South Australian Under Frequency Load Shedding – Dynamic Arming

May 2021

Implementation investigation

A Report for SA Power Networks

Important notice

PURPOSE

This report presents analysis on Under Frequency Load Shedding (UFLS) and the potential benefits of dynamic arming of UFLS relays in the South Australian distribution network operated by SA Power Networks.

This report has been prepared by AEMO using information available at 30 March 2021. Information made available after this date may have been included where practical.

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VERSION CONTROL

Version	Release date	Changes
1	13 May 2021	Initial release
2	21 May 2021	Minor updates
3	4 August 2021	Minor updates

Executive summary

Under Frequency Load Shedding (UFLS) is an emergency frequency control scheme (EFCS) designed as the last line of defence to manage severe frequency disturbances. It involves the controlled disconnection of load to correct a large supply-demand imbalance. UFLS provides an important 'safety net' that reduces the likelihood of a cascading failure when severe disturbances occur.

Significant growth in distributed PV (DPV) has reduced the net load on the South Australian UFLS scheme. AEMO's analysis indicates that the amount of total net load on the South Australian UFLS scheme is now close to zero in many periods. This means that the capability of the UFLS scheme to arrest a severe frequency decline is significantly reduced. In the next few years, in the absence of intervention, the UFLS scheme will have the potential to operate 'in reverse', acting to exacerbate an under-frequency disturbance, rather than helping to correct it.

The deterioration of UFLS capability increases the risk of cascading failure events in South Australia. Each cascading failure event is estimated to have costs to customers in the range of $300-$500 million[1], and the black system event that occurred in South Australia on 28 September 2016 was estimated to cost commercial customers approximately $367 million (based on customer surveys).[2] It is important that the UFLS safety net is available and effective, to reduce the likelihood of these significant costs being incurred.

The levels of DPV now installed in Australia were not contemplated by the authors of the NER, and traditional approaches to UFLS are no longer effective in periods with large quantities of DPV generating. New actions are required to design and implement an effective emergency frequency control scheme that can successfully arrest a severe frequency decline in periods with large quantities of DPV operating.

AEMO has notified SA Power Networks (SAPN) and ElectraNet that due to the growing impacts of DPV, new steps are required to re-design the scheme, and increase the amount of load under the control of under frequency relays in South Australia. As one of those new steps, AEMO and SAPN have explored the introduction of 'dynamic arming' of UFLS relays in the South Australian distribution network. This involves changes to UFLS relays so that they will "disarm" when a given circuit is in reverse flow. This increases the net load available under the UFLS, and also mitigates the growing potential for operation of the scheme 'in reverse'.

This report summarises AEMO's analysis of dynamic arming to inform SAPN's design and implementation. The analysis is based on extensive information and data provided by SAPN, and uses forecast scenarios and sensitivities from AEMO's 2020 NEM Electricity Statement of Opportunities (ESOO).

Key findings

- Total net UFLS load in South Australia has been recorded as low as 12 MW (on 07 Nov 2020 13:36). At this time, total net UFLS load in SAPN's network was -60 MW, and total net UFLS load in ElectraNet's network was 72 MW.
- Based on a range of metrics, AEMO estimates that the total amount of net UFLS load in South Australia should be in the range of 800 – 1,200 MW to sufficiently reduce the impact of typical multiple contingency events observed historically, to meet the requirements of the NER.
- In the lowest load periods, dynamic arming is expected to provide the following benefits:

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[1] AEMO (November 2018) AEMO Request for Protected Event Declaration, https://www.aemc.gov.au/sites/default/files/2019-04/AEMO%20Request%20for%20protected%20event%20declaration.pdf

[2] AEMC (12 December 2019) South Australian black system review, https://www.aemc.gov.au/sites/default/files/documents/aemc_-_sa_black_system_review_-_final_report.pdf

  - **Prevent reverse operation of the South Australian UFLS**
    - If dynamic arming is not implemented, total net UFLS load in South Australia will decrease year on year and could reach as low as -470 MW by 2025. Negative load on the UFLS means that it can operate in reverse and exacerbate a frequency decline rather than helping to correct it. Dynamic arming will mitigate the incidence of reverse flows at UFLS relays, addressing this issue.
    - Preventing increasing levels of reverse flows on the UFLS is a prerequisite to any other actions to restore emergency frequency response to the required levels.
  - **Increase the amount of net load in the South Australian UFLS**
    - In the lowest load period in 2022, AEMO estimates that dynamic arming would increase SAPN UFLS load from around -190 MW to around 180 to 230 MW, an increase of approximately 370 to 420 MW.
    - In 2025, based on the 2020 ESOO High DER projection of DPV growth, AEMO estimates that dynamic arming would increase total net UFLS load from around -470 MW to around 150 to 200 MW, an increase of approximately 620 to 670 MW.
  - **Reverse and prevent further undermining of NEM-wide UFLS operation** – In the absence of intervention, total net UFLS load in South Australia is likely to reach zero and negative values in some periods during 2021. Zero and negative net UFLS load in South Australia will:
    - Under system intact conditions, decrease the effectiveness of the NEM-wide UFLS scheme, which is important for managing significant non-credible contingency events occurring in any region.
    - On triggering UFLS relays in reverse flow, result in unnecessary disconnection of South Australian customers, while exacerbating frequency decline.
    - Lead to increased disconnection of customers in other NEM regions to compensate for the circuits in South Australia in reverse flows that have been tripped.
  - **Restore safety nets for SA island operation** – If South Australia is operating as an island, any contingency that results in frequency falling just below 49 Hz could trigger DPV tripping and tripping of UFLS blocks in reverse flows, with minimal or no net load on UFLS to arrest further frequency decline. Dynamic arming will restore positive net load to the UFLS, and prevent operation of the scheme in reverse to exacerbate a disturbance, restoring this important safety net when South Australia is operating as an island.
- The benefits of dynamic arming are most significant in the lowest load periods. When total net UFLS load is higher (for example, above 800 MW), dynamic arming increases net UFLS load by a smaller increment (100 MW or less). This means that dynamic arming is unlikely to significantly reduce binding of the existing constraint on Heywood Interconnector flows into South Australia at times when net UFLS load is inadequate to prevent cascading failure following a non-credible separation. This constraint typically binds when net load in South Australia (and in the UFLS) is moderate, such that high imports on the interconnector can occur. Dynamic arming therefore only alleviates this constraint in a small number of periods. Dynamic arming would be a complementary measure to this constraint, managing different risks that arise from low and negative UFLS loads.

SAPN has advised that different sites in their network have varying costs for dynamic arming implementation, and varying levels of load restored (depending on the levels of reverse flows occurring at each location). AEMO's analysis, based on SAPN's data, suggests that dynamic arming can be introduced at a proportion of SAPN sites to achieve the majority of the benefit in increased UFLS load.

Based on SAPN's cost and load data, AEMO estimates that 95% of the total additional net UFLS load available from dynamic arming could be achieved by implementing dynamic arming at all locations in SAPN's network that satisfy a cost threshold of $390-510 per MWh of UFLS load gained per year.

This is estimated to have a total cumulative cost of $17.9-20.2 million in the initial rollout (from 2021 to 2023), with an additional cost of up to $5.3 million in the subsequent rollout (2024 to 2025) as a small number of additional sites move further into reverse flows and therefore fall below the cost threshold. Targeting 95% of the total load available from dynamic arming aims to achieve a reasonable balance between the cost of implementation and the amount of UFLS load restored. AEMO therefore recommends that dynamic arming is implemented at any site where the $/MWh cost for implementation is below this indicative range.

AEMO understands that SAPN's network has complex configurations which require detailed site-specific analysis. This report is intended to provide a framework and guideline of acceptable cost thresholds to enable SAPN to determine optimal dynamic arming configurations on a site-by-site basis.

AEMO estimates that the total amount of load required for proper functioning of the South Australian UFLS is likely in the range 800 to 1,200 MW (this range will be confirmed with further studies underway at present). Although dynamic arming considerably increases the amount of net UFLS load from large negative values (as described above), even with dynamic arming implemented at all sites, total net UFLS load in the lowest load periods is only restored to 180 to 230 MW in 2022, and 150 to 200 MW in 2025. This suggests that significant further work is required to adequately restore emergency frequency control capabilities. It is noted that the commissioning of the proposed EnergyConnect interconnector will not reduce the South Australian UFLS requirement; these capabilities remain required as part of the NEM-wide UFLS scheme, for management of a wide range of possible non-credible contingency events (both foreseen and unforeseen). AEMO therefore suggests that other options for increasing UFLS load are considered in parallel with implementation of dynamic arming. This could include exploring options for moving UFLS trip devices to the customer site level, to facilitate separation of customer load and distributed generation.

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1. Introduction

Under Frequency Load Shedding

Under Frequency Load Shedding (UFLS) is activated in the event of a large disturbance that causes an extreme frequency change that is beyond the containment capability of frequency control ancillary services (FCAS). UFLS is a last resort mechanism that involves the automatic disconnection of load in an attempt to rapidly rebalance the system.

UFLS load is arranged in discrete "blocks", with each block activated at a certain frequency and time delay setting. More sensitive loads are placed in the lowest frequency blocks, so they are tripped last. The frequency and time delay settings associated with UFLS blocks are periodically reviewed by AEMO to optimise effectiveness.

AEMO's responsibilities

Under the National Electricity Rules (NER) clause 4.3.1, AEMO has responsibility for assessing the availability and adequacy of contingency reserves, to ensure appropriate levels of reserves are available to ensure the power system is maintained in a satisfactory operating state, and to arrest the impacts of a range of significant multiple contingency events (affecting up to 60% of the total power system load), taking into account under-frequency initiated load shedding capability (by emergency frequency control schemes or otherwise).

To meet these responsibilities, AEMO has assessed the availability and adequacy of emergency frequency control schemes (EFCS) in South Australia, designed as a 'last line of defence' to manage multiple contingency events including separation events. The EFCS includes the UFLS scheme. Detailed analysis of UFLS adequacy was reported as part of AEMO's 2020 Power System Frequency Risk Review (PSFRR)[3].

In traditional power systems, the network typically operates in a single direction, supplying electricity from generators to loads. Growth in distributed generation now means that some parts of the network flow in reverse in some periods. This constitutes a significant change in the operation of the power system, with implications for many systems and control schemes, including UFLS. When the NER was first drafted, power system operation in this manner was not foreseen or contemplated. This means that new steps are required to re-design this important emergency frequency control scheme.

AEMO's analysis indicates that the amount of total net load available for shedding under the UFLS scheme in South Australia in many periods is now far less than required to meet the NER objectives, due to growth in DPV. Furthermore, when UFLS circuits move into reverse flows, in the absence of intervention, the operation of UFLS relays will act to exacerbate an under-frequency disturbance, rather than helping to correct it. AEMO's analysis has demonstrated that in some periods, the South Australian UFLS scheme is now inadequate to arrest the impacts of major non-credible contingency events, including the separation of South Australia from the rest of the NEM. While such occasions are rare at present, an increasing number of periods are likely to be affected over time. Reducing net UFLS load in South Australia also reduces the effectiveness of the NEM-wide UFLS scheme.

Network Service Provider responsibilities

Network Service Provider (NSP) responsibilities relating to UFLS are outlined in Table 1.

