Project MATCH
Knowledge Sharing Report 2: 2022-23

Lead organisation: University of New South Wales (UNSW)

Project partners: AEMO, Solar Analytics

Project commencement date: 20 January 2021

Project completion date: 29 March 2024

Project information: https://arena.gov.au/projects/project-match/

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This project received funding from the Australian Renewable Energy Agency (ARENA) as part of ARENA's Advancing Renewables Program. The views expressed herein are not necessarily the views of the Australian Government. The Australian Government does not accept responsibility for any information or advice contained within this document.

Contents

Glossary

Term	Definition
AC	Alternating Current
AEMC	Australian Energy Market Commission
AEMO	Australian Energy Market Operator
AEST	Australian Eastern Standard Time
APVI	Australian PV Institute
ARENA	Australian Renewable Energy Agency
AS/NZS 4777.2	Australian/New Zealand Standard for low-voltage inverters. Several versions published (2005, 2015 and 2020). Latest version: AS/NZS 4777.2:2020.
ASEFS	Australian Solar Energy Forecasting System
BESS	Battery Energy Storage System(s)
CEC	Clean Energy Council
CER	Clean Energy Regulator
DER	Distributed Energy Resources
DERDAT	Distributed Energy Resources Disturbance Analysis Tool
DNSP	Distribution Network Service Provider
DPV	Distributed Solar Photovoltaics
DUID	Data unit identifier
EQL	Energy Queensland
FCAS	Frequency Control Ancillary Services
FCASVT	FCAS Verification Tool
F-W	Frequency-Watt
GLM	Generalised Linear Model
GPS	Global Positioning System
GW	Gigawatts
ISP	Integrated System Plan
MATCH	Monitoring and Analysis Toolbox for Compliance in a High DER future
MASS	Market Ancillary Service Specification
MSO	Model standing offer(s)
NED	Not enough data
NEM	National Electricity Market
NER	National Electricity Rules
NOFB	Normal Operating Frequency Band
OEM	Original Equipment Manufacturer
PQ	Power quality
PSCAD	Power Systems Computer-Aided Design
PSSE	Power System Simulator for Engineering
PV	Solar Photovoltaics
QNI	Queensland-New South Wales Interconnector
RIS	Renewable Integration Study

Term	Definition
RoCoF	Rate of Change of Frequency
SAPN	SA Power Networks
SoC	State of Charge
SRES	Small-scale Renewable Energy Scheme
SRG	Stakeholder Reference Group
UFLS	Under Frequency Load Shedding
UI	User Interface
UNSW	University of New South Wales
VAr	Volt-Ampere Reactive
VARMA	Volt-VAr Response Mode Analysis
V-Var	Volt-VAr
VDRT	Voltage Disturbance Ride-Through
VPP	Virtual Power Plant
WEM	Wholesale Electricity Market

Executive summary

Background

Distributed Energy Resources (DER)[1] such as distributed solar photovoltaics (DPV) and battery energy storage systems (BESS) are contributing significantly to the Australian power system. When taken in aggregate, DPV now represents the single largest generator in the National Electricity Market and substantial deployment of DER by energy users is forecast to continue (see section 1.1). The deployment of DPV has been a key contributor to the decarbonisation of the Australian power system.

The shift to an increasingly distributed, inverter-based power system is significant, and DER offer both opportunities and challenges for maintaining power system security.

Specifically, maintaining power system security under very high levels of DER operation requires disturbance ride-through capabilities to be widely adopted across the DER fleet. These ride-through functions – in addition to important power quality response functions – are defined in the standard AS/NZS4777.2:2020 *Grid connection of energy systems via inverters, Part 2: Inverter requirements* ('the 2020 Standard'). It is critical that there is compliance to the 2020 Standard in the field going forward.

Project MATCH

Project MATCH (Monitoring and Analysis Toolbox for Compliance in a High DER future) commenced in January 2021 and is scheduled to conclude in 2024. The project is led by UNSW Sydney in close collaboration with the Australian Energy Market Operator (AEMO) and Solar Analytics.

The objective of Project MATCH is to **establish robust characterisation of DER during power system disturbances using data driven tools**, to support a safe, secure and reliable power system with high levels of DER.

It is a desktop study that has provided foundational datasets, tools and evidence to industry, to support DER integration initiatives regarding power system security, including:

- An improved range of **data streams** to support robust analysis (section 3),
- Improved **tools and techniques** for data driven analysis of DER installed in the field (section 2.2), and
- Improved **understanding** of DER fleet behaviour during disturbance events (section 2.1), including DER compliance with AS4777.2 (section 2.3).

Collaboration with a diverse range of industry stakeholders has formed a core component of the Project. There are 42 organisations in the Project MATCH Stakeholder Reference Group and 25 stakeholders have provided real-world datasets over the course of the project. The Project team is very appreciative to all stakeholders for their engagement.

This report summarises lessons learnt, and collates key investigations. Whilst significant progress has been achieved over the course of the project, efforts to improve access to data, tools for analysis and overall understanding of DER behaviour in the field are ongoing. Project MATCH has provided a valuable opportunity for pioneering new analysis techniques, which are now being transitioned into industry operational practice.

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[1] The acronym 'DER' is used throughout this report, however it is noted that 'Consumer Energy Resources' or CER is widely used within the Australian industry to encompass a similar range of technologies.

Solar Analytics data capture triggers

Solar Analytics further developed its data capture systems to collect high resolution (5s) data during disturbance events, whilst minimising data costs overall. The refined triggers are defined in section 3.

Key findings

Compliance assessment

A core goal of Project MATCH was to assess compliance rates in the field with the 2020 Standard. The functionalities defined in this standard are critical to maintaining power system security under very high levels of DER, and therefore understanding compliance rates is important to AEMO, as well as the broader industry.

Prior work focused on analysing DER performance during disturbance events to assess compliance and the performance of power quality response modes such as Volt-VAr performance in the field.

Project MATCH found that it was possible to assess compliance at install (e.g. whether an installer had correctly selected a 2020 Standard grid code) using datasets provided by inverter Original Equipment Manufacturers (OEMs). Analysis in early 2022 found that **compliance was only around 40% for new installs in Q1 2022** at the time of installation. This evidence supported actions to improve compliance with **significant improvement to ~75-80% compliance with the 2020 Standard for new installations in Q1-Q2 2023** (section 2.3). The actions taken by OEMs were found to be highly influential. Analysis will be published in a forthcoming report[2].

Consideration of compliance is complex, with different 'types' of compliance able to be assessed using a variety of methods and datasets (section 4.1.1) and consideration of governance arrangements into the future is critical (section 4.3).

Disturbance events

Contributions were made to seven incident reports (see section 2.1 for links), including two highly significant power system disturbance events:

- 25 May 2021 'Callide event' in which there was significant Under Frequency Load Shedding (UFLS) in Queensland and some UFLS in New South Wales.
- 12 November 2022 separation of South Australia and subsequent week of island operation, during which DPV was curtailed in order to maintain power system security.

Analysis of the 12 November 2022 events is ongoing, with further work to understand impacts of the emergency backstop measure Enhanced Voltage Management (EVM) on Virtual Power Plants (VPPs).

Datasets

Project MATCH is underpinned by the array of valuable datasets. As noted above, 25 stakeholder organisations have provided datasets over the course of the project, for which the project team are deeply appreciative. Six types of data have been analysed to date within the project:

- Operational timeseries datasets (1s-5min time increments) for PV, BESS and load
- Metadata to support the operational timeseries data e.g. including postcode
- Error/response codes
- Inverter standard/grid code selected at installation

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[2] To be made available here: https://aemo.com.au/en/initiatives/major-programs/nem-distributed-energy-resources-der-program/standards-and-connections/compliance-of-der-with-technical-settings

- DNSP compliance analysis outputs
- DNSP power quality monitoring data

The diverse and multiple datasets are critical for the project as they provide a broader view of events and allow comparison and validation with each other.

We acknowledge the complexities in providing these datasets to the project including the cost involved in collecting, storing and sharing data, as well as management of privacy concerns, and time taken to answer the project team's questions so that we could analyse the data appropriately.

We would like to extend our gratitude and appreciation to those that have contributed. Thank you!

Challenges remain regarding the ongoing availability and suitability of operational data for analysis of DER behaviours during disturbance events. This is a key area for future work (section 4.1.2).

Analysis tools

Significant uplift to the DER Disturbance Analysis Tool (DERDAT) was completed over the course of the project (summarised in section 2.2). DERDAT is currently being used by AEMO as part of its post-event analysis into DER behaviours. A new VPP FCAS analysis tool was also developed over the course of Project MATCH[3]

As noted in section 4.2, open-source tools provide important transparency, which is likely to be valuable for maintaining a collaborative industry environment.

Recommendations and future work

The work undertaken through Project MATCH has provided timely insights and supported action to improve compliance in the field with the 2020 Standard.

However there remains much to be done. As detailed in section 4, it is recommended that efforts continue to:

- Build an evidence base of DER performance during disturbance events and compliance in the field to support appropriate operational, policy and regulatory decision making,
- Improve records of DER installations, retirements and upgrades,
- Bring together stakeholders with different backgrounds to discuss challenges and share evidence of DER behaviour in the field as a basis for decision making,
- Build consensus between industry stakeholders, to support the availability of consistent and complete information for energy users.

The Project MATCH team also add to the chorus of voices supporting the development of appropriate DER governance arrangements, particularly regarding technical requirements.

Further recommendations to support continued improvements with 2020 Standard compliance are identified in the compliance update[4].

Finally, we wish to again thank and acknowledge the many stakeholders who have engaged with Project MATCH. Your contributions are deeply appreciated and have made this work possible.

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[3] See Knowledge Sharing Report 1, available at: https://arena.gov.au/assets/2022/12/project-match-knowledge-sharing-report-2021-2022.pdf

[4] This report will be made available at: https://aemo.com.au/initiatives/major-programs/nem-distributed-energy-resources-der-program/standards-and-connections/compliance-of-der-with-technical-settings

1 Introduction

Project MATCH ('Monitoring and Analysis Toolbox for Compliance in a High DER future') is a three-year, Australian Renewable Energy Agency (ARENA) funded, research project focused on distributed energy resource (DER) behaviour during major power system disturbances. It is being led by the University of New South Wales (UNSW) in partnership with the Australian Energy Market Operator (AEMO) and Solar Analytics[5].

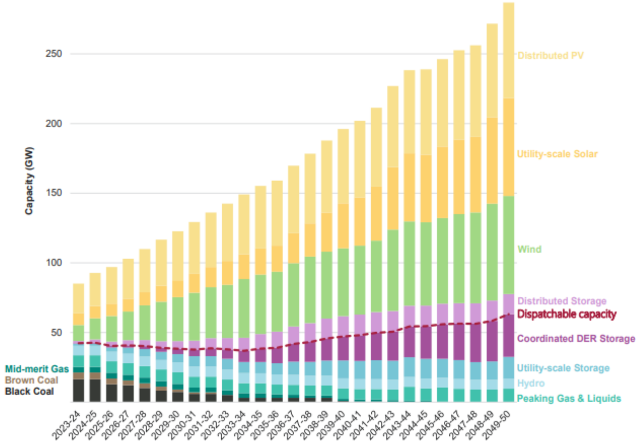
The purpose of this report is to share findings from Project MATCH and seek industry feedback. If you have questions, suggestions, or are collecting datasets that could support the analysis, please reach out to the report contact. The project is currently scheduled to conclude in March 2024, however efforts to analyse DER behaviours during disturbance events in the field, and particularly compliance with standards, are expected to continue through a number of avenues.

