Topic 8 – Distributed Energy Resources (DERs)

2024/25 DOE export limit quantification for individual customers, incorporating Volt-var/Watt response

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1 Introduction

1.1 Background

This report provides an overview of the project titled "Dynamic Operating Envelope (DOE) export limit quantification incorporating Volt-var/Watt response," currently undertaken by GridQube in collaboration with CSIRO. The project is funded by CSIRO as part of Stage 4 of the "Australian Research for Global Power Systems Transformation (G-PST)". This report also highlights the significance of this project for Australia's energy transition and its global implications. Lastly, it provides recommendations for future activities and research areas in Topic 8 – Distributed Energy Resources (DER).

Australia leads in rooftop solar photovoltaic (PV) adoption, with more than one-third of households equipped with PV systems [1]. To prevent local network congestion resulting from the increasing adoption of solar PV by customers, Distribution Network Service Providers (DNSPs) in Australia have implemented measures to limit the amount of solar energy households can generate and export to the grid. Traditionally, these export limits, enforced through network connection agreements, have been static, with some DNSPs setting limits as low as 1.5kW [2].

To better accommodate the growth of solar PV and its effects on network system security, DNSPs are moving from static export limits, which are inherently conservative by design, to flexible connection agreements known as DOEs. These DOEs manage bidirectional power flows while preserving infrastructure integrity, i.e. operating the network within the combined thermal and technical envelopes. DOEs account for the temporal nature of network constraints, limiting customer exports only during specific periods of network congestion while allowing greater PV injection when the network isn't congested.

DOEs effectively project the network's operational envelopes to the customer connection point, given an understanding of the state (loading) of the network. In recent years, progress has been made to tailor DOEs to individual customers, with varying trade-offs between ensuring fair treatment to customers and achieving competitive outcomes.

Volt-Watt and Volt-var are advanced inverter functions required by the AS/NZS 4777.2:2020 standard, which governs grid connection requirements for inverters in Australia [3]. These mandatory Volt-Watt and Volt-var requirements on PV inverters can limit the full utilization of calculated DOEs by flexible customers. These requirements may curtail PV generation due to voltage constraints, even when a generous DOE is available, thereby reducing the services that aggregators can provide to Australian Energy Market Operator (AEMO). It is crucial to identify scenarios where PV inverter requirements align with DOEs and those where conflicts arise. This issue is significant for multiple stakeholders, including DNSPs, AEMO, and end users.

1.2 Scope of the work in FY 2024-2025

Current DOE quantification methods have several shortcomings: they do not yield individualised export limits for customers; they may rely on inaccurate, unvalidated network data and therefore create biased outcomes; they ignore the response of behind-the-meter resources [4] [5] [6].

Smart inverters and active filters can have specialised control loops, to support inter-phase power exchange, unbalanced reactive power set points, and harmonic compensation. These kinds of models can be integrated into physics-based network optimisation frameworks.

Optimisation models are an intuitive way to formulate the following distribution network questions:

- What is the maximum load I can place at this location in the network before the customer experiences undervoltage?
- What is the maximum demand the network can supply before hitting overcurrent?
- What is the maximum aggregate PV injection the network can accommodate before anyone experiences over-voltage?

Simulation-only models can be used (partially) to give answers to these questions, but they require iteration [7] [8]. For example, such models establish a base case scenario for the loads, simulate the network, validate compliance with network limits, and---if still within limits---increase the load. This iteration itself is an algorithm, functioning as an outer loop around an existing implementation of a simulation engine. Optimisation models, when used in conjunction with advanced numerical algorithms, don't necessarily have to go through the same series of steps of increasing the load until the network limits are hit, but can find the extreme points more directly and efficiently [9] [10].

Four-wire Unbalanced Optimal Power Flow (UBOPF) serves as the framework for optimisation models constrained by the "distribution network physics" [11] [12]. UBOPF represents the steady-state AC multiconductor version of Kirchhoff's circuit laws, thereby capturing electrical phenomena such as phase unbalance and neutral voltage shift. Phase unbalance necessitates the use of matrices, rather than scalars, for line impedances, as well as the phase connectivity between power delivery elements, and the phase connectivity of loads and generators. Analysis of network services, such as voltage regulation, benefit from detailed models of network physics. This includes the consideration of mutual inductance between conductors carrying unbalanced currents and the ability of inverters to control current independently across phases.

To address the challenges previously discussed, we aim to improve existing DOE quantification methods in the following ways:

- use state-of-the-art four-wire optimisation frameworks as the foundation;
- represent smart inverter response as part of such framework;
- yield customer-specific DOEs and explore trade-offs in fairness and competitiveness in the context of imperfect information, such as noise and errors in data.