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[3] AEMO (July 2020) 2020 Power System Frequency Risk Review – Stage 1, Appendix A1. https://aemo.com.au/-/media/files/stakeholder_consultation/consultations/nem-consultations/2020/psfrr/stage-1/psfrr-stage-1-after-consultation.pdf?la=en

Table 1 NSP responsibilities relating to UFLS

NER clause	Requirement
4.3.4(b1)	Each Network Service Provider must, in accordance with clause S5.1.10.1a of schedule 5.1, cooperate with AEMO in relation to, design, procure, commission, maintain, monitor, test, modify and report to AEMO in respect of, each emergency frequency control scheme which is applicable in respect of the Network Service Provider's transmission or distribution system.
S5.1.10.1a	Each Network Service Provider in consultation with AEMO must ensure that sufficient load is under the control of underfrequency relays or other facilities where required to minimise or reduce the risk that in the event of the sudden, unplanned simultaneous occurrence of multiple contingency events, the power system frequency moves outside the extreme frequency excursion tolerance limits.
S5.1.10.1c	A Network Service Provider must use reasonable endeavours to achieve commissioning of a new or upgraded emergency frequency control scheme within the time contemplated by the relevant power system frequency risk review or, where applicable, AEMO's request to the Reliability Panel for declaration of a non-credible contingency event as a protected event and the decision of the Reliability Panel with respect to that request.
S5.1.10.2	A Distribution Network Service Provider must: (a) provide, install, operate and maintain facilities for load shedding in respect of any connection point at which the maximum load exceeds 10MW in accordance with clause 4.3.5 of the Rules; (c) apply frequency settings to relays or other facilities as determined by AEMO in consultation with the Network Service Provider;
S5.1.8	In planning a network a Network Service Provider must consider non-credible contingency events such as busbar faults which result in tripping of several circuits, uncleared faults, double circuit faults and multiple contingencies which could potentially endanger the stability of the power system. In those cases where the consequences to any network or to any Registered Participant of such events are likely to be severe disruption a Network Service Provider and/or a Registered Participant must in consultation with AEMO, install, maintain and upgrade emergency controls within the Network Service Provider's or Registered Participant's system or in both, as necessary, to minimise disruption to any transmission or distribution network and to significantly reduce the probability of cascading failure.

AEMO has notified SAPN and ElectraNet that the amount of load under the control of under frequency relays in South Australia is no longer sufficient to meet the requirements of the NER, due to substantial growth in DPV. DPV at these levels was not foreseen or contemplated by the authors of the NER, and new steps are required to re-design the scheme. In response, SAPN and ElectraNet have collaborated with the Office of the Technical Regulator (OTR) to identify a number of further loads to be added to the UFLS scheme. This provides an incremental improvement to UFLS capability, but limited further load is available to be added via this approach and the amount of net load under the UFLS remains far less than required. Where there are opportunities to add further customers to the UFLS it is recommended that these be pursued, but this will not be sufficient in isolation.

To further increase net load available for UFLS and mitigate the risks associated with tripping circuits in reverse flows, as part of a suite of potential additional measures, AEMO has proposed that SAPN consider implementing "dynamic arming" capability for UFLS relays.

Definition of dynamic arming

For the purposes of this report, "dynamic arming" refers to UFLS relays arming and disarming automatically as the relevant UFLS circuit moves in and out of reverse flows. The relay continuously monitors flows on the circuit, and updates the arming status of that relay accordingly. This prevents tripping of UFLS circuits that are in reverse flows, helping to slow the decline in UFLS effectiveness as DPV continues to be connected to the network.

In some locations this can be implemented via changes to the settings of existing relays, and in other locations a replacement of the relay is required.

Impacts of reverse flows

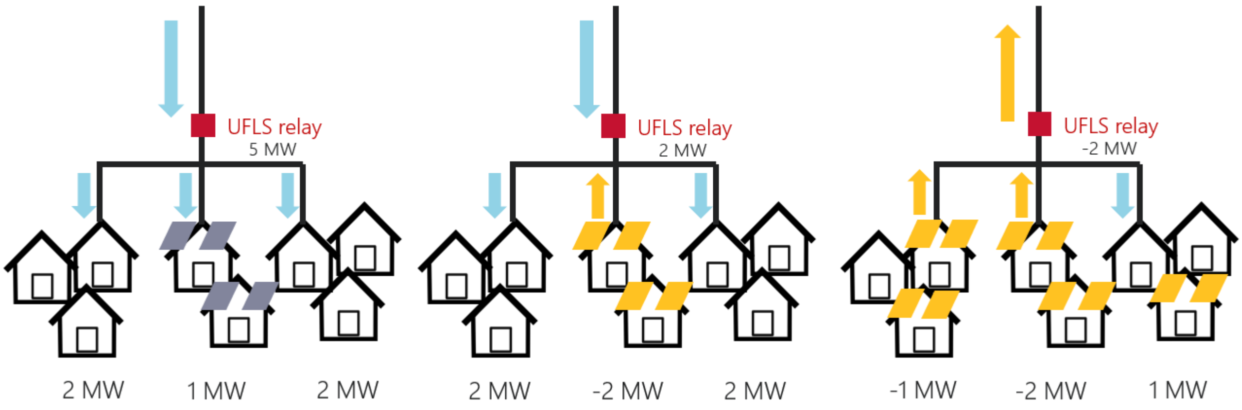
The continued growth of DPV in South Australia means that many feeders now operate in reverse flows during the day, as illustrated in Figure 1. At present, UFLS relays do not measure the direction of active power flow on their circuits.

Reverse flows have a two-pronged impact on the effectiveness of UFLS:

- **Reducing net load –** As illustrated in the middle panel in Figure 1, feeders in reverse flow offset load from other feeders, reducing the amount of net load available to be shed on the UFLS circuit.
- **Exacerbating frequency decline on UFLS activation –** As more DPV is installed, the total load on the UFLS circuit will go into reverse flows, as shown in the right hand panel in Figure 1. In the absence of dynamic arming, UFLS operation will open the circuit regardless of the direction of active power flow. This outcome is directly opposite to the intention of the UFLS, and reduces UFLS effectiveness. It also results in unnecessary disconnection of customers.

Figure 1 Reduction in load from reverse flows

Night time load	Reduced net load	Exacerbating frequency decline



When many of the UFLS circuits at a certain frequency trip setting are simultaneously in reverse flows, the entire UFLS load block at that trip frequency will move into reverse flows. When an entire UFLS load block is in reverse flow, the tripping of that block at its designed frequency threshold will act to accelerate frequency decline across the network.

The impacts of reverse flows are already being extensively observed in SAPN's network. In 2020:

- In some periods, more than half of the UFLS load blocks in South Australia were in reverse flows.
- At least one UFLS trip frequency block in SAPN's network was in reverse flow for approximately 6% of the year.
- UFLS blocks most often observed in reverse flow were those at the start of the scheme, designed to trip at higher frequency thresholds of 48.75 Hz and above. This means that reverse flow impacts are affecting the frequency blocks that are triggered first.

Dynamic arming mitigates the risks posed by reverse flows by disarming UFLS relays when they are in reverse flows. This aids in preserving load on the UFLS and prevents UFLS activation from accelerating frequency decline.

SAPN has advised AEMO that the majority of existing UFLS relays in their network do not have the capability to detect active power flow direction and use this information to dynamically arm or disarm. This means that existing relays will need to be upgraded or reprogrammed to introduce this capability.

Purpose of this report

This report summarises analysis on the dynamic arming approach, including:

- Estimation of the minimum amount of load in the South Australian UFLS that would be sufficient to arrest frequency decline following a major underfrequency event.
- The estimated benefits of implementing dynamic arming of UFLS circuits, which include:
  - Increasing the net load in the scheme, improving the effectiveness of the UFLS in arresting a frequency decline
  - Power system security benefits for managing non-credible contingency events when operating a South Australian island
  - Improving performance of NEM-wide UFLS operation
  - Avoiding unnecessary disconnection of customers in both South Australia and other regions
  - Some economic benefits of alleviating constraints on the Heywood interconnector
- An indicative proposal for the proportion of UFLS circuits that should have dynamic arming capabilities introduced, balancing costs and benefits.
- The potential additional benefits available from “adaptive arming” (real-time adjustments to UFLS frequency settings, beyond a simple arm/disarm when reverse flows are detected).
- Other additional work to restore UFLS load.

This is intended to inform SAPN’s design and implementation of dynamic arming, and further work programs to restore UFLS capabilities.

2. Amount of UFLS load required

2.1 Amount of load in the SA UFLS scheme

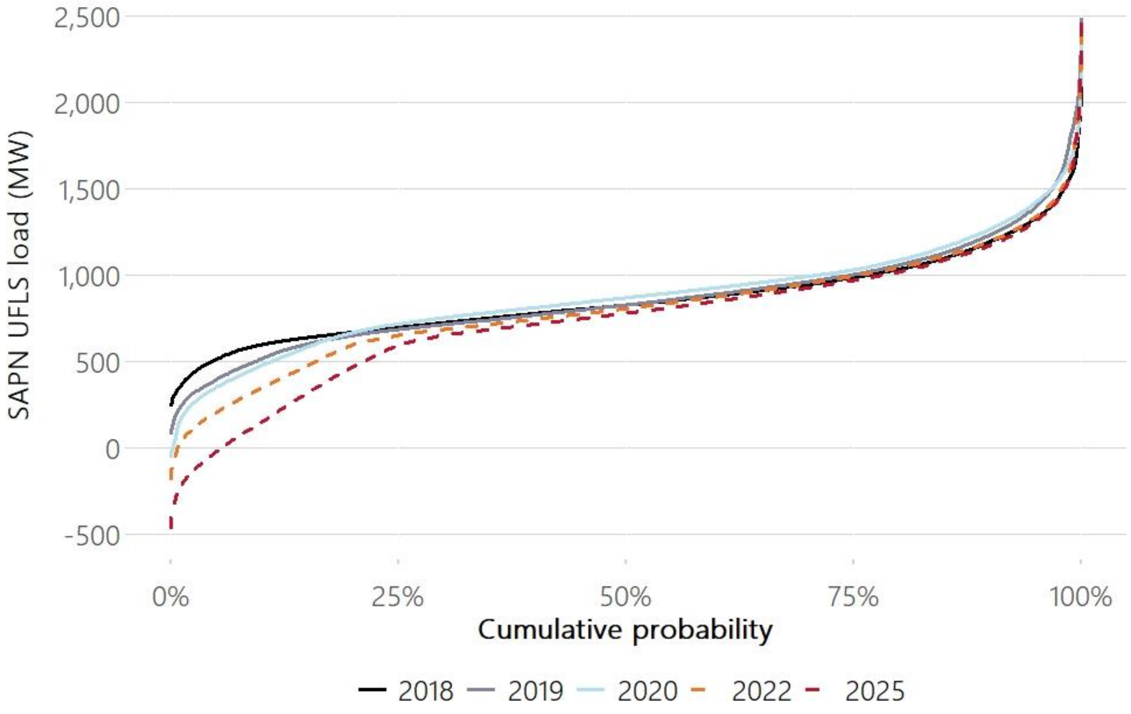
Continuing growth in DPV has considerably reduced, and is continuing to reduce the amount of net load in the South Australian UFLS scheme, as shown in Figure 2. In 2020, AEMO measured historical periods with total SA UFLS load as low as 12 MW, with SAPN UFLS load reaching negative values as low as -60 MW, as shown in Table 2.

Table 2 Minimum load measured on SA UFLS

Date/time (ACST)	SAPN UFLS load	ElectraNet UFLS load	Total SA UFLS load
13-Sep-20 12:36:00	7	53	60
11-Oct-20 13:01:00	-26	66	40
07-Nov-20 13:36:00	-60	72	12

Figure 2 shows the distribution of total SAPN UFLS load over time. Total SAPN UFLS load was below 600 MW 10% of the time in 2018, 14.8% of the time in 2019 and 15.3% of the time in 2020. Based on the 2020 ESOO High DER forecast, by 2025 total net SAPN UFLS load is projected to be less than 600 MW 25% of the time, and below zero 6% of the time.