1.1 Market context

Australia's power system has seen a rapid growth of consumer-driven DER uptake that is expected to continue, in particular distributed solar photovoltaics (DPV) and battery energy storage systems (BESS). DER are distributed and inverter connected, leading to unique behaviour and specific challenges to integrate on to the power system.

In aggregate, DPV are currently the largest generator in Australia with nearly 20GW installed to date (Figure 2). DPV (and DER more broadly) is therefore playing a significant role in the power system and this is expected to continue with AEMO currently forecasting an up to four-fold increase in DPV[6]. It is imperative that the behaviour of DER is well understood and that this can be leveraged to ensure secure power system operation under these forecast high DER penetration conditions.

Figure 1 – Forecast NEM capacity to 2050, Step change scenario[7]



1.1.1 Performance Standards

Currently DER behaviours are largely dictated by inverter connection standards that define the operational envelope according to grid conditions. AS/NZS4777.2 is the performance standard for DER

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[5] UNSW Collaboration on Energy and Environmental Markets Project MATCH, available at: https://www.ceem.unsw.edu.au/project-match
ARENA Project MATCH, available at: https://arena.gov.au/projects/project-match/

[6] AEMO Integrated System Plan 2023 assumptions, available at: https://aemo.com.au/consultations/current-and-closed-consultations/2023-inputs-assumptions-and-scenarios-consultation

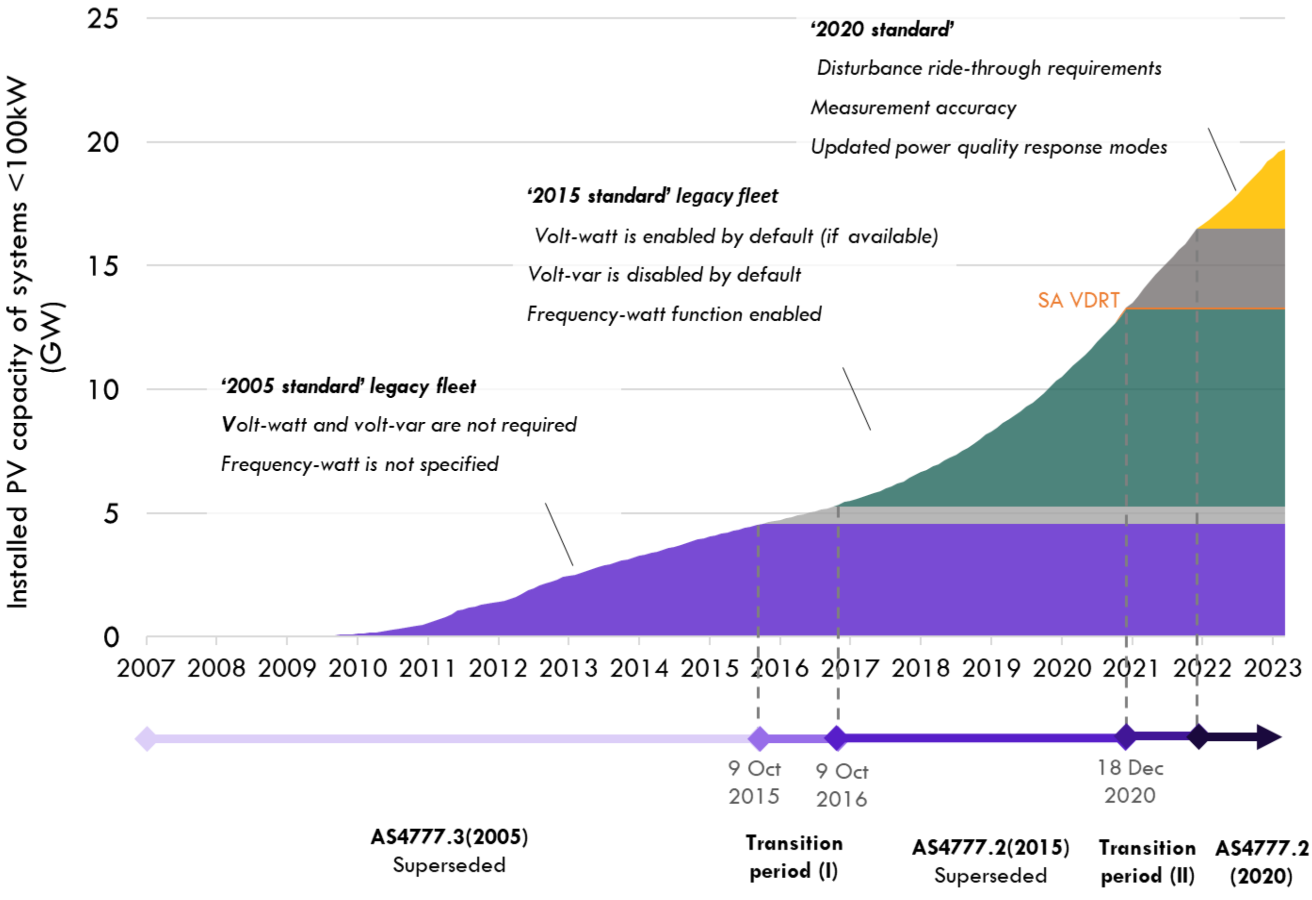
[7] AEMO, June 2022, 2022 Integrated System Plan available at: https://aemo.com.au/-/media/files/major-publications/isp/2022/2022-documents/2022-integrated-system-plan-isp.pdf?la=en

inverters, and defines its behaviour in response to power system events. The Standard and associated regulation has had several relevant iterations:

- Systems installed before October 2015 were required to be installed under AS/NZS4777.3:2005 (the "***2005 Standard***")
- Systems installed after October 2016 were required to be installed under AS/NZS4777.2:2015 (the "***2015 Standard***")
- During the period in which AS/NZS4777.2:2015 was applicable, some distribution network service provider (DNSP) Connection Standards introduced power quality requirements making mandatory volt-watt and Volt-VAr specifications on inverters, the timing and settings are unique for each DNSP.
- Systems installed after 28 September 2020 in South Australia were required to meet additional voltage ride-through requirements (termed the South Australian Voltage Disturbance Ride-Through Standard, or the "SA VDRT")[8] introduced by the Office of the Technical Regulator[9].
- Systems installed after 18 December 2021 are required to be installed under AS/NZS4777.2:2020 (the ***"2020 Standard"***).

A summary of when each of these Standards applied and the cumulative capacity of DPV installed under each Standard is provided in Figure 2.

Figure 2 – Installed capacity of DPV systems by Standard



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[8] AEMO, Short Duration Undervoltage Disturbance Ride-Through Test Procedure, at https://aemo.com.au/en/initiatives/major-programs/nem-distributedenergy-resources-der-program/standards-and-connections/vdrt-test-procedure.

[9] Government of South Australia, Voltage Ride Through, at https://www.energymining.sa.gov.au/energy_and_technical_regulation/energy_resources_and_supply/regulatory_changes_for_smarter_homes/voltage_ride_through.

1.1.2 Governance of DER Technical Standards and Compliance

To complement the review of the Standard, in 2020 the Australian Energy Market Commission (AEMC) undertook a rule change establishing a framework to set minimum technical standards for DER within the National Electricity Rules (NER). The rule[10] requires that all new or replacement micro embedded generators connecting to distribution networks must be compliant with the DER Technical Standards, set out in AS/NZS4777.2:2020. This was required through the model standing offers (MSO) for basic micro embedded generator connections required by the DNSP and came into effect upon the introduction of the new Standard on 18 December 2021.

As an extension of this work during 2022 – 2023 the AEMC undertook a review of governance arrangements, with a key focus on the compliance of inverters to AS/NZS4777.2:2020[11]. The review recommended a number of actions to improve compliance, including actions underway currently. It also recommended that *'jurisdictions lead the development of a national regulatory framework for CER (Consumer Energy Resources) technical standards'*.

The Energy and Climate Change Ministerial Council (ECMC) met in November 2023 and '*Ministers agreed to give consideration to implementing a national approach to technical regulatory settings for consumer energy resources in 2024.'*[12].

1.2 Prior and ongoing work

Project MATCH builds on a long-term collaboration between UNSW, AEMO and Solar Analytics. Figure 3 provides a simplified overview of events leading up to the commencement of Project MATCH, key 'discovery' points, namely the observation of DPV response to a disturbance event in the field (2017), observation of compliance challenges in the field (2018) and collaboration with OEMs to access compliance at install data (2022).

Despite the significant deployment of DPV in Australia, as at 2017, power system security impacts were largely unstudied. At this point, existing research by UNSW using Solar Analytics data had shown evidence of DPV responding *en masse* to a voltage disturbance event in the field[13]. In parallel, another team at UNSW was collaborating with AEMO and other relevant industry stakeholders on an ARENA 'bench testing' project[14] to understand inverter behaviour under disturbance conditions in the lab.

UNSW, AEMO and Solar Analytics began collaborating in 2018 to undertake further analysis of DER disturbance response in the field using real-world operating data, and first identified the challenges of compliance with the inverter performance standards in the field.

AEMO called for an update to AS/NZS4777.2:2015 *Grid connection of energy systems via inverters, Part 2: Inverter requirements* to include disturbance ride-through capabilities (similar to those adopted in 2018 in the international standard IEEE1547), via its *Technical Integration of DER report*[15]. The standard went

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[10] AEMC Rule Determination Technical Standards for DER, available at: https://www.aemc.gov.au/rule-changes/technical-standards-distributed-energy-resources

[11] AEMC Review into customer energy resources (CER) technical standards, consultation paper. Available at: https://www.aemc.gov.au/market-reviews-advice/review-consumer-energy-resources-technical-standards

[12] ECMC Meetings and communiques, available at: https://www.energy.gov.au/government-priorities/energy-and-climate-change-ministerial-council/meetings-and-communiques

[13] N Stringer, N Haghdadi, A Bruce, J Riesz, I MacGill, 'Observed behaviour of distributed photovoltaic systems during major voltage disturbances and implications for power system security' (2020) Applied Energy https://doi.org/10.1016/j.apenergy.2019.114283

[14] UNSW Addressing barriers to efficient renewable integration 2016 – 2022: https://arena.gov.au/projects/addressing-barriers-efficient-renewable-integration/

[15] AEMO, Technical Integration of Distributed Energy Resources, April 2019, available at: https://www.aemo.com.au/-/media/Files/Electricity/NEM/DER/2019/Technical-Integration/Technical-Integration-of-DER-Report.pdf

through an expedited review process with the new standard, including ride-through requirements critical for power system security, was published in December 2020.

