
        $V^{\phi}_{SC} \leftarrow 1.1$
      end if
      if $V^{\phi}_{SC} < -1.1$ **then**
        $V^{\phi}_{SC} \leftarrow -1.1$
      end if
      $\theta^{\phi}_{SC} \leftarrow \theta^{\phi}_{DT}$
    end for
  else
    for all $\phi \in \{a, b, c\}$ **do**
      $V^{\phi}_{SC} \leftarrow 0$
      $\theta^{\phi}_{SC} \leftarrow \theta^{\phi}_{DT}$
    end for
  end if
end if
$iter \leftarrow iter + 1$

Here, I^{ϕ}_{real} is the real component of the load current of phase ϕ, I^{ϕ} is the current magnitude of phase ϕ, θ^{ϕ}_{iv} is the difference between the current and voltage angles of phase ϕ, and I^{ϕ}_{imag} is the imaginary component of the current of phase ϕ.

To maintain the DC link voltage during SConv operation, the PConv must inject or absorb active power from the grid. The average real power exchange of the SConv is therefore calculated as shown in (3).

$$P^{avg}_{SC} = \frac{P^{a}_{SC} + P^{b}_{SC} + P^{c}_{SC}}{3} \tag{3}$$

Here, P^{a}_{SC}, P^{b}_{SC}, and P^{c}_{SC} are the active power exchanges of the phases a, b, and c, respectively.

If power factor correction functionality is enabled, the required reactive component of the current flowing by the PConv of each phase (I^{ϕ}_{q}) is the negative value of the calculated I^{ϕ}_{imag}. For the current balancing functionality to operate successfully, the transformer terminals of each phase must draw equal currents. The PConv then matches the load current required for each phase. This means that several phases could draw higher or lower currents than required, depending on the level of current imbalance at the transformer terminals. To achieve current balancing, the PConv ensures that the transformer terminal currents are equal. The mean real component of current (I_{dx}) across all three phases can be expressed as shown in (4).

$$I_{dx} = \frac{1}{3} \sum_{\phi \in \{a,b,c\}} I^{\phi}_{real} \tag{4}$$

The corresponding correction current (I^{ϕ}_{d}) required in each phase is calculated according to (5).

$$I^{\phi}_{d} = I_{dx} - I^{\phi}_{real} \tag{5}$$

The required voltage components of the PConv, expressed relative to the point of common coupling (PCC) voltage angle, and assuming current direction into the converter, are obtained as shown in (6a) and (6b).

$$V^{\phi}_{imag} = \left(\frac{-P^{avg}_{SC}}{V^{\phi}_{pcc}} - I^{\phi}_{d} \right) X \quad \forall \phi \in \{a, b, c\}, \tag{6a}$$

$$V^{\phi}_{real} = V^{\phi}_{pcc} + X I^{\phi}_{q} \quad \forall \phi \in \{a, b, c\}. \tag{6b}$$

Here, V^{ϕ}_{pcc} is the PCC voltage magnitude of phase ϕ and X denotes the filter reactance. From these components, the required PConv voltage magnitude and angle are calculated as shown in (7a) and (7b).

$$V^{\phi}_{PC,mag} = \sqrt{(V^{\phi}_{imag})^2 + (V^{\phi}_{real})^2} \quad \forall \phi \in \{a, b, c\}, \tag{7a}$$

$$V^{\phi}_{PC,\theta} = tan^{-1}\left(\frac{V^{\phi}_{imag}}{V^{\phi}_{real}}\right) \quad \forall \phi \in \{a, b, c\}. \tag{7b}$$

Since the operating phase angle has been calculated with reference to the voltage angle at the connection point, the phase angle of the voltage source is re-evaluated with respect to the actual voltage angle observed at the connection point of the PConv ($V^{\phi}_{pcc,\theta}$) of each phase as shown in (7c).

$$V^{\phi}_{PC,\theta} = V^{\phi}_{PC,\theta} + V^{\phi}_{pcc,\theta} \quad \forall \phi \in \{a, b, c\} \tag{7c}$$