Figure 2 Total net SAPN load on UFLS



The total UFLS load from ElectraNet's transmission connected customers is somewhat erratic and can vary substantially over time. As an interim measure to incrementally restore UFLS load, ElectraNet has added a number of new transmission-connected customers to the UFLS scheme from October to November 2020, with additional loads to be added in 2021. In the period prior to introduction of new customers, UFLS load from ElectraNet's transmission connected customers ranged from 0 to 80 MW with extensive intra- and inter-day variability. Following the addition of new loads in Oct-Nov 2020, total transmission-connected load was still low in some periods, reaching as low as 5 MW on 14 December 2020.

Outages of major customers can also significantly reduce the ElectraNet load on UFLS. These factors mean that this transmission connected load, while significant when present, might not always be available in low demand periods. Further, significant reverse flows occur most frequently on SAPN's network. For these reasons, AEMO's analysis on dynamic arming has focused on SAPN UFLS load, which can be complemented by the load from ElectraNet customers when available.

2.2 Amount of UFLS load required

The NER requires:

- Sufficient load should be under the control of underfrequency relays or other facilities to minimise or reduce the risk that in the event of the sudden, unplanned simultaneous occurrence of multiple contingency events, the power system frequency moves outside the extreme frequency excursion tolerance limits (defined in the Frequency Operating Standard[4] to be 47 – 52 Hz) (NER clause S5.1.10.1a).
- The amount of reserves should be sufficient to arrest the impacts of a range of significant multiple contingency events affecting up to 60% of the total power system load (NER clause 4.3.1).

A wide range of possible multiple contingency events could be considered relevant. The following sections explore a number of different methods for estimating the amount of UFLS load that could be considered "sufficient".

2.2.1 Plausible multiple contingency events

Plausible multiple contingency events for consideration can be informed by observed historical events. Historical multiple contingency events in South Australia, and historical events where UFLS was activated, are summarised in Table 3. **These historical events suggest that multiple contingency events causing supply-demand imbalances and load shedding in South Australia of up to 1,000 MW are plausible.**

Table 3 Historical contingency events

Date, Time (AEST)	Description	Supply interrupted in SA	Contingency size	Sufficient load shed by UFLS?	Minimum frequency (Hz)
2 Dec 1999, 13:11	Trip of both units at Northern Power Station (520 MW). This led to a significant increase in imported power flowing through the Heywood Interconnector, leading to SA separation from the rest of the NEM.	1,130 MW 1,050 MW load shed on UFLS	Northern Units: Unit 1 and then 2 (520 MW in 40s) Loss of interconnector (469 MW) Total supply imbalance: 989 MW	Yes	47.8

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[4] AEMC Reliability Panel (effective 1 January 2020), Frequency Operating Standard, https://www.aemc.gov.au/sites/default/files/2019-12/Frequency%20operating%20standard%20-%20effective%201%20January%202020%20-%20TYPO%20corrected%2019DEC2019.PDF

Date, Time (AEST)	**Description**	**Supply interrupted in SA**	**Contingency size**	**Sufficient load shed by UFLS?**	**Minimum frequency (Hz)**
8 Mar 2004, 11:28	Runback of both units at Northern Power Station (480 MW)	650 MW	480 MW	Yes	47.6
14 Mar 2005, 06:39	Runback of both units at Northern Power Station (465 MW)	580 MW	465 MW	Yes	47.6
1 Nov 2015, 21:51[5]	Trip of the South East – Heywood No.1 275 kV transmission line (Line 1), that resulted in the SA power system partially separating from the rest of the NEM (232 MW)	105 MW of UFLS load (49Hz band) 160 MW load tripped due to disturbance (not UFLS)	232 MW	Yes	48.96
28 Sept 2016, 16:18[6]	Tornadoes caused a sequence of faults in quick succession, leading to a sustained reduction of 456 MW from nine wind farms. This led to a significant increase in imported power flowing through the Heywood Interconnector, leading to SA separation from the rest of the NEM.	1,895 MW (Black System)	Loss of multiple wind farms: 456 MW Supply demand imbalance: ~900 MW	No	NA
1 Dec 2016, 00:16[7]	Trip of the Moorabool–Tarrone 500 kilovolt (kV) transmission line, as a result of equipment failure, resulting in separation of South Australia from the rest of the NEM	190 MW UFLS load shed	242 MW	Yes	48.8

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[5] AEMO (February 2016) Load Shedding in South Australian on Sunday 1 November 2015, at https://aemo.com.au/-/media/archive/load-shedding-in-south-australia-on-sunday-1-november-2015.pdf

[6] AEMO (March 2017) Black System South Australia 28 September 2016, at https://aemo.com.au/-/media/files/electricity/nem/market_notices_and_events/power_system_incident_reports/2017/integrated-final-report-sa-black-system-28-september-2016.pdf?la=en&hash=7C24C97478319A0F21F7B17F470DCA65

[7] AEMO (28 February 2017) Final Report – South Australia Separation Event, 1 December 2016, at https://aemo.com.au/-/media/files/electricity/nem/market_notices_and_events/power_system_incident_reports/2017/final-report---sa-separation-event-1-december-2016.pdf?la=en&hash=E38712992D459AFA19421E48925A4B7D

Date, Time (AEST)	Description	Supply interrupted in SA	Contingency size	Sufficient load shed by UFLS?	Minimum frequency (Hz)
3 Mar 2017, 15:03[8]	A series of faults at ElectraNet's Torrens Island 275kV switchyard resulted in the loss of approximately 610 MW of generation in South Australia across five generating units.	There was no operation of UFLS in this event, and SA separation did not occur. A net 400 MW drop in demand in SA was observed as a result of this incident, which was related to unintended disconnection of customer load and DPV in response to the severe faults that occurred. With the levels of DPV now operating in South Australia in some periods, AEMO's analysis indicates that the same faults could result in a net increase in load (due to disconnection of DPV exceeding disconnection of load), which would increase the contingency size.	610 MW	NA	49.77 Hz (NEM mainland)

2.2.2 Loss of the Heywood Interconnector

AEMO's analysis on South Australian UFLS adequacy to date[9] has focused on the non-credible loss of the Heywood Interconnector, since this is a significant non-credible contingency event that has occurred on multiple occasions, and for which South Australia relies on UFLS response to avoid cascading failure.

A set of constraints were developed to limit imports (flows from Victoria to South Australia)[10] on the Heywood interconnector when UFLS load is insufficient to confidently avoid cascading failure if a non-credible separation event occurs[11]. The constraint set adjusts dynamically in real-time based on measured factors and contains a rate of change of frequency (RoCoF) constraint and a regression-based UFLS component constraint.

The RoCoF constraint is an update and extension of the constraint set originally introduced to meet the requirements of the limits advice provided to AEMO by ElectraNet under regulation 88A of the Electricity (General) Regulations 2012 (SA). Due to the risks identified at RoCoF levels in the 2-3 Hz/s range, the updated constraint reduces instantaneous RoCoF limit for imports into South Australia from 3Hz/s to 2Hz/s, and only applies to periods where the Heywood interconnector is importing into South Australia. The limit for exports across Heywood from South Australia into Victoria will remain unchanged at 3Hz/s.

The UFLS constraint requires that when total UFLS load in South Australia is less than 1,000 MW:

> *VIC to SA flows on the Heywood Interconnector are limited to the maximum of:*
>
> - *Available Fast Active Power Response (FAPR)*
> - *-50.7 + 1.3*Inertia - 0.1*DPV generation + 0.6*(UFLS load – 30) + 0.3*FAPR – 25*
> - *0*

For typical levels of inertia, DPV generation and FAPR, binding of the UFLS constraint can generally be avoided if net UFLS load remains in the range 800 – 1,000 MW[12]. This level is higher than the original contingency size (with imports on the Heywood interconnector limited to 650 MW) partly due to unintended disconnection of DPV (which increases the contingency size when the frequency falls below 49Hz), and partly

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[8] AEMO (10 March 2017) Fault at Torrens Island switchyard and loss of multiple generating units on 3 March 2017, at https://www.aemo.com.au/-/media/Files/Electricity/NEM/Market_Notices_and_Events/Power_System_Incident_Reports/2017/Report-SA-on-3-March-2017.pdf

[9] AEMO (December 2020) Power System Frequency Risk Review – Stage 2 Final Report, at https://aemo.com.au/-/media/files/stakeholder_consultation/consultations/nem-consultations/2020/psfrr/stage-2/2020-psfrr-stage-2-final-report.pdf?la=en

[10] Regarding flows across the Heywood interconnector, this report uses the term 'import' to refer to flows from Victoria into South Australia, and 'export' to refer to flows from South Australia to Victoria.

[11] AEMO (October 2020), Heywood UFLS Constraints, https://www.aemo.com.au/-/media/files/initiatives/der/2020/heywood-ufls-constraints-fact-sheet.pdf?la=en

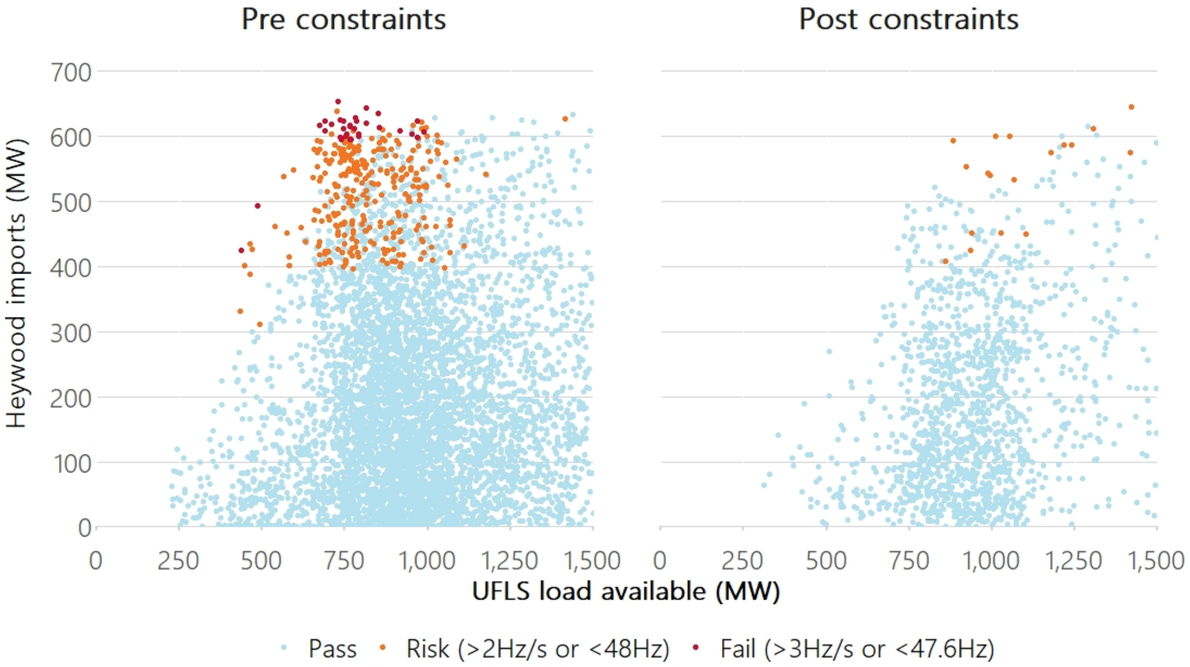
[12] Analysis considered inertia in the range of 4,500 MWs to 16,000 MWs, DPV in the range of 0 GW to 1 GW, and FAPR of 150 MW.

because of margins allowed in the constraint design (for example, the constraint is designed to provide confidence that "risk" conditions will be avoided, which requires allowing a buffer above the minimum allowable frequency nadir).