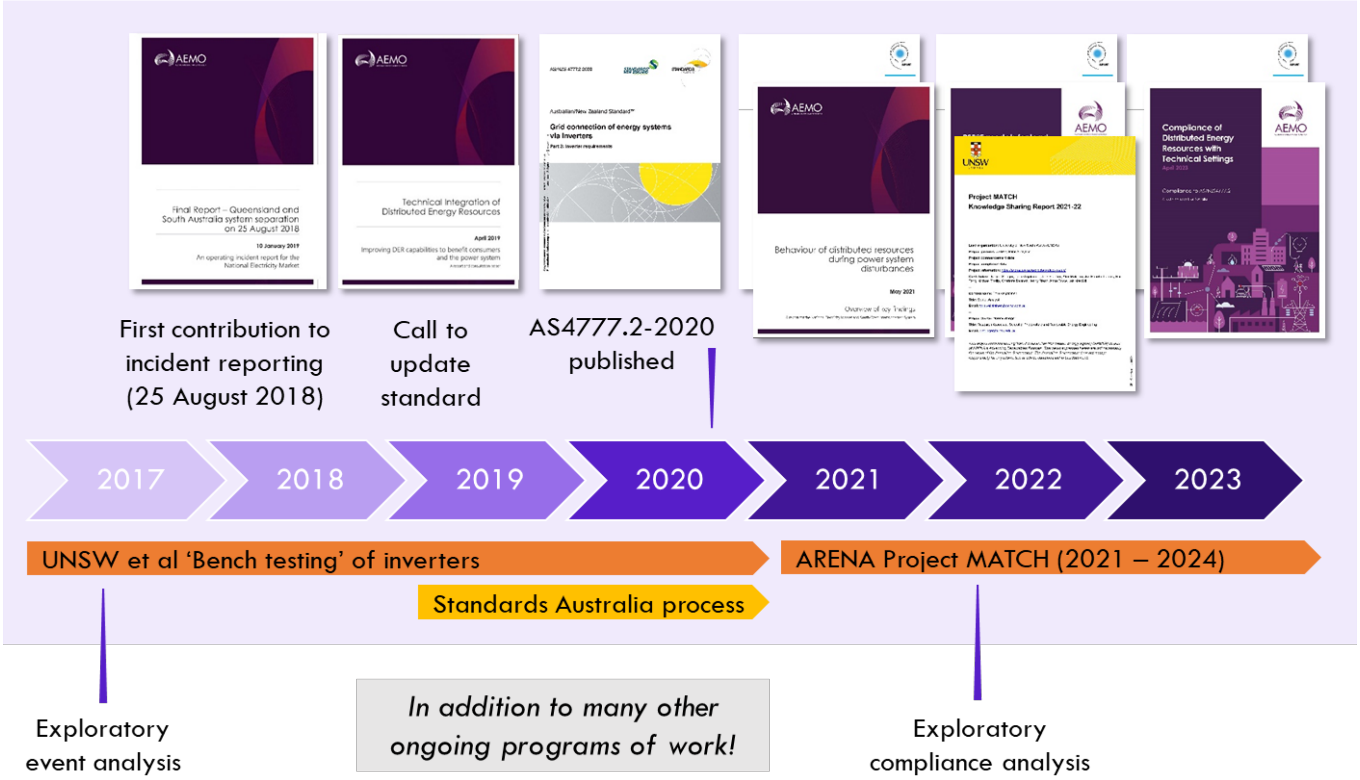

Figure 3 – Industry context and timeline

AEMO also developed the first iteration of the DER Disturbance Analysis Tool (DERDAT) to support further analysis, and collected and analysed a wide range of data sources to summarise the response of DPV to power system disturbances during 2018 to 2021, these findings are detailed in the compendium of the *behaviour of distributed PV during power system disturbances*[16].

Project MATCH then commenced in January 2021 with the goal of supporting secure power system operation under very high levels of DER. As a research project, and extension of a well-established collaboration, the project was intended to allow time for pioneering analysis and stakeholder engagement to support industry outcomes.

Based on the understanding to date of DER behaviour during disturbances, AEMO has developed power system models for use in PSSE and PSCAD to represent the behaviour observed. The models are used by AEMO for system security studies, such as understanding the impacts of DPV on system operations at times of high DPV operation. As new learnings of DER behaviour are uncovered, it is important these findings are reflected in these models.

1.3 Project MATCH overview

The objective of Project MATCH is to **establish robust characterisation of DER during power system disturbances using data driven tools**, to support a safe, secure and reliable power system with high levels of DER. It is a desktop study that intends to provide necessary foundational datasets, tools and evidence to AEMO, to support its DER integration initiatives regarding power system security.

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[16] AEMO, April 2021 Behaviour of distributed PV during power system disturbances. Available at: https://aemo.com.au/-/media/files/initiatives/der/2021/capstone-report.pdf?la=en&hash=BF184AC51804652E268B3117EC12327A

The objectives for the Project are achieved through:

- An improved range of **data streams** to support robust analysis (section 3),
- Improved **tools and techniques** for data driven analysis of DER installed in the field (section 2.2), and
- Improved **understanding** of DER fleet behaviour during disturbance events (section 2.1), including DER compliance with AS4777.2 (section 2.3).

The outputs from the project are informing industry efforts to improve compliance with the 2020 Standard in the field, informing AEMO's power system models, supporting AEMO's management of DER response to disturbances, such as implementing changes to constraints or contingency Frequency Ancillary Control Services (FCAS) requirements linked to real-time DER generation. These measures are expected to contribute to ensuring the power system is operated safely, securely and reliably with increasing quantities of DER.

Project MATCH is scheduled to run for three years from January 2021 until March 2024 and includes three workstreams, the scope of each is detailed in Table 1, with flexibility given the iterative nature of the work.

Table 1 Project MATCH workstreams

Workstream	Activities	Outputs
Workstream 1: Disturbance alerts and automated high-resolution (5s) data collection	Development of alert triggers, Solar Analytics software development and automated system testing and validation.	1. Automated high-res (5s) data collection system 2. Data collection triggers 3. New data sets
Workstream 2: Inverter compliance assessment	Extension of current analysis tools to leverage new data streams from workstream 1, and incorporate a wider array of data sources.	4. DER Disturbance Analysis Tool V2.0* 5. VPP FCAS Analysis Tool † 6. New inverter compliance estimates 7. Knowledge sharing
Workstream 3: DER data analysis to support AEMO DER modelling	Development of new statistical analysis capabilities to reflect diverse infield behaviours. Outputs will inform AEMO's DER modelling in PSSE and PSCAD.	8. DER Disturbance Analysis Tool V3.0* 9. New understanding of DPV performance during disturbances 10. Knowledge sharing

*The DER Disturbance Analysis Tool V1.0 is a data analysis tool developed in collaboration between AEMO and UNSW for analysing DPV performance during disturbances against some measures within AS/NZS4777.2:2015. The proposed V2.0 and V3.0 will extend the capabilities of the tool to assess compliance against AS/NZS4777.2:2020 and improve statistical methods utilised within the tool, respectively.

† The VPP FCAS Analysis tool was identified as an extension of Project MATCH that would provide enhanced outcomes to AEMO for a minor uplift in the project (as a modified version of the existing DER Disturbance Analysis Tool). It was added as a variation to the scope in April 2021. See Section **Error! Reference source not found.** for further details.

1.3.1 Project Collaboration

Project MATCH is being led by UNSW in partnership with AEMO and Solar Analytics (Figure 4). A core element of the project has been collaboration with a broad range of relevant stakeholders to seek guidance on the analysis and to access real world datasets. At the time of writing, 25 stakeholder organisations have provided data to Project MATCH.

The project is supported by a Stakeholder Reference Group (SRG), that includes Original Equipment Manufacturers (OEMs) for inverter and battery technologies, Distribution Network Service Providers (DNSPs), Virtual Power Plants (VPPs) and aggregators, metering providers, regulatory and market bodies, consumer representatives and research organisations. The SRG has grown from 23 to 42 participants over the course of the project.

We acknowledge and thank all industry stakeholders engaging in Project MATCH for their contributions. The expertise, data and guidance shared to date have been invaluable, and greatly enhanced project learnings.

Figure 4 – Project MATCH governance and stakeholder engagement

1.3.2 Datasets

Project MATCH is underpinned by the array of valuable datasets received from its many stakeholders. Six types of data have been analysed to date within the project:

- Operational timeseries datasets (1s-60s time increments) for PV, BESS and load
- Meta data to support the operational timeseries data, including postcode, install date, inverter OEM, installed capacity (kW) etc.
- Error/response codes
- Inverter standard/grid code selected at installation
- DNSP compliance analysis outputs
- DNSP power quality monitoring data

The diverse and multiple datasets are critical for the project as they provide a broader view of events and allow comparison and validation with each other. This ensures that the objectives of the project can be reached and that an improved understanding of DER behaviour is achieved across a range of stakeholders.

We acknowledge the complexities in providing these datasets to the project including the cost involved in collecting, storing and sharing data, as well as management of privacy concerns, and time taken to answer the project team's questions so that we could analyse the data appropriately.

We would like to extend our gratitude and appreciation to those that have contributed.

1.3.3 Complementary work programs

Considerable efforts are underway across the industry to effectively integrate DER (or Consumer Energy Resources) – a complete review is not provided here. Ongoing programs of work that are highly relevant and complementary to Project MATCH include:

- **'Bench testing':** UNSW Addressing barriers to efficient integration of renewable energy/Global Power System Transformation (GPST) Topic 9 DER and Stability[17] is focused on lab testing of inverters under a range of disturbance conditions. This complements the in-field analysis work through Project MATCH by providing evidence of inverter behaviour under bench-tested conditions, to better identify any disparities in compliance behaviour.
- **Western Power distributed PV modelling:** is a parallel work program looking at similar methods for estimating DPV loss during major grid disturbances using distribution monitoring, for Australian regions not covered by this Project. The findings from this work may be useful for cross-checking findings and comparison of results.
- **Project CANVAS**[18] (Curtailment and Network Voltage Analysis Scoping study): analysis of DPV curtailment due to power quality response modes including Volt-VAr, Volt-Watt and disconnection on over-voltage settings. Analysis included consideration of compliance (particularly delivery of Volt-VAr functionality).
- **DNSP assessment of DER compliance:** leverages Advanced Metering Infrastructure (AMI) data to assess DER compliance with Volt-VAr functions in the field. DNSPs are also making efforts to articulate the need for uplift to these capabilities.
- **Governance arrangements:** are anticipated to support clarity regarding role and responsibilities around DER/CER technical integration including compliance analysis and enforcement (see section 1.1.2)

The project team are endeavouring to leverage findings from these bodies of work where possible. In particular to support validation of in-field observations and develop understanding of why certain in-field behaviours may be occurring.

2 Key investigations

2.1 Disturbance events

Project MATCH has directly contributed to the incident reports listed in Table 2 over the course of the project. The 25 May 2021 and 12 November 2022 were particularly significant events, with widespread DER response and substantial analyses completed.

Analysis on implications for VPPs during the 12-19 November 2022 week of SA island operation is ongoing.