III. DER PROJECTIONS AND CHARACTERISTICS

The uptake of PV systems and EVs under the progressive change (PC) and step change (SC) energy-transition scenarios is calculated per household in Queensland for each financial year. The distribution network model adopted from [8] supplies 13,535 residential customers spread across 229 LV areas, as well as 785 commercial and industrial (C&I) customers. The current network model consists of 5,338 PV systems with a total rated capacity of approximately 27 MW, equipped with Volt-Watt and Volt-Var functions, in line with their commissioning dates and the applicable standards at that time. The distributed PV projections relevant to Queensland are obtained from the ISP for each financial year [1]. These projections are disaggregated into residential and small-scale business sectors using an average residential capacity ratio of 0.83, calculated

979-8-3315-8138-1

Fig. 2. Topological overview of the distribution network [8].

from [9]. The number of residential dwellings in Queensland is obtained from the Australian Bureau of Statistics (ABS) and extrapolated using population growth rates for each scenario (1.3% for SC, 1.1% for PC [10]). Using data from [9] on the share of separate dwellings over time, the number of separate dwellings (most likely to host PV systems) is calculated for each financial year. The average residential PV capacity is then calculated by dividing the total residential PV capacity by the number of separate dwellings for each scenario. The calculated projections are shown in fig. 3. The baseline capacity for small-scale business PVs in the model was rescaled each year to reflect the annual increase in Queensland's total rooftop PV under the relevant scenario, while decoupling the impact of population growth.

According to recent transport census data, the average number of motor vehicles per household is 1.8. Similar to the PV projections, the average number of EVs per household was calculated for each financial year using this statistic together with data from [10], which provides the expected share of EVs in the overall vehicle market over time (as EVs replace ICE vehicles) for each scenario. Future versions of the network model are constructed at 5-year intervals for each scenario to reflect the calculated average PV and EV penetrations. New PVs and EVs are added via iterative random selection of existing customers until average capacities are achieved for each study year. New PV installations are assumed to be 8 kW across the study horizon. EV owners are assumed to use AC chargers rated at 3.68 kW (single-phase) or 7.36 kW (three-phase), with a maximum of two EVs per customer. Diversified EV charging curves (weekday) are adopted from [11] to determine the number of EVs charging at each time step, thereby reflecting diversified charging behavior (i.e., not all EVs charge simultaneously).

IV. RESULTS

A. *Impact of DER growth*

Time-series simulations are conducted for each half-hour period from the present year 2025 to the projected year 2050 for the PC and SC scenarios in DIgSILENT PowerFactory [7]. To highlight the greatest impact of PV uptake, the simulation results focus on noon during spring (which has lower loading levels than summer). Similarly, to capture the highest impact

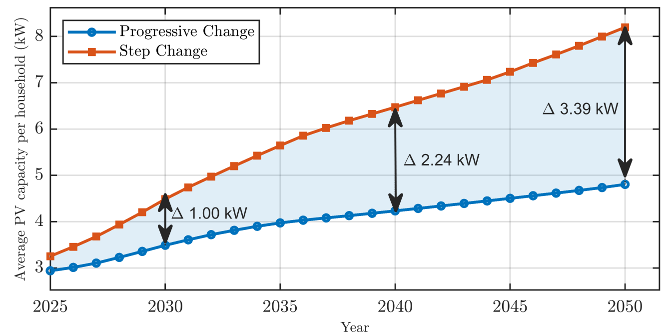

Fig. 3. Projections for average PV capacity per household across Queensland.

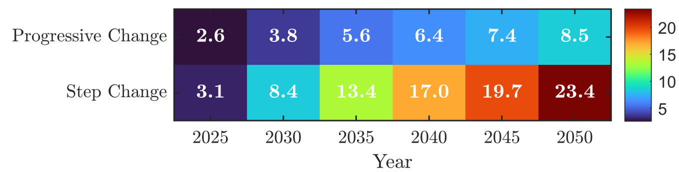

Fig. 4. Proportion of LV buses (%) with maximum phase voltage exceeding the upper voltage limit during spring at midday under high solar conditions.