The constraint set performance was assessed using a modelled representation of the South Australian network. The model used 2020 historical dispatch outcomes, Frequency Control Ancillary Service (FCAS) availabilities and half-hourly UFLS load data from SAPN and ElectraNet. Model outcomes are summarised in Figure 3, with each dot representing a simulation of a dispatch interval with various levels of Heywood imports and UFLS load. Light blue dots represent simulations that met all acceptance criteria, red dots represent simulations that are very likely to lead to cascading failure, and orange dots represent 'risk' conditions. Grey and navy dots represent half-hour periods in which the UFLS constraints bound in at least one five-minute dispatch interval, with grey representing the RoCoF constraint and navy the UFLS constraint.

The Heywood UFLS constraints were implemented in October 2020, and Figure 3 illustrates that they have acted to remove all fail cases and the majority of risk cases. The risk cases post constraint implementation are from RoCoF levels slightly above 2 Hz/s, which arise due to timestep issues: because the RoCoF constraint is always one dispatch interval behind real-time inertia, deviation occurs in some periods.

Figure 3 Summary of SA model outcomes for using historical dispatch, FCAS and UFLS load availabilities from 2020



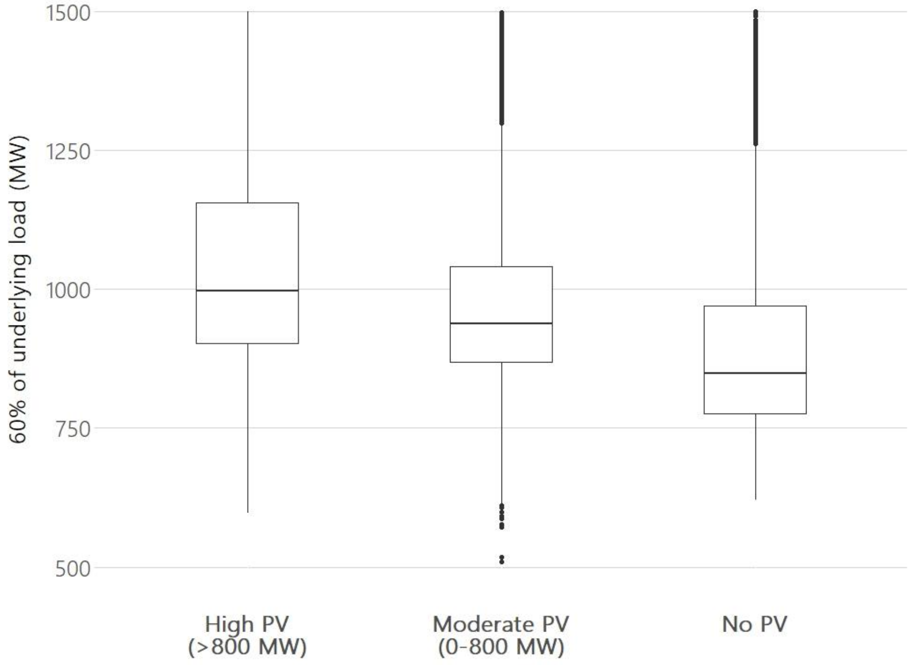
2.2.3 60% of power system load

The NER indicate that the amount of reserves should be sufficient to arrest the impacts of a range of significant multiple contingency events affecting up to 60% of the total power system load (NER clause 4.3.1). With the emergence of large quantities of DPV, not contemplated by the authors of the NER, the precise definition of 'load' in this clause has become unclear. Interpreting the original intention of the NER authors, AEMO have assessed this 60% level against total underlying customer load, as the best measure of total "actual" customer load in the new context with high levels of DPV. The alternative is to assess this measure against operational (net) demand, which would imply no load reserves are required as operational demand approaches zero. It is considered unlikely that the authors of the NER contemplated, or would accept, negative or zero load reserves as adequate. Therefore, assessing against total underlying customer load is proposed as the more sensible measure of total power system load, better reflecting the original intentions of the NER.

In previous UFLS assessments, the definition of load and how it relates to DPV generation has not been considered. Given the substantial growth in DPV, there is now a new requirement to consider DPV when assessing UFLS adequacy in daytime periods in South Australia.

Figure 4 shows the range of load equating to 60% of underlying load in South Australia. The central bar in each box shows the median, while the outer edges of each box show the first and third quartiles (25th and 75th percentiles). In periods with high PV generation, the 60% of underlying load measure would require total SA UFLS load in the range 900 – 1,150 MW (based on the first and third quartiles), while in periods with no PV generation, target total UFLS load based on the first and third quartiles for the 60% measure would be in the range 770 – 950 MW.

Figure 4 60% of underlying load in South Australia – 2020



This suggests that contingency events affecting up to 60% of the total power system load (the level indicated in the NER) are in the range of approximately 800 – 1,200 MW (based on the interquartile ranges in Figure 4).

2.2.4 Summary

Table 4 provides a summary of the various reference points that indicate the approximate level of net UFLS load required in South Australia. **These various measures converge on an estimated net UFLS load requirement in the range 800 – 1,200 MW.**

Table 4 Reference points for estimating total amount of net UFLS load required in South Australia

Indicative measure	Details	Indicative MW level
Plausible multiple contingency events	Observed historical multiple contingency events have caused supply-demand imbalance/UFLS activation in this range.	Up to 1,000 MW

Indicative measure	Details	Indicative MW level
Loss of the Heywood interconnector (based on Heywood import constraint formulation)	Sufficient UFLS load to avoid binding of the present Heywood import limit (avoiding cascading failure if separation occurs).	UFLS load required: 800 to 1,000 MW
60% of the total power system load (NER reference)	Calculated as 60% of underlying load in historical year 2019-20 (interquartile ranges)	800 to 1,200 MW

Based on this analysis, AEMO recommends that ElectraNet and SAPN take immediate action with the objective of increasing net UFLS load in South Australia to the range of 800 – 1,200 MW, as far as this is economically and technically feasible. If UFLS load levels are not increased to this range, South Australia will be operating without the last resort 'safety net' that was originally intended by the authors of the NER, and will be at increased risk of cascading failure. The emergence of large quantities of DPV means that traditional approaches to UFLS are no longer effective, and new steps are required to redesign the UFLS scheme. Novel approaches are likely to be required, and are explored further in Section 5. Implementation of the most effective and economical options for restoration of an effective emergency under frequency response may require rule changes.

3. Benefits from dynamic arming

3.1 Load gained from dynamic arming

This section provides an estimate of the amount of additional UFLS load that will be gained by implementing dynamic arming. As noted in previous sections, the level of load in the UFLS at present is insufficient, which means that South Australia is operating without the intended last resort 'safety net', and is therefore at increased risk of cascading failure until this capability is restored.

3.1.1 Approach

Forward projections of feeder level load and DPV generation

SAPN provided feeder-level half-hourly net load measurements and DPV installed capacity estimates for each feeder in their network for 2018-19.

AEMO calculated a forward projection of the half-hourly load and DPV generation on each feeder, assuming historical half hourly patterns of underlying load at each feeder, and DPV capacity factor for South Australia, were identical to the historical reference year (2018-19). For each feeder, in each half hour, underlying load in the reference year was estimated as follows:

Underlying load (2018-19) = Net load (2018-19)

+ DPV installed capacity (2018-19) x DPV capacity factor (2018-19)

DPV installed capacity and underlying load was then proportionally increased at each feeder, at the growth rates projected for the South Australian region in three different scenarios:

- **Central scenario** – from the 2020 Electricity Statement of Opportunities (ESOO)[13]
- **High DER scenario** – from the 2020 ESOO
- **Linear growth scenario** – Assuming linear growth in DPV continuing at the rate observed in South Australia in 2019 (208 MW pa), with no load growth. Note that DPV increased by 290 MW in South Australia in 2020, the highest recorded yearly growth rate for DPV in the region[14]. This scenario therefore projects a significant slowing in DPV growth from the present rate.

Net load at each feeder in each half hour in the future projection was then calculated as follows:

Net load (2022-23) = Underlying load (2018-19) x load growth scaling factor

- DPV installed capacity (2018-19) x DPV growth scaling factor x DPV capacity factor (2018-19)

Benefits of dynamic arming

The maximum possible benefits from dynamic arming were estimated by assuming that any UFLS relay on a circuit that moves into reverse flows would be "disarmed", such that negative net load on that circuit would not reduce the total net UFLS load available. The analysis considers two different levels at which dynamic arming can be implemented:

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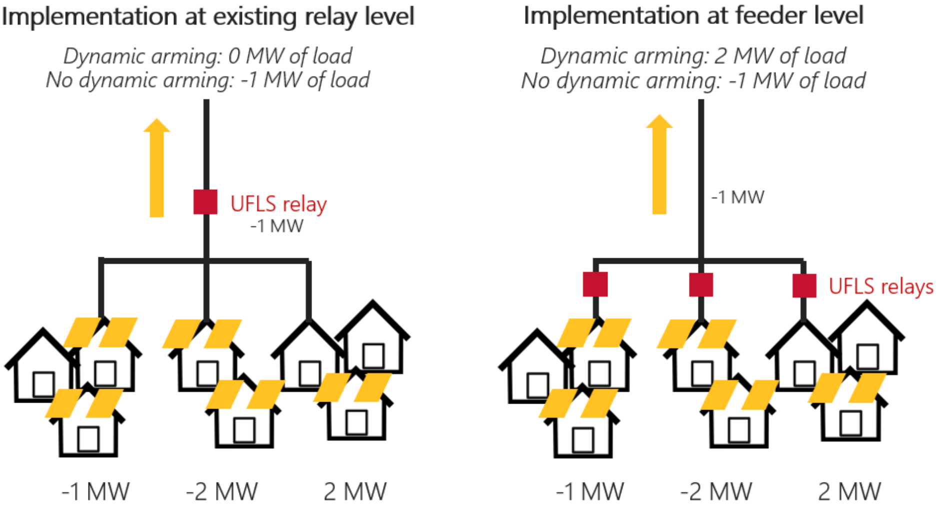
[13] AEMO (August 2020) 2020 Electricity Statement of Opportunities, at https://aemo.com.au/-/media/files/electricity/nem/planning_and_forecasting/nem_esoo/2020/2020-electricity-statement-of-opportunities.pdf?la=en&hash=85DC43733822F2B03B23518229C6F1B2

[14] This unusually high rate of growth may be related to the COVID-19 pandemic.

- **Existing relay level** – Introducing dynamic arming at the existing UFLS relay level throughout the network. Where existing relays incorporate multiple feeders, the UFLS relay will only be disarmed if the sum of all feeders relating to that circuit breaker is in reverse flows. In some cases this results in a reduced amount of load being recovered for UFLS, as illustrated in the left panel of Figure 5.
- **Feeder level** – In some locations, it may be cost effective to move the location of relays so individual feeders can be armed and disarmed separately. Each feeder would be disarmed separately as they individually reach reverse flows, as illustrated in the right panel of Figure 5. In some cases, an increased amount of load is recovered for UFLS. Modelling the load gained from dynamic arming at the feeder level therefore provides an estimate of the maximum benefit available from dynamic arming.

Figure 5 Levels at which dynamic arming can be implemented



3.1.2 Findings

Figure 6 shows the total net UFLS load in South Australia on SAPN's network in the period of the lowest UFLS load, which reached a minimum of -60 MW in 2020. Under the existing UFLS configuration, without implementation of dynamic arming, UFLS load is projected to fall to an estimated -120 to -360 MW in the lowest period in 2022.