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[17] *ARENA UNSW Addressing barriers to efficient renewable integration*, available at: https://arena.gov.au/projects/addressing-barriers-efficient-renewable-integration/ *GPST Topic 9 DER and Stability*, available at: http://pvinverters.ee.unsw.edu.au/

[18] Project CANVAS reporting available at: https://racefor2030.com.au/project/low-voltage-network-visibility-and-optimising-der-hosting-capacity-fast-track/

Table 2 – Contributions to incident reports

Event date	Region	Key features	Incident reporting
24 Jan 2021	SA	Bushfire near Cherry Gardens substation tripped multiple lines. Minimum voltage of 0.6pu observed on single phase. Phase angle jump: 44-56° on two phases at 66kV level, 23-27° on two phases at 11kV.	Link to system event report[19]
12 Mar 2021	SA	Simultaneous trip of Torrens Island A West and Torrens Island B West 275kV busbars. Minimum single-phase voltage ~0.16pu at 275kV	Link to system event report[20]
25 May 2021	NEM	Trip of multiple generators (Callide C4 and C3) and lines in Central Queensland (most notably QNI). Initiated UFLS in Queensland and northern NSW. Frequency dipped to 49.68 Hz for NEM, and 48.53Hz for Qld. Minimum voltage of ~0.49pu in Bouldercombe and 0.2pu in Sapphire.	Link to system event report[21]
16 Nov 2021	Vic, NSW	Voltage oscillations were observed in the region between Victora and New South Wales over a period of ~40 minutes from ~6am to 6:40am AEST. DPV disconnection was not observed, however given the 5-60s data resolution, it is possible that sub-second behaviours were occurring and could not be identified.	Link to system event report[22]
23 June 2022	SA	Voltage and reactive power oscillations observed in SA from around 1am to 6am AEST. Minimal DPV response, however one battery manufacturer observed 95% of their fleet to disconnect, caused by an external device that is a typical part of their installation.	Link to system event report[23]
12 Nov 2022 (and 12-19 Nov 2022)	SA	Islanding of SA and then week of island operation of SA during minimum demand conditions. During this period DPV was curtailed on multiple occasions to support power system security.	Link to system event report[24]
29 June 2023	Vic	Voltage dip in Victoria, report pending.	Link to system event report[25]

Four further events (that were not reviewable operating incidents under the NER) were also analysed through Project MATCH, however DPV response was not found to be significant. Many other events occurred prior to the formal commencement of Project MATCH, which underwent the same analysis, these events, and their learnings are reported in AEMO's *Behaviour of distributed resources during power system disturbances*[26] report.

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[19] AEMO June 2021, Trip of Multiple Cherry Gardens lines on 24 January 2021, available at: https://www.aemo.com.au/-/media/files/electricity/nem/market_notices_and_events/power_system_incident_reports/2021/trip-of-multiple-cherry-gardens.pdf?la=en

[20] AEMO November 2021, Final Report – Trip of Torrens Island A and B West 275kV busbars on 12 March 2021, available at: https://aemo.com.au/-/media/files/electricity/nem/market_notices_and_events/power_system_incident_reports/2021/final-report-torrens-island-275-kv-west-busbar-trip.pdf?la=en

[21] AEMO October 2021, Trip of multiple generators and lines in Central Queensland and associated under-frequency load shedding on 25 May 2021, available at: https://aemo.com.au/-/media/files/electricity/nem/market_notices_and_events/power_system_incident_reports/2021/final-report-trip-of-multiple-generators-and-lines-in-qld-and-under-frequency-load-shedding.pdf?la=en

[22] AEMO February 2023, West Murray Zone Power System Oscillations on 16 November 2021, available at: https://aemo.com.au/-/media/files/electricity/nem/market_notices_and_events/power_system_incident_reports/2023/west-murray-zone-power-system-oscillations.pdf?la=en

[23] AEMO February 2023, Power System Oscillations in South Australia on 23 June 2022, available at: https://aemo.com.au/-/media/files/electricity/nem/market_notices_and_events/power_system_incident_reports/2022/south-australia-power-system-oscillations.pdf?la=en

[24] AEMO May 2023, Trip of South East – Tailem Bend 275 kV lines on 12 November 2022, available at: https://aemo.com.au/-/media/files/electricity/nem/market_notices_and_events/power_system_incident_reports/2022/trip-of-south-east-tailem-bend-275-kv-lines-november-2022.pdf?la=en

[25] Incident report will be made available at: https://aemo.com.au/en/energy-systems/electricity/national-electricity-market-nem/nem-events-and-reports/power-system-operating-incident-reports

[26] AEMO May 2021, Behaviour of distributed resources during power system disturbances, available at: https://aemo.com.au/-/media/files/initiatives/der/2021/capstone-report.pdfBF184AC51804652E268B3117EC12327A

2.2 DER Disturbance Analysis Tool (DERDAT)

The DER Disturbance Analysis Tool (DERDAT) is open source and freely available at:

https://github.com/UNSW-CEEM/DER_disturbance_analysis

Analysis requires 60s (or smaller time increment) data on DER operation. This is because the 2015 and 2020 Standards require DER to remain disconnected for 60s following an excursion and so disconnections are not necessarily 'visible' in less granular datasets such as 5min AMI data. The operational datasets analysed through Project MATCH include those provided by Solar Analytics, Tesla and Energy Queensland hosted on the Luceo platform.

To the authors knowledge, there are no sub-60s DER operational datasets currently open source/freely available. The Solar Analytics datasets can be procured.

The purpose of DERDAT is to provide streamlined, robust, repeatable analysis of DER behaviour during disturbance events based on real-world operating data. Figure 5 summarises the input datasets, output observations on DER behaviour and applications. AEMO is currently using DERDAT as part of its business-as-usual operations.

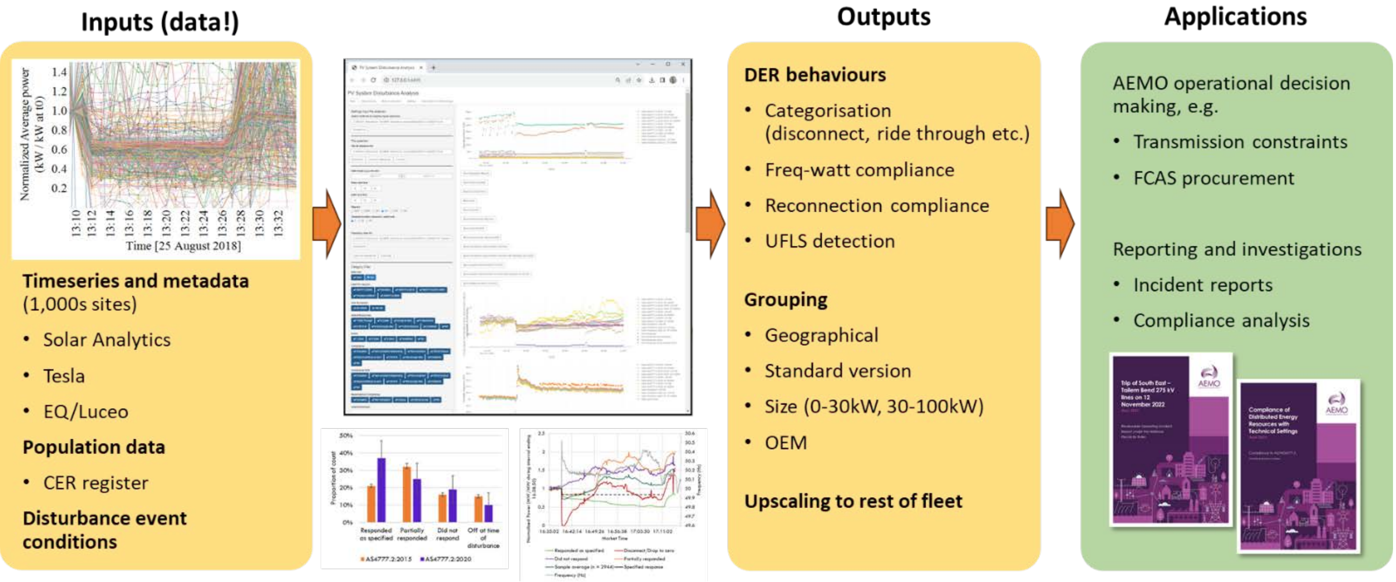

Figure 5 – DERDAT overview

2.2.1 Extensions completed

Project MATCH has extended DERDAT's capabilities as summarised in Table 3, including features under development. DERDAT is expected to continue to evolve over time as AEMO's understanding of the DER fleet develops, and analytical needs change.

Table 3 – DERDAT extensions

Feature	Description	Status / Further information
Overall functionality		
Refactor for extensibility	Code base was restructured to support ease of further developments below.	● **Complete** See Knowledge Sharing Report 1[27]

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[27] Project MATCH Knowledge Sharing Report 2021-22, available at: https://arena.gov.au/assets/2022/12/project-match-knowledge-sharing-report-2021-2022.pdf

Feature	Description	Status / Further information
Code version stamping	Outputs are stamped with the version of the code base applied to do the analysis.	● **Complete**
Benchmark results	When developments are made to the code base benchmarking is applied to confirm that other functions have not been inadvertently impacted.	● Complete See Knowledge Sharing Report 1[24]
Code review processes	Formal code review processes put in place, utilising github features.	● **Complete** See Knowledge Sharing Report 1[24]
Analytics / algorithm development		
UFLS detection	Detects sites impacted by UFLS drop out (as opposed to sites where only the inverter disconnects due to the disturbance event, for instance under voltage conditions).	● **Complete** See Knowledge Sharing Report 1[24]
2020 Standard frequency-watt	Analyses compliance with the frequency-watt function as specified under the 2020 Standard.	● **Complete**
Upscaling and error estimation	Allows for increased sophistication in the treatment of data bias, with tools to visualise the bias in a particular dataset and select appropriate upscaling criteria.	● **Complete** See Appendix B Upscaling DPV disconnection and error estimation using linear models
Voltage anti-islanding analysis and visualisation	Identifies sites with voltage measures outside anti-islanding bounds. Provides visualisation of voltage measures to support identification of widespread over/under voltage.	● **Complete** See section 2.2.2
Validation and dataset capabilities		
Tesla data analysis	Tesla data was down-sampled to 30s intervals in order to do initial analysis using pre-existing DERDAT functionalities. Analysis was undertaken for 25 May 2021 disturbance event to cross-check DER behaviours.	● **Complete** See Knowledge Sharing Report 1[24]
Energy Queensland data (hosed on the Luceo platform) analysis	Analysis undertaken on EQ-Luceo data for 25 May 2021 event to cross-check DER behaviours.	● **Complete** See Knowledge Sharing Report 1[24]
Extending range of data sample rates	Ability to analyse 1s data underway. Review of key functions/logic to ensure methods remain robust.	● In progress
Mixed duration analysis	Ability to analyse datasets containing a mix of timestamp durations, both between sites (e.g. some sites with 1s data and some 30s data) and at individual sites (e.g. power measures reported at 1s intervals and voltage measures reported at 30s intervals for the one site).	● In progress
Validation between datasets	Comparison of upscaled disconnections leveraging different underlying DER operational datasets.	● **Complete**
BESS analysis	Currently analysis is only performed on PV outputs. Battery/hybrid systems have bidirectional flow and extra requirements which make them a challenge to assess, however their growing prevalence warrants attention as soon as possible.	● **Future work**

2.2.2 Key limitations

It has been determined that it is not possible to analyse the following aspects of DER disturbance response using the DER operational datasets currently available under Project MATCH:

- Voltage ride-through including multiple voltage dips, and
- Phase angle jump ride-through.

This is due to (1) voltage disturbance events typically occurring over a very short timeframe of around 200ms whereas most voltage datasets are captured on a 5-10s basis, and (2) DER operational datasets do not currently include waveform data necessary for calculating phase angle jump.

In order to analyse these aspects of DER disturbance response – and particularly compliance with the 2020 Standard – high speed datasets are required. These datasets may be required at the point of DER installation, or within the distribution network. Further work is required to understand how disturbances permeate the network, and the minimum data requirements. See section 2.4.