from EVs, the evening peak is considered. Fig. 4 shows the fraction of LV buses in the DN with a maximum phase voltage higher than the threshold during spring at noon. In the PC scenario, 8.5% of LV buses exceed the limit (253 V) by 2050, increasing to 23.4% under the SC scenario. In terms of energy curtailed due to AS 4777.2:2020, 2.1% and 4.39% of energy are wasted during the half-hour period at midday in spring under the PC and SC scenarios, respectively. Although the impact appears limited, the curtailment is spread unevenly among PV owners. Fig. 5 shows several percentiles of curtailment among PVs during spring at midday in the SC scenario, which illustrates this phenomenon. The impact on transformer loading levels is also significant: approximately 29% and 68% of all transformers in the DN exceed 100% loading by 2050 under the PC and SC scenarios, respectively. Furthermore, approximately 5.8% of both MV and LV cables exceed their rated capacity by 2050 in the SC scenario, indicating that large-scale network upgrades would be necessary under BAU conditions. An increased voltage imbalance is also observed throughout the investigated years. The impact of EVs on DN voltage is found to be insignificant compared to PV systems. Only 1.07% of all LV buses exceeded the lower voltage limit (216 V) during the evening peak in summer (with higher loading levels than in other seasons) under the SC scenario. This is attributed to the diversified EV charging curves used in this work, which replicate a realistic distribution of EVs charging over similar time intervals. Furthermore, the OLTCs installed at the zone substation help improve voltage levels during this period. However, 23.14% of the transformers exceeded their rated capacity during this period, highlighting the need for upgrades under BAU conditions.

B. *Evaluation of NEx*

To investigate the performance of the NEx, the year 2035 is chosen under an SC scenario. Six different LV areas (denoted

979-8-3315-8138-1

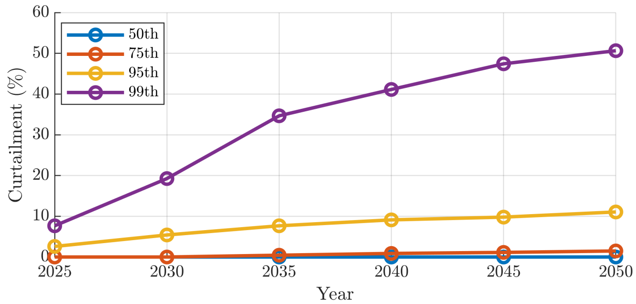

Fig. 5. Percentiles of curtailment (%) observed among PVs during spring at midday under high solar conditions in a SC scenario.

TABLE I
COMPARISON OF VOLTAGE LIMIT VIOLATIONS AND CURTAILMENT ACROSS THE HALF-HOUR PERIOD AT NOON DURING SPRING.

LV area	BAU - VV (%)	NEx - VV (%)	BAU - Curtailment (kWh)	NEx - Curtailment (kWh)
A	83.2	0.0	23.5	0.5
B	88.0	0.0	24.5	0.0
C	72.2	0.0	16.9	2.5
D	27.8	0.0	14.0	1.1
E	51.6	0.0	15.0	0.4
F	73.1	0.0	14.2	0.6
Total	62.9	0.0	108.1	5.1

by A-F) that exhibited significant voltage issues, higher curtailment, and loading levels were chosen for analysis. Simulations are conducted under BAU conditions, and with the integration of the NEx. Table I shows the voltage limit violations (VV) and the energy curtailed from PV systems across the half-hour period at noon during spring in each LV area. The NEx was able to resolve all voltage limit violations in the investigated LV areas while minimizing the energy curtailment of PVs significantly. The curtailment observed with the integration of NEx is due to the necessity of providing reactive power as per AS 4777.2:2020. As NEx is integrated at the start of LV circuits, it provides a broader network-wide voltage improvement in the presence of multiple circuits in the LV DN. The other significant advantage of the NEx is its ability to perform per-phase voltage regulation, which is advantageous in highly unbalanced DNs. For instance, on-load tap changers can perform only a uniform upward or downward voltage change, which affects all 3 phases of the DN and could be disadvantageous in unbalanced scenarios.