Figure 6 Total SAPN UFLS load in the lowest UFLS load period – no dynamic arming

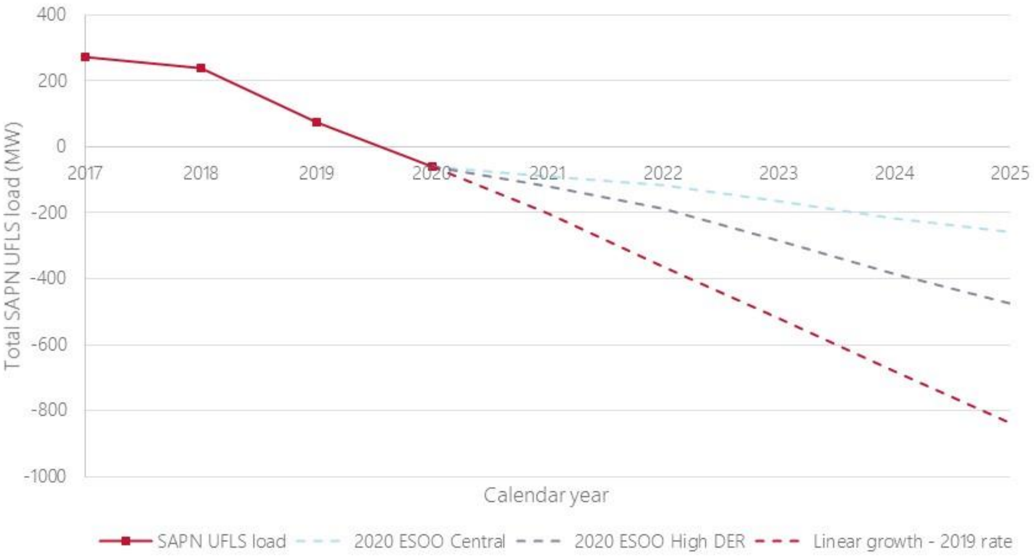


Figure 7 shows the amount of net UFLS load that could be achieved by introducing dynamic arming at all sites where reverse flows are occurring, comparing implementation at the existing relay level with implementation at the more granular feeder level, for the ESOO High DER scenario. In 2022, introduction of dynamic arming at all existing relays would increase minimum total SAPN UFLS load from -190 MW to a minimum of 180 MW in 2022, or to 230 MW if dynamic arming were introduced at the more granular feeder level. Dynamic arming would therefore increase total net UFLS load in the lowest load period in late 2022 by approximately 370 to 420 MW.

By 2025, in the absence of intervention, total net UFLS load will decline to -470 MW. If dynamic arming is introduced at the existing relay level, total net UFLS load could be increased from this level to 150 MW in the minimum period in 2025, or to 200 MW with implementation at the feeder level. Dynamic arming would therefore increase total net UFLS load in the lowest load period in late 2025 by approximately 620 to 670 MW.

Figure 7 Total SAPN UFLS load in the lowest UFLS load period – with and without dynamic arming

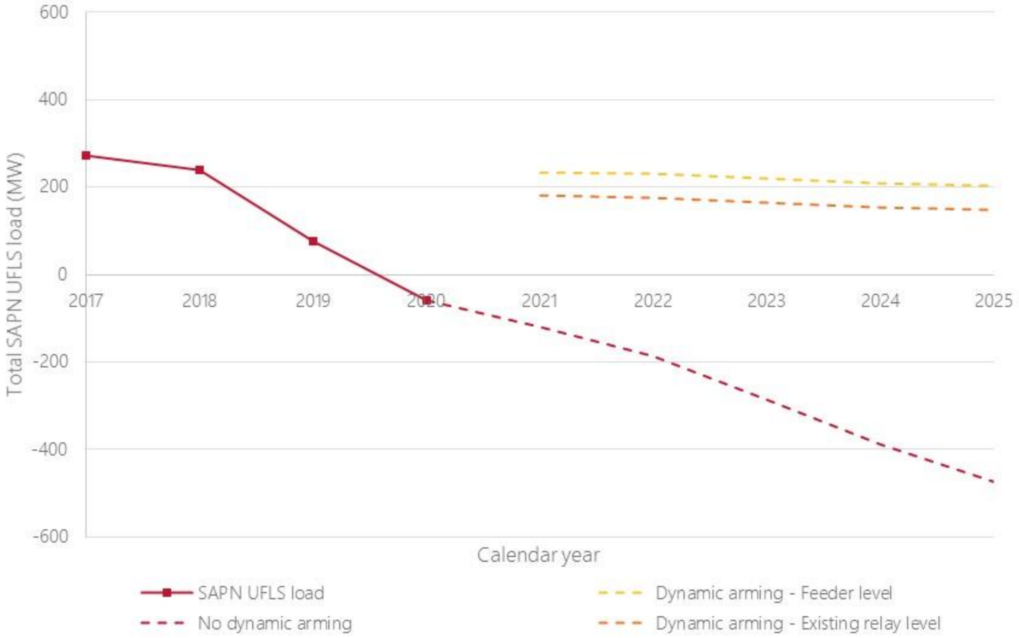


Figure 8 shows the additional load gained from implementation of dynamic arming in different projected periods (with implementation at the existing relay level shown in dark purple, and implementation at the feeder level shown in pale blue). In periods with total net UFLS load exceeding 800 MW, the benefits from dynamic arming are smaller (100 MW or less). In periods with the lowest levels of total net UFLS load, dynamic arming delivers much higher benefits (up to 420 MW in 2022, and up to 680 MW in 2025).

The dual distribution shape shown in Figure 8 is related to the difference between weekdays and weekends, which have a different profile of underlying load but a similar profile of DPV generation. For the same level of UFLS load, weekday underlying load and DPV generation tend to be higher, as illustrated in Figure 9.

Figure 8 Additional load gained from dynamic arming (High DER Scenario)

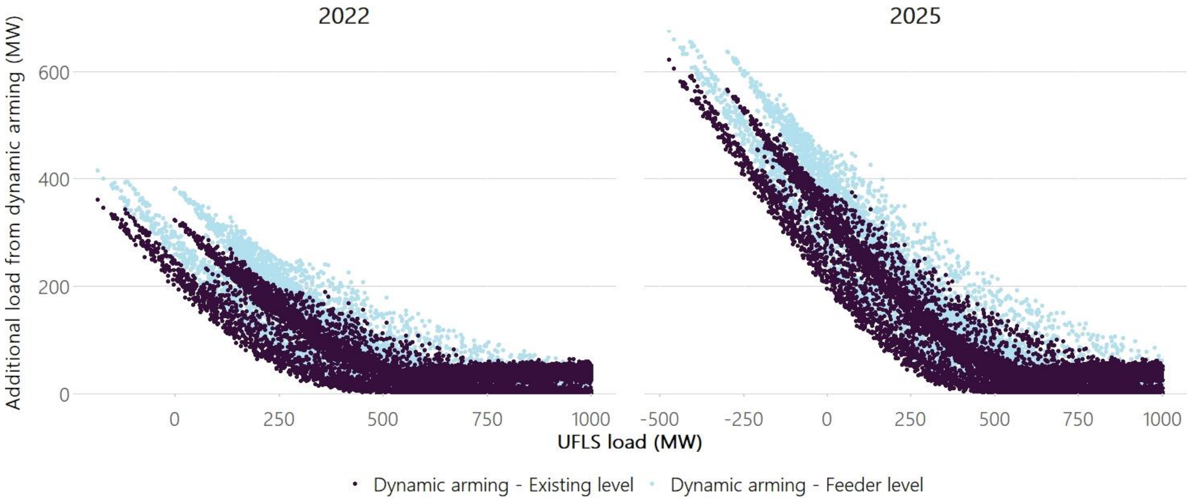
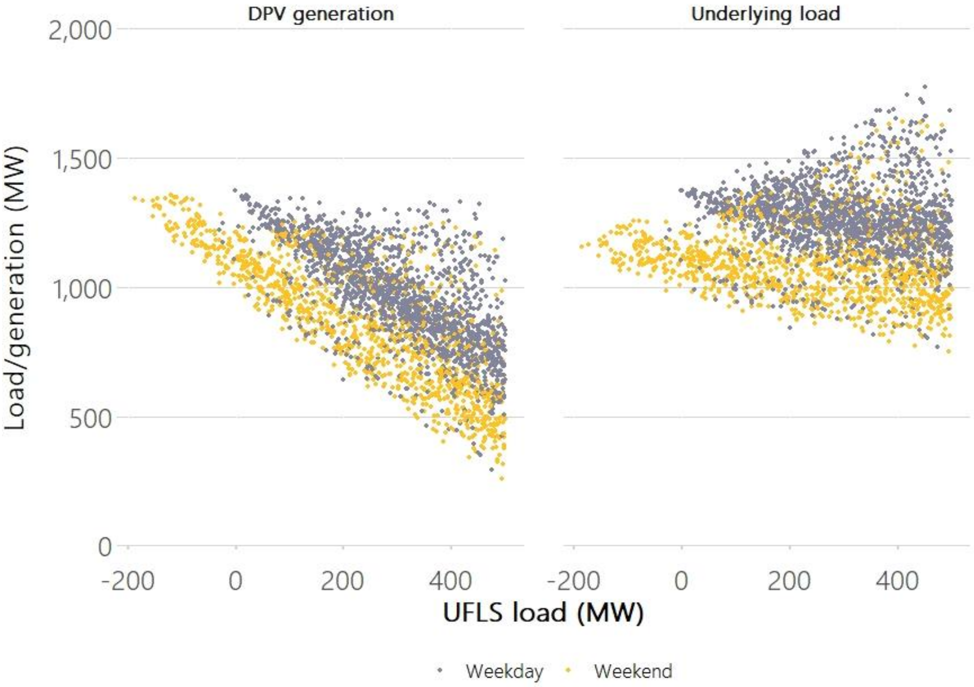


Figure 9 Trends in total net UFLS load on weekdays versus weekends (2022, High DER scenario)



This analysis shows that:

- Dynamic arming can deliver significant increases in net UFLS load, particularly in the lowest load periods.
- While dynamic arming at the more granular feeder level delivers more load, this comes at a higher cost. The additional cost of implementing dynamic arming at the feeder level may be warranted on a case by case basis, following SAPN analysis on a site-by-site basis. This is explored further in Section 4.

3.2 Benefits from alleviation of the Heywood constraint

As discussed in Section 2.2, a constraint set has been introduced to limits imports into South Australia on the Heywood interconnector in periods where the total net UFLS load is low[15]. This is necessary to meet the requirements of Regulation 88A of the South Australian Electricity Regulations. The UFLS constraint is most likely to bind when load is moderate, such that there is enough load in South Australia for the Heywood interconnector to be importing at moderate to high levels (but the amount of UFLS load in South Australia is insufficient to confidently prevent cascading failure in the event of a separation).

Figure 10 shows the amount of load gained by introducing dynamic arming at the existing relay level in two periods where the UFLS constraint is projected to bind the most. These are based on historical periods in the 2019 reference year, with the DPV installed capacity and load growing each year as per the 2020 ESOO Central scenario[16]. The impact of dynamic arming in the lowest load period is also included for reference.

As shown in Figure 10, introduction of dynamic arming increases net UFLS load considerably in the lowest load period (comparing the red dashed and solid lines, showing total SAPN UFLS load with and without dynamic arming respectively). However, the impact of dynamic arming is less in periods where the Heywood UFLS constraint is binding. In periods where the Heywood UFLS constraint resulted in the largest reduction in imports across Heywood[17] (defined as the 'most onerous' period), dynamic arming increases total net UFLS load by around 140 MW in 2022, and 290 MW in 2025 (shown in purple in Figure 10). In the second most onerous binding period (comparing the yellow solid and dashed lines in Figure 10), dynamic arming increases total net UFLS load by around 80 MW in 2022, and 210 MW in 2025. The load increase in each year and period from dynamic arming implementation is shown in Table 5. This shows that dynamic arming will have some effect to reduce binding of the Heywood import constraint, but the amount of UFLS load added is less pronounced than in the lowest load periods.