2.3 Compliance assessment

Early compliance assessment

As reported in Project MATCH Knowledge Sharing report 1, in Q1 2022 only ~40% of new DPV installations were commissioned with the 2020 Standard, presenting a significant risk to power system security. This analysis relied upon data voluntarily provided by inverter OEMs under Project MATCH.

In April 2023 AEMO published a report: *Compliance of Distributed Energy Resources with Technical Settings*[28], that outlined the power system security risk of ongoing low compliance rates, and compliance rates reported by a number of different stakeholders. The Project MATCH analysis provided a key motivation and source of compliance understanding.

Compliance update

In May 2023, UNSW and AEMO together reached out to the inverter OEMs again to seek updated data for installs during Q4 2022, Q1 and Q2 2023. Overall compliance rates for new installations appear to have significantly improved to around 75-80%, noting key limitations regarding sample size and sample bias linked to internet connectivity. This improvement in compliance appears to be largely driven by voluntary actions taken by OEMs following AEMO and UNSW identifying the need to improve compliance at the point of install.

Details of this analysis are to be made available in late 2023 at: https://aemo.com.au/initiatives/major-programs/nem-distributed-energy-resources-der-program/standards-and-connections/compliance-of-der-with-technical-settings

2.4 Disturbance permeation

As identified in Knowledge Sharing report 1, disturbance permeation represents an important area for further exploratory analysis. Support has been provided through ACAP[29] to undertake an investigative piece of work in collaboration with AEMO and SA Power Networks. SA Power Networks has generously deployed a number of power quality monitors at specific locations within their distribution network to support visibility from transmission through to downstream sub-transmission and distribution sites.

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[28] AEMO 2023, *Compliance of Distributed Energy Resources with Technical Settings*, available at: https://aemo.com.au/-/media/files/initiatives/der/2023/compliance-of-der-with-technical-settings.pdf?la=en

[29] The work is supported by the Australian Centre for Advanced Photovoltaics (ACAP) and received funding from the Australian Renewable Energy Agency (ARENA).

Improved understanding of how voltage disturbance events (including phase angle jump) permeate from the transmission system down to the point of DER connection is important for two reasons:

(1) Event understanding: it may improve our ability to estimate aggregate DER behaviour during disturbances and particularly identify 'less severe' disturbances that could have significant DER response, and

(2) Compliance assessment in the field: it may make it possible to assess DER compliance with voltage and phase and jump ride through requirements established in the 2020 Standard (see 2.2.2 for limitations of current DER operational datasets).

SA Power Networks has kindly provided data for a number of events in 2022 and 2023, with analysis ongoing. Tentative insights to date are as follows:

- *The specific phase(s) at high voltages that experience a voltage dip impact the specific phase(s) that experience a voltage dip in the distribution network.* The majority of DER remain single phase systems, and therefore different DER populations would be impacted by similar voltage disturbances (i.e. same transmission location/depth of dip) impacting different phases.
- *Voltage measurements at specific points in the transmission system are not necessarily indicative of downstream voltage.* This may be due to complexities in the network topology and local load/generation response. For the purpose of assessing compliance, the most conservative assumption is that the most extreme voltage dip observed at the transmission level could also plausibly occur in the distribution network. Further investigation is required.

Work is ongoing, and findings are expected to be published in 2024.

3 Solar Analytics data collection triggers

Solar Analytics refined its data collection triggers ('Leadbeater triggers') over the course of Project MATCH to support robust data collection during disturbance events, whilst avoiding excessive data collection due to false positives. The approach taken is summarised in Table 1.

Table 4 – Solar Analytics data collection triggers

Trigger type	Required data	Tasmania threshold	NEM mainland/SWIS threshold
Voltage	5-minute Vmin and Vmax values (measured every 250ms) at all devices	At least 5% of devices in a region or 20 devices in a region (whichever is higher) record (Vmax – Vmin) > 30V within a single 5min window	
Frequency	Frequency recorded at five selected sites in each NEM region every 5s with a region trigger occurring if frequency exceeds the thresholds at any two of these sites during the same 5s interval	<49.0Hz or >51.0Hz	<49.8Hz or >50.2Hz

Where voltage is captured over roughly 2 cycles (40ms) every 250ms, and the minimum, maximum and mean are calculated every 5s (Figure 6), then again every 5min.

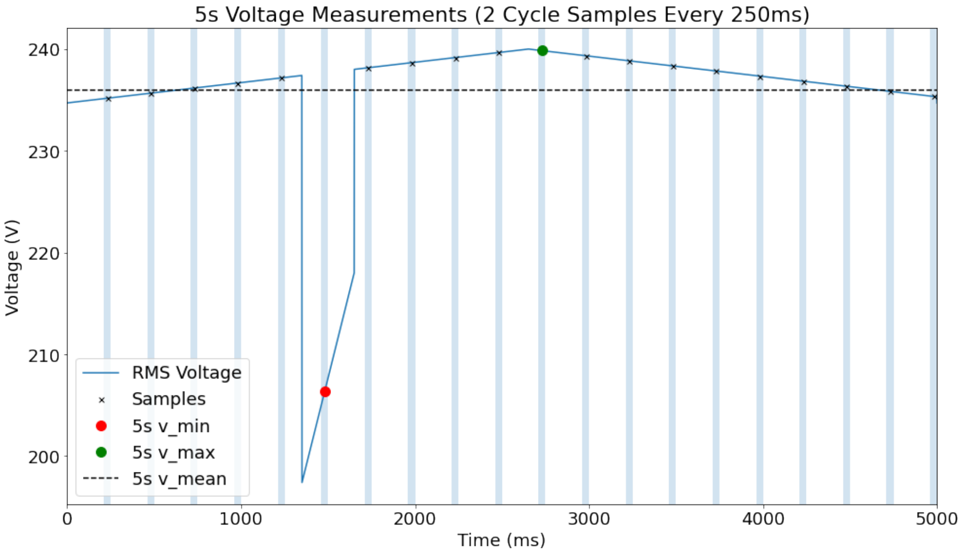

Figure 6 – Illustrative voltage measurement capture

The operation of these triggers is shown in Figure 7. Triggers utilise ongoing buffering of 'high resolution' (5s) data to report 10min prior to the disturbance event, and then capture 7min of high resolution data following the trigger operation. Logic is in place to ensure further events occurring within the 7min window (or continued disturbance conditions such as a prolonged over-frequency) are also captured.

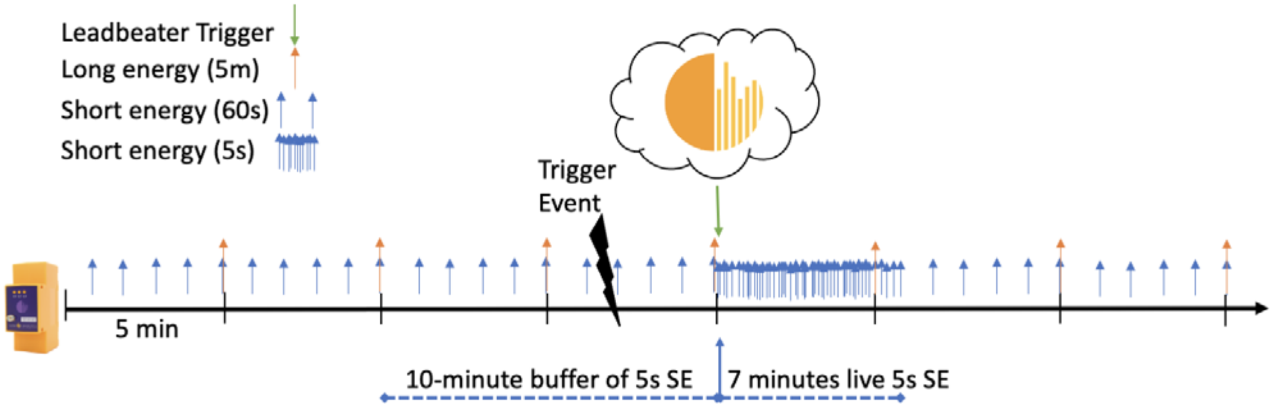

Figure 7 – Illustration of Solar Analytics data collection trigger operation

4 Lessons learnt

4.1 Project objectives: DER, power system security and compliance

The objective of Project MATCH is to **establish robust characterisation of DER during power system disturbances using data driven tools**, to support a safe, secure and reliable power system with high levels of DER. In particular through:

- Improved data collection (section 3),
- Understanding of DER behaviours during disturbance events (sections 2.1, 2.2),
- Understanding of compliance in the field with the 2020 Standard (section 2.3) and
- Identification of potential actions to improve compliance/DER disturbance response.

Key lessons learnt regarding the project objectives and particularly compliance, datasets and limitations are summarised here.

4.1.1 Assessing compliance with the 2020 Standard

Over the course of the project different 'types' of compliance with the 2020 Standard have been identified, as summarised in Table 5. In particular it is worth noting that the OEM datasets on grid code settings selected at install were identified as a useful avenue for analysis through Project MATCH and had not previously been used to understand in-field compliance.

It is also worth noting that different aspects of DER inverter performance impact different parts of the power system and are therefore of more/less concern to certain stakeholders. For instance, compliance with Volt-VAr settings is of high importance to DNSPs given the implications for voltage management. However non-compliance with the 2020 Standard Volt-VAr settings does not necessarily indicate non-compliance with the 2020 Standard disturbance ride-through requirements - which are of greater concern to AEMO given the power system security implications. Compliance with the 2020 Standard is therefore important in many different contexts, and consideration of compliance rates for the purpose of policy/regulatory development should carefully consider the 'type' of compliance under consideration.

The assessments of compliance summarised in Table 5 do not consider a broader definition of compliance that may also consider for instance, electrical safety.

Table 5 – 'Type' of compliance with the 2020 Standard and data requirements

'Type' of compliance	Description	How is it checked?	What data is required?
Pre-install compliance with the standard	Inverters are expected to meet the tests set out in the 2020 Standard	Lab-testing[30]	Very high resolution (waveform) DER operational data
Grid code selection at install	Requires installers to correctly select the 2020 Standard during commissioning	The Project MATCH team requested data from OEMs and developed bespoke scripts to complete analysis (section 2.3)	Grid code data from installed, internet-connected DER provided by OEMs
Ongoing in-field compliance	Requires the inverters to operate as specified in the 2020 Standard on an ongoing basis (delivering a range of functions, including following any firmware updates etc.)	Can be assessed by analysing: • Ride-through performance during disturbance events • Frequency-watt delivery during frequency excursion events • Volt-VAr and/or Volt-Watt performance during ongoing high voltage conditions (e.g. during spring time in high DPV areas) • The reconnection profile following disconnection (either during disturbance events, or ongoing high voltage conditions) DERDAT has been developed to analyse DER behaviour during disturbance events (section 2.2)	Real-world DER operational data, noting: • 'High resolution' (typically 60s or smaller) data is required for disturbance analysis • AMI can be used for power quality response mode analysis

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[30] UNSW has an ongoing program of work lab-testing inverters against the 2015 and 2020 Standard, as well as a range of further tests. Further details are available here:

4.1.2 Datasets, limitations and areas for future work

Real-world DER data (including operational time series data and supporting meta-data) are critical to understanding DER behaviour during major power system disturbance events and compliance in the field.