The goal of this research is to develop a quantification approach that accurately models the physics of the network and its voltage/current/power limits, while taking into account customer energy resources and their expected responses.

2 Research completed

A summary of the work conducted to date:

- Conducted a literature review on the state-of-the-art DOE quantification methods, with a focus on simulation-based versus optimisation-based approaches.
- Developed interactive (code) notebooks to educate on the effectiveness of Volt-var/Watt control, building on OpenDSSDirect (*see Figure 1*).
- Implemented mathematical models for finding DOE export limits on top of four-wire UBOPF with volt-var/Watt response for inverters. This was done in Julia using JuMP and PowerModelsDistribution (a Julia/JuMP-based package), with the open-source nonlinear optimisation solver Ipopt employed throughout.
- Implemented objective functions for determining DOEs, including maximum competitive export, maximum equal export, and various "fairness" trade-offs.
- Tested DOE functions using example feeders adapted from ENWL - Low Voltage Network Solutions project.
- Set up a repository for final code release, i.e. **https://github.com/frederikgeth/GPSTTopic82024**, which is used for version control and continuous integration between the two organisations.
- Set up an Overleaf project to document the work in progress.
- Performed network data parsing, conversion and cleaning for CMA9A, a feeder that will be kindly made publicly available thanks to Energy Queensland (EQL).
- Submitted a paper abstract to the 28th Conference and Exhibition on Electricity Distribution (CIRED 2025) and got it accepted for full paper submission. The full paper is currently under preparation and is expected to be completed by mid-January.
- Implemented quality control processes for the coding, i.e. automatic unit testing using continuous integration on the issue tracker.
- Fred launched a new initiative (approved in November 2024) within the IEEE Power and Energy Society, AMPS (Technical Committee on Analytic Methods for Power Systems), i.e. the *Taskforce on Distribution Network Optimisation Benchmarking,* which he will be leading together with Matthew Deakin (University of Newcastle, UK) and Amrit Pandey (University of Vermont). This platform can be used to further the dissemination of the network data sets cleaned up as part of this activity.

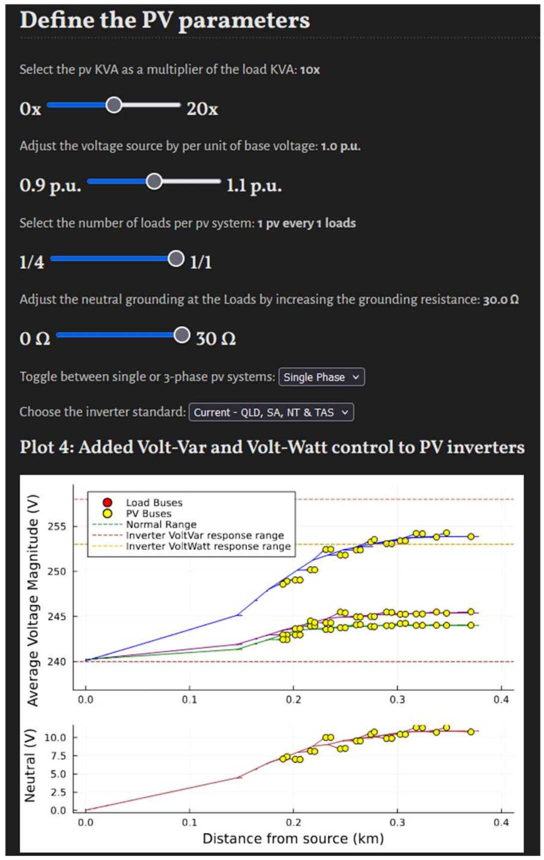

Figure 1. Screenshot from interactive Pluto.jl Notebook

3 Outstanding activities

- Further numerical studies need to be performed based on the real-world EQL network models. During development we prioritized working with publicly available clean network data to avoid any delays caused by the cleaning process of real-world data.
- Assessing sensitivity of the DOE quantification approach and the fairness outcomes to the presence of noise and errors in data.
- Full paper submission for CIRED 2025 (due in late January), with presentation in June if accepted.
- Preparation of the final report, presentation and a public webinar.
- Final public release of the real-world feeder data (with permission from EQL), project code, and notebooks.

4 Progress against the Roadmap

RQ0.1 What data flows (DER specs, measurements, forecasts, etc.) are needed to ensure AEMO has enough DER/net demand visibility to adequately operate a DER-rich system in different time scales (mins to hours)?

This project partially addresses this question by demonstrating that DOEs can be quantified across MV feeders down to individual customers. This provides AEMO with insights into the extent to which behind-the-meter DERs can be utilised through aggregators. AEMO can use this information to estimate the minimum demand on a given area and help with forecasts at higher voltage levels.