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[15] AEMO (October 2020) Heywood UFLS constraints, at https://aemo.com.au/-/media/files/initiatives/der/2020/heywood-ufls-constraints-fact-sheet.pdf?la=en&hash=066F80AE0EE3CF9701A0509818A239BB

[16] AEMO (August 2020) 2020 Electricity Statement of Opportunities, at https://aemo.com.au/-/media/files/electricity/nem/planning_and_forecasting/nem_esoo/2020/2020-electricity-statement-of-opportunities.pdf?la=en&hash=85DC43733822F2B03B23518229C6F1B2

[17] As compared to a counterfactual where the Heywood constraint was not implemented.

Figure 10 **UFLS load gained from dynamic arming at the existing relay level – case studies (High DER Scenario)**

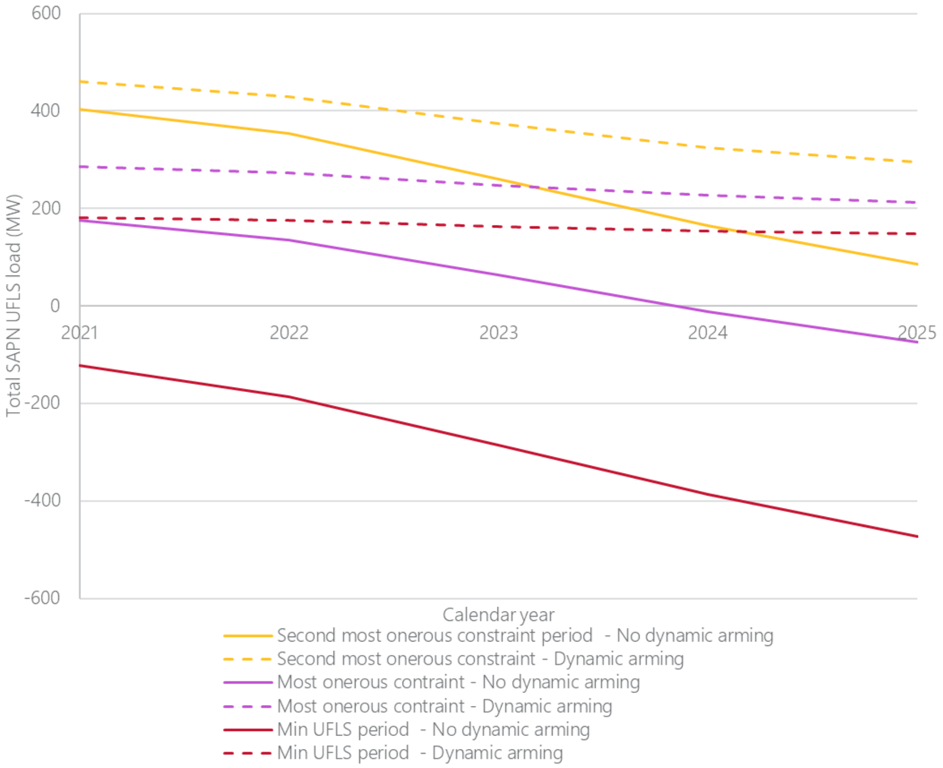

Table 5 **SAPN UFLS load gained by dynamic arming implementation at all sites at the existing relay level – Key periods relevant to binding of Heywood import constraint**

Calendar year	Period of minimum UFLS load (21 Oct 13:30 ACST)	Period of most onerous constraint binding (daytime) (11 Nov 15:30 ACST)	Period of second most onerous constraint binding (daytime) (26 Dec 12:00 ACST)
2021	302	109	58
2022	362	138	77
2023	448	184	113
2024	540	238	161
2025	622	287	210

Based on feeder load data from the 2020 historical year, and 2020 ESOO High DER scenario forecast PV and load growth

A simple projection of the approximate economic benefit from alleviating the Heywood UFLS constraint was estimated as follows:

- The increase in UFLS load following the implementation of dynamic arming was estimated in each half hour period of the forecast 2020-21 year.
- Simulations from the 2020 ESOO Central scenario provided dispatch outcomes. The number of trading intervals in which the Heywood constraint is expected to bind was estimated with and without implementation of dynamic arming, and for the various dynamic arming options.
- The alleviation of the cost impacts of the Heywood UFLS constraint were estimated, comparing each of the cases with dynamic arming with the case without dynamic arming. The constraint imposes some cost due to reduced interconnector transfer, and with increased UFLS load the constraint binds less often.

Table 6 shows the estimated impacts of dynamic arming on the existing Heywood import constraint in 2020-21. Without dynamic arming, the constraint is projected to bind for around 465 hours. Dynamic arming at the existing relay level reduces this by 38 hours, and dynamic arming at the individual feeder level reduces this by 56 hours. This has estimated economic benefits to the market of around $90,000 - $130,000 in 2020-21.

Table 6 Constraint alleviation for each dynamic arming option – 2020 ESOO Central forecast, 2020-21[18]

Option	Hours binding	Hours alleviated	$ benefit
No dynamic arming	465.5	-	-
Dynamic arming – Existing relay level	427.5	38	$88,331
Dynamic arming – Feeder level	409.5	56	$130,173

These results indicate that dynamic arming will only alleviate the Heywood import constraint in a small number of periods, and should not be implemented with the primary motivation being to remove or reduce the impacts of this constraint. Instead, dynamic arming aims to improve UFLS capabilities in different periods (when UFLS load is low, but the constraint is not binding), and should be implemented as a complementary measure to the Heywood import constraint. The constraint is designed such that it will automatically alleviate the limit as UFLS load increases, taking into account the increased UFLS load delivered by dynamic arming, in periods where this applies.

The Heywood import constraint and dynamic arming are complementary measures that work together to reduce the likelihood of cascading failure events in South Australia.

3.3 Benefits during SA island operation

When South Australia is operating as an island (separated from the rest of the NEM), a functional UFLS scheme is required to arrest frequency decline below 49Hz. Multiple contingency events can occur under islanded operation, and credible events may exceed the 49Hz threshold defined in the Frequency Operating Standards due to uncertainty in AEMO's models and assumptions for planning studies. During islanded operation, no additional support from the NEM UFLS is available, and it is crucial to ensure safety nets in South Australia (such as UFLS) are robust and adequate to manage contingencies and prevent cascading failure. Without adequate safety nets, multiple contingency events may lead to cascading failure, with significant costs to South Australian customers.

Based on the assessment in Section 3.1, dynamic arming will considerably increase the amount of net UFLS load in South Australia in the lowest load periods, which will deliver a significant improvement in the UFLS safety net to support South Australian island operation in these lowest load periods.

AEMO is conducting further analysis on South Australian island operation and the operation of the South Australian UFLS under these conditions.

3.4 Benefits for NEM-wide UFLS operation

South Australian UFLS is an important component of a NEM-wide UFLS scheme, protecting against multiple contingency events occurring in any NEM region when the NEM is fully interconnected. In many periods, the whole NEM experiences conditions of high DPV generation simultaneously. This means that maintaining a functional NEM-wide UFLS scheme will require new steps to be actioned across all NEM regions as DPV levels grow. South Australia forms an important component of the NEM-wide scheme.

If dynamic arming is not implemented, negative net loads in the South Australian UFLS could reach as low as -360 MW by 2022 under the linear growth PV scenario, or as low as -120 MW under the 2020 ESOO Central

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[18] Beyond 2020-21, if the separation of South Australia is declared a protected event, the constraints on Heywood flows may change.

scenario. This will actively exacerbate severe frequency disturbances occurring anywhere in the NEM. This has the following effects:

- Reduced effectiveness of the NEM-wide UFLS in arresting severe frequency disturbances (originating in any region)
- Lower frequency nadir due to DPV disconnection.
- Unnecessary disconnection of DPV resources.
- Unnecessary disconnection of South Australian customers (with no net benefit provided).
- A larger number of customers in other NEM regions being unnecessarily disconnected, to offset the action of the South Australian UFLS.
- Disproportionate sharing of UFLS across the NEM.

It is anticipated that dynamic arming will be required in all NEM regions, as DPV levels continue to grow, and a larger number of regions start to experience high levels of reverse flows.

NEM-wide UFLS studies are underway at present. AEMO is working with network service providers in all regions to compile the datasets required to deliver these studies.

3.5 Avoiding unnecessary disconnection of customers

As noted above, allowing UFLS circuits in reverse flows results in unnecessary disconnection of customers while also exacerbating frequency decline. Furthermore, additional customers need to be disconnected (in South Australia, or in other connected NEM regions) to offset the circuits in reverse flows in South Australia that have tripped. This means that the present UFLS arrangements result in larger amounts of unserved energy and customer disconnection than is necessary.

Implementation of dynamic arming will reduce unnecessary disconnection of customers, both in South Australia and in other NEM regions. This will act to reduce unserved energy from unnecessary disconnections.

4. Indicative dynamic arming design

Dynamic arming can be implemented in different ways on a site by site basis, with a range of options for each site which deliver various levels of sophistication in the capabilities delivered. SAPN calculated various options for implementation of dynamic arming, delivering various capabilities and amounts of net UFLS load increase. SAPN requested that AEMO provide advice on which option should be implemented.

4.1 Approach

SAPN provided AEMO with information on the capabilities of their existing relays at each site, and the options and costs for upgrade to introduce dynamic arming capabilities at each substation in their network. The options at each substation depend on the types of relays already at the substation:

- **Electromechanical or solid state relay** – These older relays cannot be reprogrammed for dynamic arming, so replacement of the relay is required to introduce this capability. All new installations will be the latest equivalent modern electronic relay, which introduces dynamic arming capability (arming/disarming when in reverse flows), and are adaptive arming ready (which means they can change frequency trip settings in real time once programmed to do so). The replacement can be done either:
  - At the existing relay level, or
  - At the feeder level. This will be higher cost due to increased equipment requirements and longer hours required to install and test each relay.
- **Legacy electronic relay** – This is the most common relay in SAPN's network. Options considered at these sites are:
  - Upgrade the decision-making process, allowing the existing relay to perform a simple dynamic arming function (disarming when in reverse flow) at the existing relay level. This requires a site visit and testing, with associated costs. Adaptive arming capabilities are not introduced.
  - Replace with the latest modern electronic relay at the feeder level, which is higher cost due to new equipment requirements.
- **Modern electronic relay** – These are advanced digital relays capable of performing all the functions required for dynamic arming, and are adaptive arming ready. Updating these relays with dynamic arming capability requires a site visit and testing, with associated costs.[19]

SAPN has also identified rural substations likely to demonstrate reverse flows which have site-specific costs to upgrade with dynamic arming capability. Upgrading these substations at the feeder level would require the replacement of existing relays with modern electronic relays, which can also deliver additional benefits such as more accurate metering[20]. AEMO's cost calculation has accounted for each rural substation individually, based on data provided by SAPN.

Based on the half-hourly load data provided by SAPN for each feeder, AEMO calculated the amount of net load added to the UFLS in each half hour period at each site, with dynamic arming implemented at the feeder level and existing relay level. This was then summed across the year (in GWh) at each site. Based on SAPN's

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[19] Currently installed modern electronic relays are already located at the feeder level.

[20] Existing UFLS load metering for several rural substations is delivered by amp meters, which can only detect the magnitude of electricity flow and are unable to detect flow direction. Due to variability in DPV generation (e.g. due to cloud cover) and load, reverse flows are therefore challenging to identify at amp-metered sites.