The datasets analysed through Project MATCH were each unique, and required considerable engagement from the data providers and Project MATCH team to ensure the data was analysed appropriately. ***The project team is very grateful to the many stakeholders who worked with us to provide data, share their understanding of how it was captured, and discuss findings. Thank you!***

Notwithstanding the generous engagement of stakeholders, challenges relating to data remain, including:

- **Ongoing availability:** the Solar Analytics 5s and 60s datasets (suitable for analysing DER behaviour during disturbance events) is reducing in the number of sites over time due to a change in technology at Solar Analytics and the retirement of 3G internet.
- **Voluntary provision:** datasets are largely provided voluntarily, for which the Project MATCH team is very appreciative. However as a result, there is no guarantee data will be available into the future, and indeed, does not recognise the costs incurred by data providers in capturing, storing and sharing data.
- **Sampling biases and limited sample sizes:** there is not universal visibility of DER and every dataset analysed over the course of this project has had its own set of sampling biases (e.g. over-representation of a particular inverter OEM, relative to the broader population). Further, sample sizes are generally limited. These challenges are currently managed through the upscaling and error estimation approaches developed (Appendix B), however there are limited means of validation and it is recommended that efforts to build an evidence base of DER performance (to support appropriate operational, policy and regulatory decision making) are continued.
- **No 'source of truth' for DER population data:** currently we rely upon the CER register as the 'source of truth' for the installed DPV population. However it has several limitations, including that replacement rates may not be fully captured (and anecdotally represent a significant new trend), there can be up to a one year delay between install and a site appearing in the register, and the proportion of sites captured is expected to decrease as we approach the end of the SRES subsidy in 2030. Whilst AEMO's DER register is expected to play an increasingly significant role, challenges remain for its accuracy. It is recommended that efforts to improve records of DER installations, retirements and upgrades are continued.

The work completed under Project MATCH will help to inform the requirements for DER operational data going forwards. This will support ongoing discussions around establishing permanent DER operational data streams for the purpose of disturbance analysis.

4.2 Stakeholder engagement and consultation

As noted in Knowledge Sharing Report 1, there has been strong support across industry for the work being undertaken through Project MATCH, with engagement during the stakeholder reference group sessions increasing each session, and over 40 organisations engaged. The Project MATCH team remains very appreciative of the time, expertise, advice and valued contributions of all the stakeholders to date and acknowledges the importance of the diverse range of views and feedback to the success of the project.

Establishing and managing data sharing relationships also remains a critical component of the project. Including the careful anonymisation and aggregation of data to promote transparency, whilst protecting competitive interests.

The current lack of governance arrangements regarding DER means that progress on DER integration (for instance, improving compliance rates) relies heavily on good will, cooperation and voluntary actions by different stakeholders. Maintaining a transparent and respectful conversation is therefore particularly important. However there are many interlocking issues at play, and confusion is difficult to avoid.

It is recommended that efforts continue across the industry to bring together stakeholders with different backgrounds to discuss challenges and share evidence of DER behaviour in the field as a basis for decision making. Specifically, evidence that goes beyond anecdotal or case study accounts (which are also useful) and provides *statistically significant* understanding of DER performance in the field, with consideration for limitations and error bounds. With over 3.5 million DPV installations across a highly diverse range of distribution conditions, it is possible to find an example of many behaviours (positive or negative). Data-driven findings can provide a valuable common basis for these conversations, with transparent methods and ideally open-source datasets.

4.3 Regulatory, financial and economic lessons

In addition to the lessons summarised in Knowledge Sharing Report 1, it is noted that a number of inverter OEMs have gone to great lengths to improve compliance rates. These efforts have been largely voluntary and have sometimes been resource intensive. The actions follow engagement by the Project MATCH team to analyse compliance rates using OEM data in early 2022.

Notwithstanding these efforts, a key challenge observed throughout Project MATCH remains the lack of clear governance arrangements regarding DER including the setting and enforcement of technical requirements. The need for clear governance arrangements regarding DER technical operation is broadly accepted across the industry, further work is required as noted in section 1.1.2. This has been observed in the following ways through Project MATCH:

- It is not clear who is responsible for monitoring (or enforcing) compliance with the 2020 Standard. The compliance rates reported through Project MATCH required considerable resource to seek/understand/analyse data and relied heavily on the goodwill of OEMs to engage.
- It is not clear who is responsible for improving compliance. Whilst it could be argued that it is ‘everyone’s responsibility’ to improve compliance in order to support power system security and the ongoing deployment of DER, actions to improve compliance can be resource intensive, with unclear material benefit – for instance for OEMs – in the context of a highly competitive market.
- OEMs are critical stakeholders for improving compliance rates, however to the authors’ knowledge, there is no existing regulatory/legal pathway to engage OEMs (for instance, they are not named in the National Electricity Rules).

The need for improved governance arrangements has been raised in Stakeholder Reference Group meetings by stakeholders on a number of occasions and it is observed that there may be growing frustration and consultation fatigue on this point.

4.4 Social and consumer lessons

As outlined in section 4.2, there are many complex and interlocking aspects of DER integration[31], and views on the appropriate actions differ. This is likely to make it particularly difficult for energy users to understand what their DER may be expected to do, and what is reasonable. It is recommended that efforts continue to build consensus between industry stakeholders including consumer advocates, to support the availability of consistent and complete information for energy users.

It is important to note that the issues of non-compliance discussed in this report do not relate to electrical safety compliance. Whilst compliance to the 2020 Standard is of concern for power system security more broadly, it should not impact energy users directly.

5 Next steps and recommendations

The work undertaken through Project MATCH has provided timely insights and supported action to improve compliance in the field with the 2020 Standard.

However there remains much to be done. As detailed in section 4, it is recommended that efforts continue to:

- Build an evidence base of DER performance during disturbance events to support appropriate operational, policy and regulatory decision making,
- Improve records of DER installations, retirements and upgrades,
- Bring together stakeholders with different backgrounds to discuss challenges and share evidence of DER behaviour in the field as a basis for decision making,
- Build consensus between industry stakeholders, to support the availability of consistent and complete information for energy users.

Further recommendations to support continued improvements with 2020 Standard compliance are identified in the compliance update, which will be made available at:

https://aemo.com.au/initiatives/major-programs/nem-distributed-energy-resources-der-program/standards-and-connections/compliance-of-der-with-technical-settings

Several tasks also remain in progress within Project MATCH, as summarised in Table 6. These will form the key focus areas in the final months of the project.

Table 6 – Summary of the Project MATCH work in progress

Category	Next steps
DER disturbance analysis tool	• Expand tool capability to handle a varied range of data sample rates beyond 5, 30 and 60 second datasets. • Improved assessment and understanding of BESS and hybrid systems, DPV systems >30kW.
Data specification	• Complete development of minimum data specification for DER operational data during disturbance events.
VPP FCAS Analysis tool	As noted in Knowledge Sharing Report 1, this tool has been handed over to AEMO's Systems performance team however Project MATCH proposed next steps include: • Extend the tool functionality to accept additional types of observations such as voltage, and battery SOC.
Disturbance permeation	Through the ACAP collaboration between UNSW, SA Power Networks and AEMO:

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[31] For instance, the operation of power quality response modes and how these may impact real power output (for self-consumption and export), the existence/application of emergency back stop measures to support power system security.

Category	Next steps
	• Further analyse datasets provided from PQ monitoring sites for 2022 and 2023 disturbance events and share findings via a short report

Finally, it is recommended that the areas for future work are continued/initiated.

5.1 Future work

Throughout the Project a number of other areas were identified, which are out-of-scope, however may be valuable to the understanding and improvement of compliance for DPV and DER. A number of these actions are already underway and include, but are not limited to:

- Documenting data requirements for DER behaviour and compliance analysis, including development of some form of standardisation, encompassing:
    - Error codes
    - Technical settings provision upon connection
- Development of robust datasets / analysis tools for analysing compliance with Emergency Backstop Measures.
- Investigation of the real-world impacts of power quality response modes (e.g. Volt-VAr and Volt-Watt functions) compared with Dynamic Operating Envelopes and implications for Emergency Back Stop measures and DER disturbance event response.
- Translate findings from upscaling methods to other upscaling applications (for instance, ASEFS2) as appropriate.
- Collaboration with networks (namely Western Power) to estimate DPV disconnection through an alternative top-down approach.
- Analysis of load data to understand its behaviour during power system disturbance events.

Appendix A Stakeholder Reference Group Meetings

Meeting	Date	Number of Attendees
Stakeholder Reference Group Kick Off Meeting (SRG 1)	2021-03-15	36
Stakeholder Reference Group – Meeting 2 (SRG 2)	2021-10-26	35
Stakeholder Reference Group – Meeting 3 (SRG 3)	2022-05-26	48
Stakeholder Reference Group – Meeting 4 (SRG 4)	2022-10-18	34
Stakeholder Reference Group – Meeting 5 (SRG 5)	2023-06-06	33

Appendix B Upscaling DPV disconnection and error estimation using linear models

B.1 Background

A key part of Project MATCH analysis is the upscaling of datasets to estimate the behaviour of the wider DPV fleet. This functionality is embedded as part of the DERDAT tool to determine a representative view of broader DPV disconnections.

Once DPV disconnection rates within the data sample have been identified using DERDAT, the results can be extrapolated to estimate the behaviour of the wider DPV fleet. An overall kW loss figure is calculated, which is important for understanding the risk to system security and evaluating the impact of DPV on the effectiveness of schemes such as UFLS.

Linear scaling is not appropriate because of the sample biases in the available data, hence an upscaling approach with weighting was developed and integrated into the DER tool. For this method, we use the term 'predictors' to refer to the categories used for weighting.

There are three key requirements to consider when determining the predictors:

1. PV systems behave differently across a given category,
2. The data is thought to be biased with respect to a given category, and
3. There are sufficient samples within each category to estimate the behaviour of the category.

Previously, upscaling was performed using the inverter installation standard and the inverter manufacturer as the predictor variables.

Validation of upscaled DPV disconnections remains a challenge for any method as the true amount of DPV disconnection across the region is unknown. DPV generation prior to an event is determined from estimates through AEMO's Energy Forecasting process, ASEFS2.

B.2 Previous method

The steps are described below:

- First, sites that were classified as Not Enough Data (NED), Undefined, NA or UFLS dropout are removed from the sample since they don't have meaningful data on the inverter disconnection.

- Then the remaining samples are grouped by Standard version and manufacturer, finding the sum of disconnections and total number of sites for each pair.
    - Sites with unknown, mixed, missing, or < 30 samples are combined into the 'other' group.
- The proportion of disconnects for each standard-manufacturer pair is the sum of disconnections divided by the sample size, and the kW loss is the proportion multiplied by the total installed capacity with that configuration, based on CER installations data.
- The 95% confidence interval is calculated for each pair using the Clopper-Pearson interval. Then the data is grouped by the standard, where predicted kw loss is the sum of the losses by manufacturer, and disconnections is the sum of kW loss divided by the sum of CER capacity.
- The final confidence interval is found by adding the bounds for each standard-manufacturer pair.

This method was used to determine the estimated upscaled response for event analysis performed prior to October 2022. Since then, both methods have been used and the results compared as a form of validation.