RQ1.3 What is the role of DER standards in concert with the future orchestration of DERs?

This project utilises the most current Australian Standard for inverters, specifically incorporating the Volt-Watt and Volt-var functions, with priority given to Volt-var as outlined in the standard.

RQ4.1 What are the minimum requirements for a DER-rich distribution network equivalent model to be adequate for its use in system planning studies?

Similar to RQ0.1, the ability to estimate DOEs across a broad area (e.g., sub 33kV feeders down to individual customers) can assist AEMO in understanding the impact of DERs based on how aggregators utilise behind-the-meter resources. This could in turn support AEMO in developing equivalent models to represent active distribution networks.

RQ5.1 What are the necessary organisational and regulatory changes to enable the provisioning of ancillary services from DERs?

DOEs are meant to be calculated by DNSPs and are largely focused on projecting the statutory voltage limits, as well as the thermal limits of lines/cables/transformers to the end customer. However, the concept of DOEs can also be applied at the TNSP-DNSP interface.

5 Research relevance to Australia

The orchestration of DERs can enable every household in Australia to have solar PV and electric vehicles, supporting the nation in meeting its 2030 renewable energy targets in a cost-effective manner. The concept of DOEs is being adopted in Australia to manage DERs while maintaining network integrity by providing time-varying export and import limits at the customer's connection point. The Australian Energy Regulator (AER) has approved the export component of DOEs for customers opting for variable flexible export limits, and some DNSPs (e.g., Energex and SA Power Networks) are already offering this new type of connection [13] [14].

DNSPs will use different approaches to calculate and allocate DOEs based on data availability and quality, which varies widely, especially in residential low-voltage networks. By pushing the boundaries of state of the art in terms of modelling capability in this research, we aim to improve the understanding of the full potential achievable through DOE deployments. Our work informs on the validity of approximations in modelling and consequences of inaccuracies in data. Such inaccuracies or inadequacies can result in structural bias with respect to the export limits of certain customers, potentially exacerbating unfair outcomes in practice, through rushed deployments. Therefore, through this work, we inform on policy related to DOE rollout and the necessity of standardising approaches across Australia. Additionally, the developed approach is computationally feasible, making it suitable for use as the underlying tech in field deployments.

The assessments and recommendations from this project will support DNSPs, AEMO, and other decision-makers in developing and adopting appropriate DOEs, ensuring network integrity, optimal DER utilisation, and minimal customer impact. The knowledge gained from this project is valuable on a global scale, as DER adoption continues to rise worldwide. Australia is well-positioned to share its learnings and lead international collaborations, contributing to the global energy transition.

6 Recommended research priorities

Improving the representation of voltage management in DOEs

Tap changers and STATCOMs also change the voltage profile in the distribution network significantly. Therefore, DOE quantification methods should take the controllability of these devices into account. For instance, if the tap changer boosts the voltage, more curtailment due to Volt-var/Watt will occur. DOE quantification methods can be improved to simultaneously to determine the tap settings that maximise the DOE limits. Additionally, for three-phase inverters, there are existing shortcomings in the standards for Volt-var/Watt that are expected to be resolved soon and will need to be incorporated into the DOE quantification going forward.

Improving automatic calibration of network models

Power system simulation software generally operates on the principle of "garbage in, garbage out". This means that the accuracy and reliability of the results depend heavily on the quality of the input data. Data quality issues in network data are well known, and expensive to fix manually. However, with smart meter deployments becoming more universal, there is an opportunity to automatically calibrate network models based on such data. Specifically, smart meters can help in automatically identifying and tagging inconsistencies in network topology, improving the accuracy of network models without the need for manual intervention.

Network planning methods taking the presence of DOEs into account

The scope and depth of network planning scenarios has increased from traditional peak demand scenarios to include minimum system demand and underlying demand [15]. Future planning will also need to account for DOEs and how they operate under each of these scenarios. More research is needed to improve planning methods and make it easier for DNSPs to accurately consider all future network conditions.

Informing on DOE market integration and policy

Real-world DOE deployments will eventually be integrated into the power markets, to enable the aggregators to understand the flexibility of their customers subject to DOEs. DOE forecasting in this context is likely to become a requirement too. The compatibility/complementarity of DOEs with distribution flex markets or technical orchestration is also an open topic that warrants further research.

Trade-offs between fairness and competitiveness can be tailored, but eventually, a specific choice needs to be made on how the different aspects are weighted in the context of customer network access. Furthermore, application of DOEs to import limits requires framing flexible and inflexible demand and controllability. Finally, to enable the AER to track DOE outcomes for customers, metrics can be developed to enable outcome-based benchmarking of different DOE designs and implementations.

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