Significant reductions in transformer loading levels are also observed with the integration of the NEx, with effective use of transformer capacity, as demonstrated in fig. 6. Three mechanisms explain the reduction enabled by NEx: (i) current balancing that equalizes phase currents and alleviates asymmetrical phase loading, (ii) voltage-profile improvement that reduces reactive power absorbed by inverters, thus reducing associated current, and (iii) transformer-side power factor correction achieved by supplying reactive power locally, sustaining unity power factor. Together, these functions yield a substantial reduction in transformer loading in the examined LV networks, potentially delaying network augmentation.

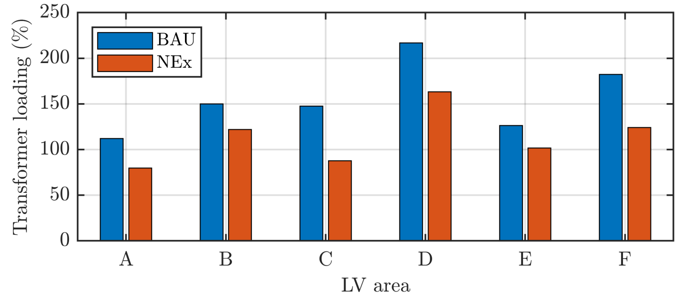

Fig. 6. Comparison of transformer loading levels with the integration of NEx at noon during spring.

V. CONCLUSION

This paper has investigated the performance of a novel technology, the NEx, in enhancing the hosting capacity of DNs. The analysis has been conducted on a realistic DN in Brisbane developed using SCADA measurement data. The PV and EV projections have first been generated per-household from ISP data and integrated into the existing network model. Challenges arising from expected DER growth—especially high PV penetration—have been observed in the simulation results, including voltage violations, increased transformer and line loading, voltage imbalance, and fairness issues. The NEx has effectively resolved voltage violations, reduced transformer loading and PV curtailment, demonstrating its effectiveness in addressing the challenges posed by increased DER penetration levels. Experimental validation has also been conducted in the laboratory, confirming the device's three main functionalities under realistic network conditions. Due to its demonstrated ability, the adoption of novel technologies such as the NEx would be a preferred option for DNOs to address DN challenges.

REFERENCES

[1] AEMO, 2024 Integrated System Plan (ISP), Australian Energy Market Operator, 2024, [Online]. Available: https://www.aemo.com.au/energy-systems/major-publications/integrated-system-plan-isp/2024-integrated-system-plan-isp.

[2] L. Blackhall, On the calculation and use of dynamic operating envelopes, Evolve Project M4 Knowledge Sharing Report (2020).

[3] AEMO, Compliance of Distributed Energy Resources with Technical Settings: Update, Tech. rep. (2023).

[4] L. O'Neil, L. Reedman, J. Braslavsky, T. Brinsmead, C. McDonald, A. Ward, B. Williams, Analysis of the VPP dynamic network constraint management (May 2021).

[5] A. Kumarawadu, M. I. Azim, M. Khorasany, R. Razzaghi, R. Heidari, Smart meter data-driven dynamic operating envelopes for DERs, Applied Energy 384 (2025) 125469.

[6] R. Razzaghi, B. Bahrani, A. Kumarawadu, A. Asbafkan, P. Blackburn, V. Moreno, Assessing the impact of Network Exchanger (NEx) on power quality in distribution networks. Prepared for RACE for 2030 (2025).

[7] DIgSILENT GmbH, "DIgSILENT PowerFactory", ver. 2023 , Gomaringen, Germany , [Online]. Available: https://www.digsilent.de.

[8] R. Razzaghi, E. Burstinghaus, Y. Gerdroodbari, M. Hibbert, J. Liu, Investigation into Voltage Management Technologies for Future Australian Suburban Distribution Networks.Prepared for RACE for 2030 (2023).

[9] CSIRO, Small-scale solar PV and battery projections 2024 (2024).

[10] CSIRO, Electric vehicle projections 2024 (2025).

[11] W. J. Nacmanson, J. Zhu, L. N. Ochoa, Milestone 8: EV Management and Time-of-Use Tariff Profiles, Tech. rep., The University of Melbourne (2022).

979-8-3315-8138-1