A number of issues were identified with this method, including:

- ***Categories must have a minimum number of sites:*** The current upscaling method is only effective for well-defined categories and may have a large number of sites in the “other” category. There are often cases where there are insufficient samples for each of the categories to undertake meaningful upscaling. For example, in the 5 March 2022 event, the “other” category was approximately 30% of the raw data set.
- ***There is a limit to the number of predictors that can be used:*** With more predictors there is a smaller sample of sites with that specific set/combination of categories. For example, there would likely be a limited number of sites that were <30kW, OEM A sites in postcode 2052 on AS/NZS 4777.2:2005, and so this group may not be valid to upscale.
- ***Treatment of “other” sites:*** Sites that do not fit one of the categories are used to estimate disconnection across all “other” sites. This is a concern as the “other” sites in the raw data may not represent the true upscaled “other” site behaviour and provide an inaccurate upscaled estimate.
- ***Final confidence bounds are too wide:*** The confidence ranges of the upscaled values could result in ranges as large as 40% in some cases, suggesting that improvements are needed to help improve the confidence bounds.

Regression models were therefore considered as an alternative that could be used to upscale datasets while also addressing the limitations in the method.

B.3 New GLM upscaling method

An updated method was developed which aimed to address the sample biases present in the available data sets and give greater flexibility over the choice of, and number of predictors used. This method involves using a generalised linear model (GLM) to fit the predictors and then make estimates of the disconnection rates for each unique set of predictors. One of the benefits of this approach is that, depending on the form of the GLM, it may be able to make estimates of the disconnection rates for unseen combinations of predictors.

The predictors that can be used for upscaling are:

- Manufacturer (ABB, SolarEdge, etc)
- Standard version (2005, Transition 2015, 2015, Transition 2020, 2020)
- Size grouping (<30 kW, 30-100kW, >100kW)

- Location: postcode, distance from event (qualitative) or distance zone (using set radii: <200km, 200-600km, 600-1000km, >1000km)

The steps are as follows:

- A set of predictors is selected based on the dataset and the event
    - Currently chosen using an evaluation matrix which weighs up each of the predictors against the 3 criteria listed in section 1
- As in the original upscaling method, sites that were classified as Not Enough Data (NED), Undefined, NA or UFLS dropout are removed from the sample since they don't have meaningful data on the inverter disconnection.
- Sites with unknown, mixed, missing, or < 30 samples are combined into the 'other' group.
- The cleaned samples are used to train a GLM of the form

$$\widehat{disconnection} = \sum_i \beta_i \times predictor_{1,i} + \sum_j \beta_j \times predictor_{2,j} + \cdots$$

where $\widehat{disconnection}$ is the predicted probability of a system disconnecting, β_i is a weight representing the effect of each category of each predictor on the disconnection rate, and all of the predictors are categorical. Since the outcome is a binary variable (representing if a site did or did not disconnect), a logistic regression model is used[32].

B.3.1 Example

Take a case with only one predictor: the standard version that the site was installed under. Using dummy data, the number of sites that did and did not disconnect following a grid disturbance is as shown in Figure 8 below.

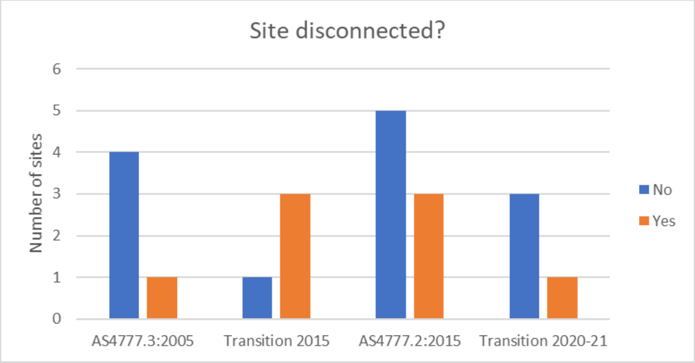

Figure 8 – Example using dummy data to illustrate disconnections vs Standard version

Fitting a GLM to this data in R gives the following equation

$$\widehat{disconnection} = -0.5108 - (0.8755 \times is2005) + (1.6094 \times isTransition2015) \\ - (0.5878 \times isTransition2020\_21)$$

Noting that the intercept (-0.5108) represents sites on the 2015 standard.

Since logistic regression was used, the coefficients are the log-odds of the outcome for each category. For a site on AS4777.3:2005, the probability of disconnection $= \frac{\exp(-0.5108-0.8755)}{1+\exp(-0.5108-0.8755)} = 0.2$. So, it is predicted to disconnect 20% of the time, which is equal to the raw percentage disconnects seen in the input data $(1/5 = 0.2)$.

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[32] Note the applied method fits each of the predictors independently – interaction terms are not considered since we may not have the data to fit them all. However, this means that changes that an individual OEM may have made in response to the 2015 or 2020 Standard are not properly represented.

Adding an extra predictor, we get interactions such as that in Figure 9 where the outcomes for each new category are added (or subtracted) when calculating the disconnection probability.

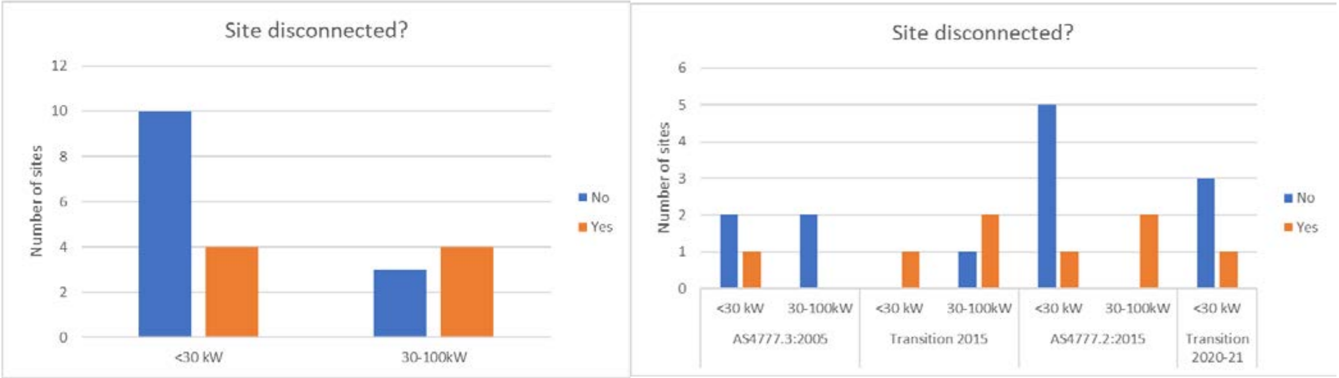


Figure 9 – (left) Example using dummy data to illustrate disconnections vs system capacity. (right) Combination of the impacts of Standard version and system capacity.

Fitting a GLM using both the standard version and the size grouping gives

$$\widehat{disconnection} = -0.7352 - (1.0414 \times is2005) + (1.2308 \times isTransition2015) \\ - (0.3635 \times isTransition2020\_21) + (0.8465 \times is30to100kW)$$

Where the intercept represents <30kW sites on the 2015 standard.

- Continuing from the example above of the 20% probability that an AS4777.3:2005 site would disconnect, in this case a site on the same standard that is <30kW is predicted to disconnect 14% of the time compared to 28% for a site in the 30-100kW range.
  Of note is the fact that these numbers are no longer exactly equal to the observed disconnection rate of the sample and ***instead represent the average impact that each category has on the chance of disconnection***. The model is then used to predict the disconnection rate for each unique combination of predictor categories. This is multiplied by the CER installed capacity figure at the time of the event filtered into the same categories to get the estimated kW loss for that tranche.
- The kW loss figures for each tranche are added together to get an overall kW loss for the event.
- The confidence interval is found by repeating this process 5000 times with different subsets of the raw samples, and then taking the 2.5 and 97.5th percentiles to get a 95% confidence range.

B.3.2 Predictor selection

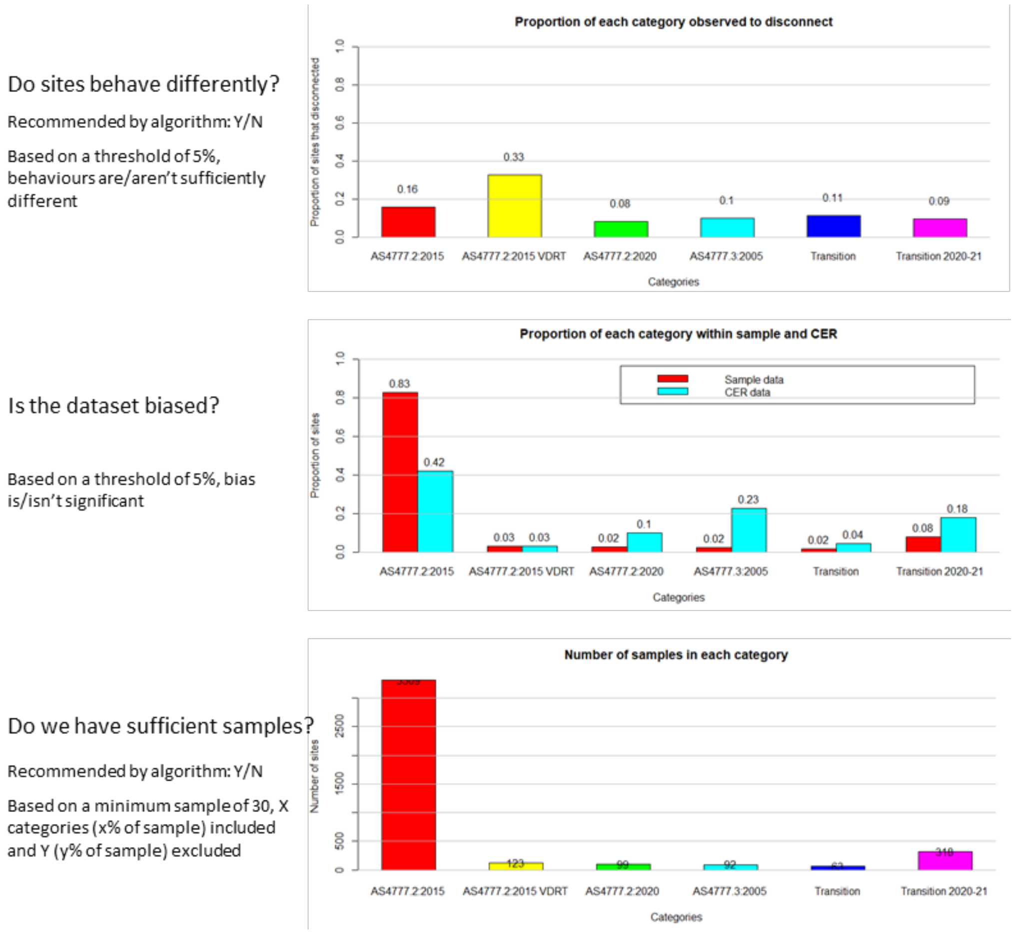
The predictors to use for upscaling are selected by assessing each of the options against the three criteria listed in Section B.1:

1. Do PV systems behave differently across a given category?
2. Is the data thought to be biased with respect to a given category?
3. Are there sufficient samples within each category to estimate the behaviour of the category?

DERDAT produces plots for each of these criteria (as in Figure 10) and performs an assessment based on set thresholds:

1. The difference in disconnection rate between categories is greater than 5%
2. The maximum difference in the proportion of the sample and proportion of the fleet in each category is greater than 5%
3. At least 40% of categories have 30 samples

The user can then choose which combination of predictors to use for upscaling or may test the predictors and compare the upscaled results.