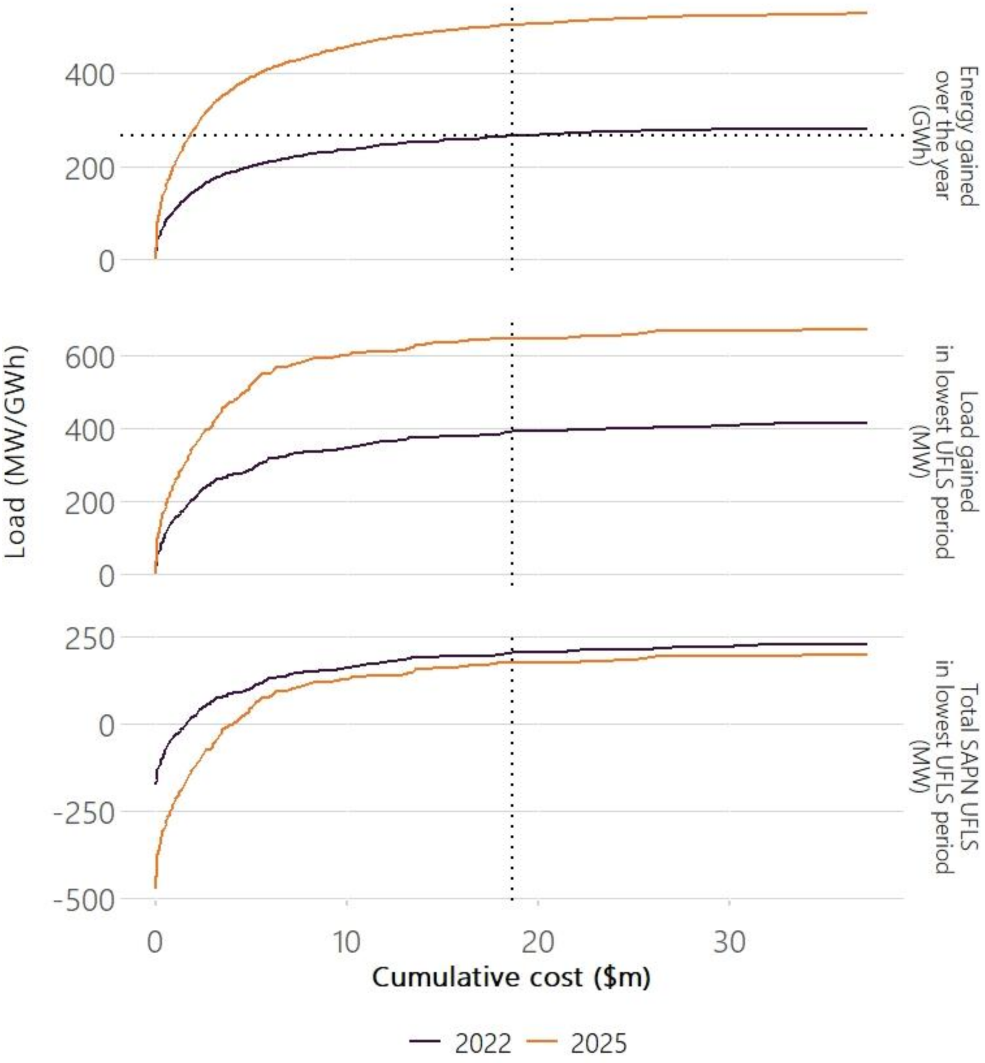
estimated costs to implement dynamic arming at each site (at the existing relay level or feeder level), the $/MWh of UFLS load added across the year was then determined for each substation. Sites and options at each site were ranked from lowest $/MWh to highest $/MWh.

4.2 Findings

Figure 11 shows the cumulative load gained from dynamic arming, as a function of the total cumulative cost, based on the ranking of $/MWh at each site where dynamic arming could be implemented. The top panel shows the total GWh gained over the year, while the bottom panel shows the MW load gained in the lowest UFLS load period. As dynamic arming is introduced at more sites (moving from left to right across Figure 11) the amount of net load added to the UFLS increases. The total cost also increases.

The amount of UFLS load gained increases over time at no additional cost (for dynamic arming implemented at the same set of sites), as shown by the comparison of load gained in 2022 (in dark purple), and the load gained in 2025 (in orange).

Figure 11 Cumulative cost vs cumulative load gained from dynamic arming



Based on 2020 ESOO High DER scenario and SAPN's 2018-19 feeder level data.

The shape of the cumulative ranking shown in Figure 11 demonstrates that much of the benefit is delivered by implementing dynamic arming at a proportion of sites. AEMO estimates that SAPN could achieve 95% of the total load gain available from dynamic arming at a total cost of $17.9-20.2 million in the initial rollout (from

2021 to 2023), with an additional cost of up to $5.3 million in the subsequent rollout (2024 to 2025), as shown in Table 7.

Table 7 Estimated total cost – targeting 95% of UFLS load available from dynamic arming

Calendar Year	Central scenario ($ million)	High DER scenario ($ million)	DPV growth at 2019 rate ($ million)
Initial rollout – 2021 to 2023	20.1	20.2	17.9
Subsequent rollout – 2024 to 2025	0.8	1.8	5.3
Total cost to 2025	**20.9**	**22**	**23.2**

Estimated total cost per annum to achieve 95% of the total UFLS load available from dynamic arming, using a $/MWh pa threshold to trigger site refurbishment.

In practice, SAPN could assess the implementation of dynamic arming on a case-by-case basis as the power system evolves, and implement dynamic arming at any site and for any option (at the existing relay level, or feeder level) identified to have a cost less than a "trigger threshold". This analysis suggests that this trigger threshold could be in the range of $390-510/MWh of UFLS load gained per year, with estimated values for each scenario shown in Table 8. This targets 95% of total load available, with the total costs noted above.

This assessment is based on an assumption that DPV continues to be installed at similar locations to where it presently exists. If the installation patterns of DPV shift to new locations in future (for example, due to increased uptake in commercial installations compared with residential installations), then dynamic arming may be warranted at a larger number of sites in future, increasing total costs.

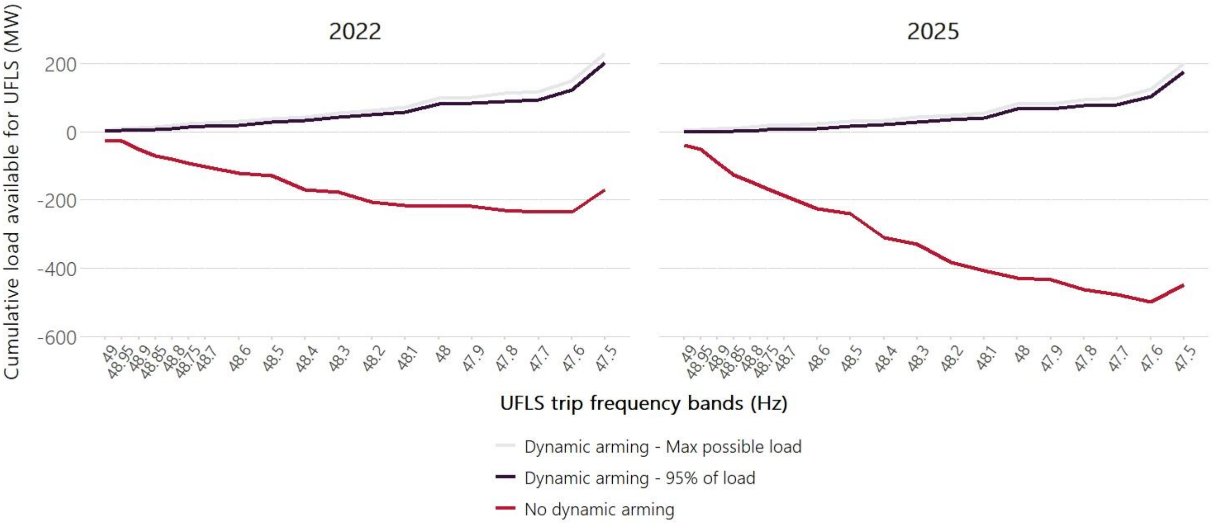
Table 8 Estimated $/MWh thresholds for 95% of UFLS load target in 2021

	Central scenario	High DER scenario	DPV growth at 2019 rate
$/MWh pa threshold	508	470	392

Load profile achieved by dynamic arming

Figure 12 shows the profile of UFLS load achieved by the 95% of load solution outlined above. This indicates that load is gained at all trip frequencies relatively equally, producing a relatively smooth profile. Positive load is restored at all trip frequencies, compared with the increasingly negative net loads in the absence of dynamic arming implementation. However, the total amount of load remains well below the target range (as discussed in section 2.2.4), so additional actions will be required to restore emergency frequency response to the levels required.

Figure 12 UFLS load profile in the minimum UFLS load interval – Dynamic vs no dynamic arming



Based on 2020 ESOO High DER Scenario and SAPN's feeder level data from 2018-19. The dynamic arming load profiles for 2022 show the level of load that would be gained if sites are dynamically armed according to AEMO's preferred strategy. These profiles exclude an additional 15-25 MW of UFLS load on the delayed 49 Hz band, which trips if load remains below 49 Hz for over 30 seconds.

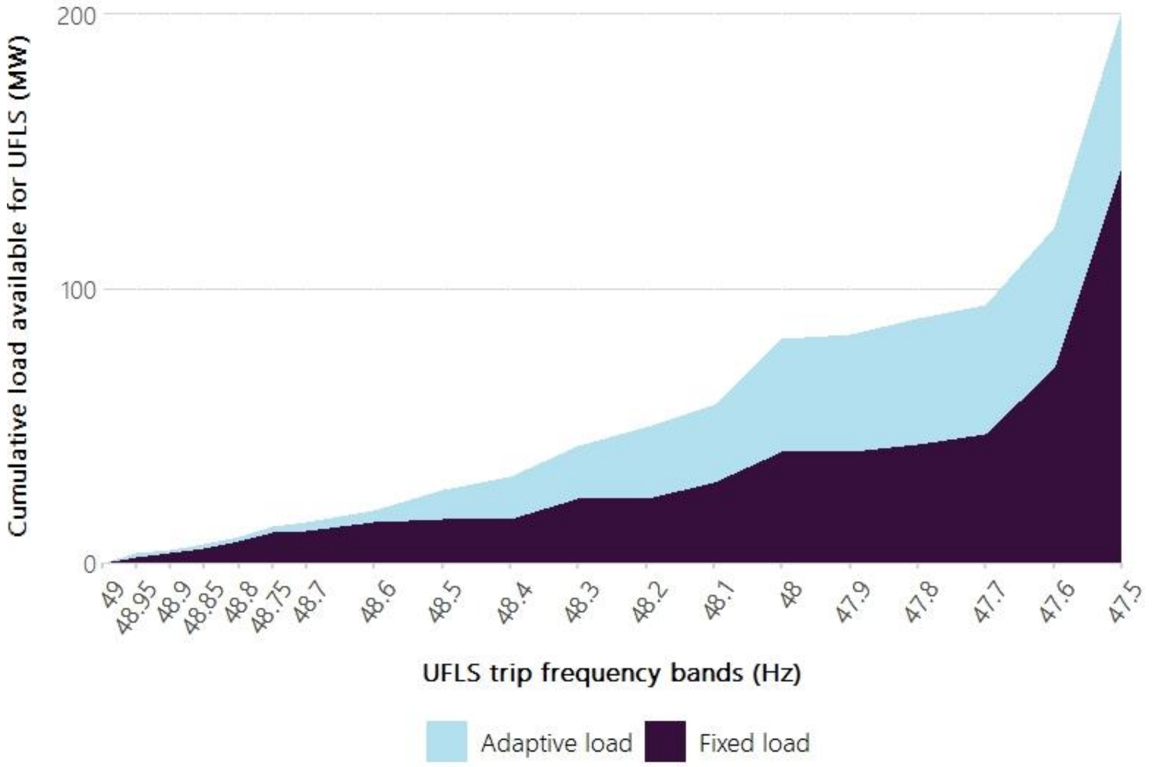
4.2.1 Adaptive arming

The more advanced modern electronic relays have the capability to accept remote signals to adapt frequency trip settings in real time (termed "adaptive arming"). Although there is no system or algorithm established at present in South Australia to implement adaptive arming, the introduction of these modern relays provides this capability for a proportion of SAPN UFLS load if these systems are introduced in future.