Do sites behave differently?

Recommended by algorithm: Y/N

Based on a threshold of 5%, behaviours are/aren't sufficiently different

Is the dataset biased?

Based on a threshold of 5%, bias is/isn't significant

Do we have sufficient samples?

Recommended by algorithm: Y/N

Based on a minimum sample of 30, X categories (x% of sample) included and Y (y% of sample) excluded

Figure 10 – Example of the predictor evaluation plots produced in the Upscaling tab of DERDAT

B.3.3 Application to 25 May 2021 'Callide' event

Four predictors were considered for the 25 May 2021 Callide event and three DER datasets were separately analysed as summarised in Table 7. Predictor selection was based on the availability of fields within the datasets as well as the predictor selection method discussed in Section B.3.2.

Table 7 – Predictors and datasets for 25 May 2021 event upscaling

Predictor	Solar Analytics	Tesla	EQL-Luceo
Inverter manufacturer (OEM)	**Applied**	**Applied**	**Applied**
Standard version	**Applied**	Not applied	**Applied**
System capacity (<30kW, 30-100kW)	**Applied**	Not applied	Not applied
Geographical location	**Applied**	**Applied**	**Applied**

The predicted kW loss generated from applying each upscaling method to each of the datasets is shown in Figure 11. The 'raw' numbers represent the results of taking the total number of disconnections observed in the dataset divided by the total sample size and multiplying by the CER installed capacity without any weighting. These results show that upscaling tends to move all of the kW loss estimates closer to each other, but the EQL-Luceo estimate is still much higher than the numbers from the other two data sources.

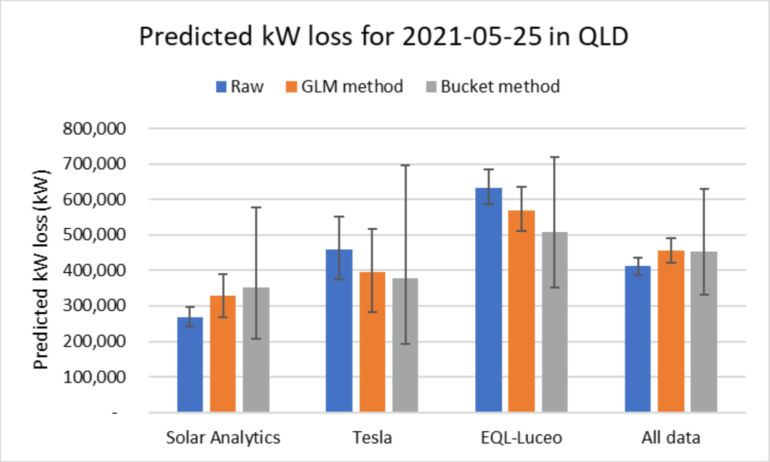


Figure 11 – Raw and upscaled kW loss estimates for each of the three datasets and the amalgamated data for the 25 May 2021 event.

Cross validation

K-folds cross validation was used to compare different GLM formulations and justify the choice of predictors used. The data was split into 10 equal sized test sets and each time the remaining 90% of the data was used to train a GLM. The GLM was then used to predict the kW loss of the other 10% of the data as if this was the fleet, and the actual and predicted kW loss figures compared.

For Solar Analytics, the GLM trained using all 4 predictors (manufacturer, standard, size group and zone) resulted in the lowest root mean square error (RMSE) and mean absolute error (MAE) of all of the formulations tested. It also had a lower error than the original bucket method, which is equivalent to a GLM m:st (trained using pairs of manufacturer and standard) and which had the highest RMSE. This provides a level of confidence in the GLM model for upscaling, and suggests that the current predictors are meaningful. This will be considered in future upscaling.

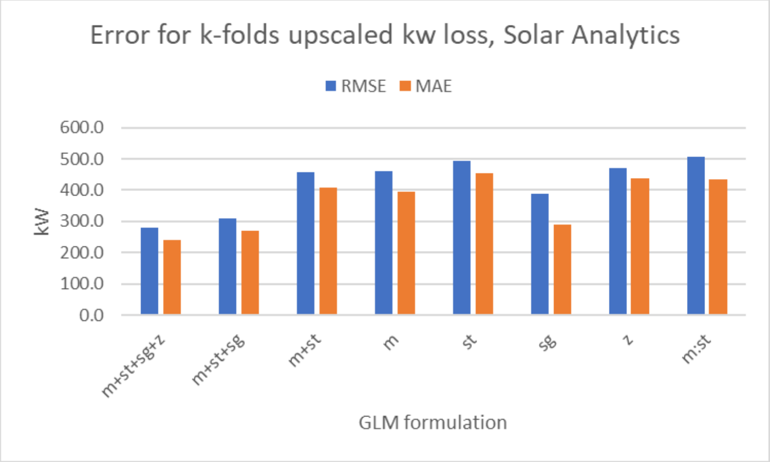


Figure 12 – K-folds cross validation errors for various GLM formulations

B.4 Error estimation

B.4.1 Background

The upscaling methods used within the DERDAT tool have an inherent level of uncertainty. Through Project MATCH, options to minimise the error bounds were considered, to improve the level of confidence in the upscaled results. The DERDAT tool processes convert a sample of thousands of inverter disturbance responses into an upscaled estimate, for instance total DPV capacity that disconnected in response to a disturbance. This upscaled estimate should ideally be accompanied by a confidence interval to reflect uncertainty caused by limitations in sample size. The uncertainty range should reflect significant differences between the complete inverter fleet and the inverter sample population across features such as inverter standard, OEM, and AC capacity.

Using the current method, the confidence intervals for the disconnection rate of a particular OEM/standard combination are relatively straightforward to compute, where the uncertainty of each tranche is added on to one another, to provide a wider band of uncertainty for the combined upscaling. It was identified that this method used for quantifying uncertainty provides a very wide range. To understand the reasoning for this, consider four disconnections from a sample of 30 inverters, all of which are from OEM A and on the 2015 standard. The sample disconnection proportion is determined to be 13.3%.

Numerically, the 95% Clopper-Pearson confidence interval for the population disconnection rate of all OEM-A, 2015-standard inverters is [0.0376, 0.3072] for this disturbance. Notice the significant skew in the confidence interval about 0.133: with 95% confidence, the population disconnection rate is estimated to be as much as 9.6% lower than the sample disconnection rate or up to 17.4% higher.

Now, assume that this asymmetrical range is apparent for multiple combinations of manufacturer and Standard. These are then summed together to provide a single uncertainty across the full dataset. This is complicated by the asymmetry in disconnection of the confidence intervals, then further magnified by the number of upscaling factors considered. For example, attempting to correct for inverter capacity in addition to manufacturer and standard adds another aggregation stage and greatly increases the number of confidence intervals produced.

The current method of quantifying uncertainty for upscaled estimates leads to wide error bounds, that will only grow as more factors are considered. Considering other numerical methods to quantify the uncertainty could reduce the error bounds. Through investigation of potential options, a numerical method known as bootstrapping was identified and is being investigated to supersede the current method.

B.4.2 Bootstrapping method

Bootstrapping initially treats the circuit sample as a population. The population is resampled with observation replacements, and the resampled circuit summary is used to produce an upscaled disconnection estimate. This process is repeated iteratively, a significant number of times (e.g. 1000 times), producing an empirical distribution of aggregate disconnection estimates. The 2.5 to 97.5 percentiles of these estimates form a 95% confidence interval for the aggregate disconnection estimate. The key to bootstrapping lies within the resampling process. Consider 100 disconnection observations from 500 circuits of a significant manufacturer and standard combination. After resampling, the disconnection rate of this combination is likely very close to 20%, and the empirical fleet disconnection distribution is tight. If only a single disconnection from a sample of 5 circuits is present for this combination, the disconnection rate could vary from 0 to 20 to 40% (or higher) after resampling. A much broader empirical disconnection distribution results, with a correspondingly wider confidence interval.

An example of how the confidence bounds change when using bootstrapping compared to the original method is shown in Figure 13.

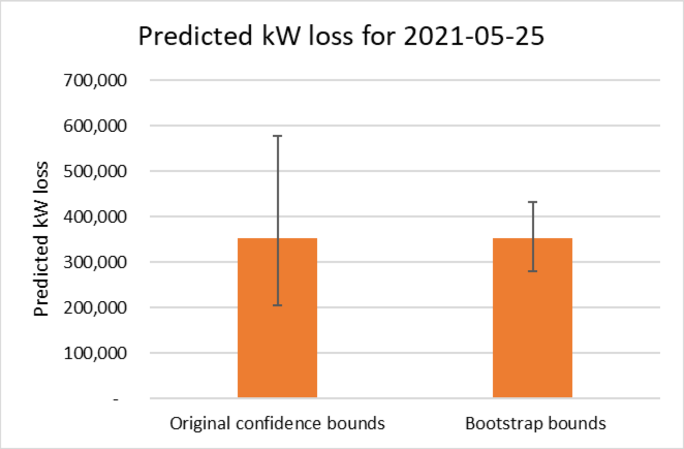


Figure 13 Comparison of confidence bounds with original and new bootstrap method.

B.5 Summary of improvements and further reading

The limitations of the previous upscaling method identified above are largely addressed through the GLM upscaling approach as summarised in Table 8.

Table 8 – Improvements gained by using the GLM method

Limitation of previous method	GLM improvements
There is a limit to the number of predictors that can be used	🟢 System capacity and geographic location were both added as options. Additional predictors may be added so long as there is information about them within the sample dataset and their prevalence in the fleet.
Categories must have a minimum number of sites	🟢 A minimum number of sites is still applied per predictor but not per unique combination of predictors. Effectively the data does not need to be divided into as many buckets, so more predictors can be used, likely improving accuracy.
Treatment of "other" sites	🟡 This is a continuing challenge. OEMs with a small number of samples are still grouped. Currently, missing predictor categories are removed and the user is required to address them separately.
Final confidence bounds are too wide	🟢 Confidence bounds are tightened through bootstrapping.

Resources for further reading can be found at the following:

Karreth, J. n.d. *Tutorial 11: Interaction terms*. Available at: http://www.jkarreth.net/files/RPOS517_Day11_Interact.html

Brambor, T., Clark, W. R., & Golder, M. (2006). Understanding Interaction Models: Improving Empirical Analyses. *Political Analysis*, 14(1), 63–82. http://www.jstor.org/stable/25791835

gung - Reinstate Monica (https://stats.stackexchange.com/users/7290/gung-reinstate-monica), Can I fit logistic regression over a dataset with only categorical data?, URL (version: 2017-10-17): https://stats.stackexchange.com/q/308470

UCLA: Statistical Consulting Group n.d., Logit Regression | R Data Analysis Examples. Available at: https://stats.oarc.ucla.edu/r/dae/logit-regression/

Ye, L., 2020. A Practical Guide to Bootstrap in R. Available at: https://towardsdatascience.com/a-practical-guide-to-bootstrap-with-r-examples-bd975ec6dcea

dfrankow (https://stats.stackexchange.com/users/2849/dfrankow), How to choose bootstrap confidence interval type from boot.ci in R?, URL (version: 2017-07-23): https://stats.stackexchange.com/q/292619