Figure 13 shows the proportion of UFLS load that would be available with adaptive arming capability (in pale blue), compared with the UFLS load that would remain at fixed frequency settings (not adaptive in real time) in dark blue. For the 95% UFLS load solution outlined above, up to 30% of load in the lowest UFLS load periods could have adaptive arming capability. This load is spread across all existing frequency bands. The proportion of load that may be available for adaptive arming in practice may be less, since many of the loads in the bottom frequency bands are considered sensitive, and would not be moved to higher frequency bands.

SAPN has advised that all the replacement modern electronic relays will be "adaptive arming ready". However, implementing adaptive arming at a later time will require recommissioning of the relays and additional system-wide updates to facilitate global adaptive arming settings in real-time. This would involve a site visit, testing, and algorithm development, with associated costs.

Figure 13 Adaptive versus fixed load in the minimum UFLS interval in 2022



Based on 2020 ESOO High DER Scenario, SAPN's 2018-19 data projected to future intervals. The load profile shows the level of load that would be gained in 2022 if sites are dynamically armed according to AEMO's preferred strategy. The profile excludes an additional 15-25 MW of UFLS load on the delayed 49 Hz band, which trips if load remains below 49 Hz for over 30 seconds.

Adaptive arming algorithms must be robust to cover a wide range of scenarios, PV generation levels, and islanding conditions. Extensive modelling is required to ensure the robustness of the adaptive scheme, as the consequences of maloperation are severe.

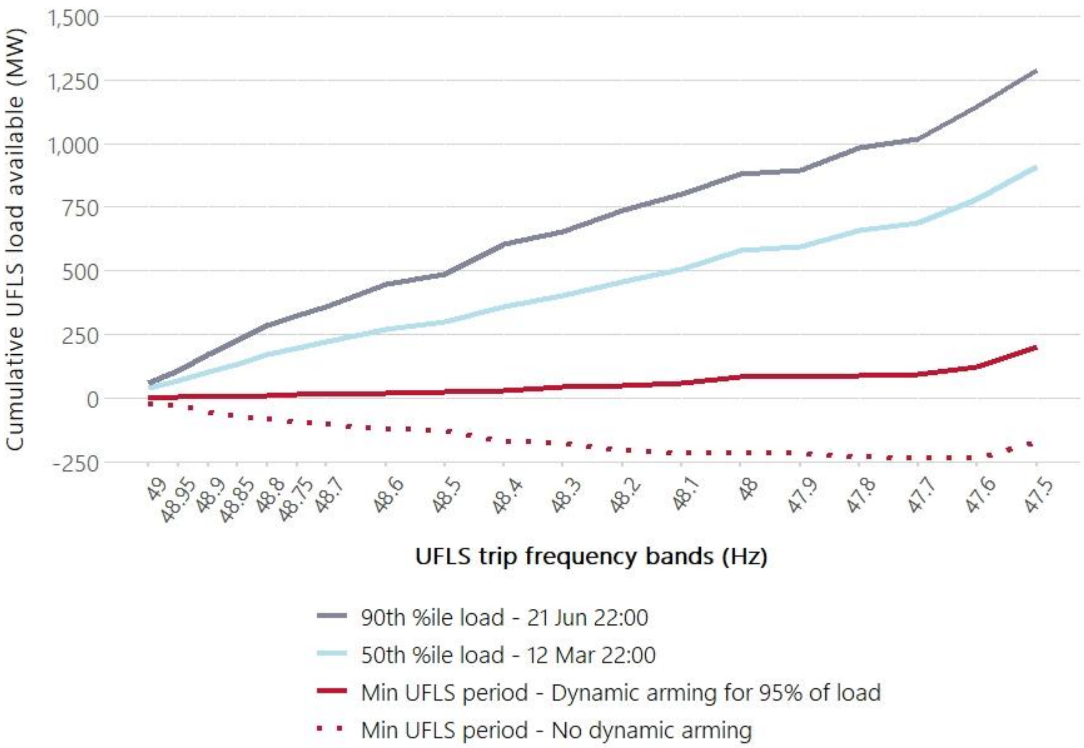
Is adaptive arming required urgently?

Figure 14 compares the cumulative profile of UFLS load in a number of periods:

- Two periods which are relatively unaffected by DPV generation (the 90th percentile and 50th percentile load for the year).
- A period of high PV generation (the minimum UFLS period in 2022).

This shows the original UFLS design load shape, compared with the reduced load shape in the minimum load period. The load restored by dynamic arming demonstrates a smooth profile that is similar in shape to the 50th and 90th percentile periods.

Figure 14 UFLS load profiles in different intervals – 2022



Based on 2020 ESOO High DER Scenario and SAPN's feeder level data from 2018-19. The dynamic arming load profiles show the level of load that would be gained in 2022 if sites are dynamically armed according to AEMO's preferred strategy. The profile excludes an additional 15-25 MW of UFLS load on the delayed 49 Hz band, which trips if load remains below 49 Hz for over 30 seconds.

The smooth distribution of load resulting from dynamic arming in the existing frequency bands suggests that the existing non-adaptive design may be adequate for the immediate future. However, it is useful to have this capability available as an incidental outcome of this work, providing an options benefit for future implementation if this new requirement arises more urgently than anticipated.

Recommendation

AEMO proposes that the first step is to introduce dynamic arming due to the urgency of the requirement for additional UFLS load. Adaptive arming can be considered for future possible implementation, drawing on learnings from implementation of the dynamic arming solution. AEMO has further investigation underway to explore development of an adaptive arming scheme for South Australia.

4.3 Summary

Dynamic arming can be introduced at a proportion of SAPN sites to achieve the majority of the benefit in increased UFLS load. Sites have varying costs for dynamic arming implementation, and varying levels of load restored (depending on the typical levels of reverse flows that occur at each location). Based on SAPN's cost and load data, AEMO estimates that 95% of the total load available from dynamic arming can be achieved if SAPN implements dynamic arming at any substation which meets the cost threshold of $390 to $510 per MWh of UFLS load gained per year. This is estimated to have a total cumulative cost of $17.9-20.2 million in the initial rollout (from 2021 to 2023), with an additional cost of up to $5.3 million in the subsequent rollout (2024 to 2025).

AEMO recommends that dynamic arming is implemented at any site (and for any implementation option) where the $/MWh cost for implementation is below this threshold. This targets 95% of the total load available from dynamic arming, balancing costs and benefits.

5. Other UFLS work required

This analysis shows that the implementation of dynamic arming will only increase UFLS net load to a maximum of approximately 200 MW in the lowest load periods. By comparison, the total amount of load required for proper functioning of the South Australian UFLS is in the range 800 – 1,200 MW. This indicates that significant further work is required to adequately restore emergency frequency control capabilities. It is noted that the commissioning of the proposed EnergyConnect interconnector will not reduce the need for an effective UFLS scheme in South Australia, since this remains required as part of the NEM-wide UFLS scheme.

AEMO therefore suggests that SAPN explore other options for increasing UFLS load in addition to dynamic arming. Some possible options for SAPN's consideration are outlined below.

Smart meter UFLS

AEMO understands that some smart meter products have the capability for high speed monitoring of frequency, and can trigger a highly granular and selective disconnection of specific loads (while leaving customer DPV operating) if a rapid decline in frequency is detected. With existing technology this can be achieved in the timeframes relevant for UFLS (approx. 500 milliseconds), meaning that this could provide a valuable boost to UFLS capability.

Approaches of this type (allowing separate shedding of load and DPV at the individual customer level) are likely to be essential for restoration of UFLS capability with very high levels of DPV, so AEMO recommends that this is investigated.

Careful consideration is required around a number of factors, including:

- There may be impacts on distribution voltage management from rapidly tripping a large proportion of customer load (while DPV remains operating). It is important to verify that subsequent disconnection of DPV from over-voltages can be avoided.
- The speed of response of this type of load shedding needs to be investigated, and carefully integrated into the UFLS scheme design. Device capabilities and total response times could be explored through laboratory bench testing of the smart meter devices with simulated frequency events. AEMO can then conduct frequency studies to explore the optimal design of this response, when integrated with the response of traditional UFLS relays.
- The locations of sites involved need to be integrated carefully with the overall UFLS scheme design. It may be possible to avoid or delay tripping of a whole feeder if a sufficient proportion of the load on the feeder is involved in tripping at the smart meter level. This could minimise the number of customers tripped to deliver the same benefit. This means there may be benefits in concentrating the rollout of this capability on a location-by-location basis.
- The process for communicating with these devices to restore customers in a controlled manner following the contingency event needs to be carefully considered and trialled.
- The potential for adaptive arming (adjusting frequency settings in real-time) should be explored.
- There may also be a series of co-benefits from this project, which could be explored. For example, it may be possible to disconnect less sensitive off peak circuits at a higher frequency (e.g. 49Hz), and disconnect the whole of premise at a lower frequency. This would provide additional benefits to customers by avoiding the disconnection of higher value loads in response to milder disturbances.

- The potential for co-benefits around increasing the proportion of controlled load could be explored. For example:
  - Introducing the ability to remotely manage a larger proportion of customer hot water load (and other controlled/off-peak loads), so they can be actively dispatched to increase demand in low load periods.
  - Increasing the ability to selectively shed a larger proportion of off-peak loads for management of LOR2 and LOR3 conditions.

AEMO's understanding is that the use of this technology for wide-spread frequency management is at a relatively nascent stage at present, and would therefore require trials. AEMO recommends that SAPN investigate a possible project in collaboration with Metering Coordinators to trial this capability.

Controlled load under frequency relays

Similar to the smart meter option explored above, some controlled load management devices have standard features that allow autonomous detection of frequency and subsequent disconnection of the load. This could be another pathway to activating more granular shedding of customer loads, while allowing DPV to continue operating. AEMO understands that some other Australian DNSPs are trialling this capability at present. This should also be explored, as an alternative or complement to the use of smart meters.

Large customers – separating PV from UFLS relays

At some industrial and commercial customers, SAPN has indicated that UFLS relays are situated such that on-site DPV will be tripped at the same time as the site load. Where possible, this arrangement should be adjusted so that DPV will not be tripped by UFLS relays.

Utility Storage

AEMO's analysis indicates that utility-scale Battery Energy Storage Systems (BESS) can deliver a fast frequency response (FFR) that is an effective supplement to UFLS. BESS can autonomously detect a fast change in frequency and trigger a rapid reduction in consumption, and power injection. AEMO's studies show that this significantly boosts emergency frequency response.

Investment in BESS services could be explored, particularly where there may be multiple co-benefits provided in management of the distribution system.

Adding further new loads and reviewing existing UFLS scheme

There may be potential to add some further remaining load to the UFLS at certain sites and these should be investigated. Additional loads and proposed frequency settings reviewed by the OTR should be considered for addition to the UFLS.

In parallel, AEMO is working on a full review of the NEM-wide UFLS, including South Australia. This may result in recommended adjustments in settings for existing customers to optimise the scheme's effectiveness. In some cases, there may be cost saving opportunities through the alignment of UFLS settings adjustments with dynamic arming deployment.

A1. Acronyms

AEMO	Australian Energy Market Operator
DER	Distributed Energy Resources
DPV	Distributed PV
EFCS	Emergency Frequency Control Scheme
ESOO	Electricity Statement of Opportunities
FCAS	Frequency Control Ancillary Services
GW	Gigawatts
Hz	Hertz, a measure of frequency
MW	Megawatts
MWh	Megawatt hour
NEM	National Electricity Market
NER	National Electricity Rules
OFGS	Over Frequency Generation Shedding
OTR	Office of the Technical Regulator
PSFRR	Power System Frequency Risk Review
SAPN	South Australian Power Networks
UFLS	Under Frequency Load Shedding