Impact of Reverse Power Flow in Distribution Feeders on Under-Frequency Load Shedding Schemes

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***Abstract*—This paper presents an analysis of the system effects of reverse power flow in distribution feeders. Continued increases in the number of small-scale photovoltaic (PV) panel installations within the network has led to low or reverse power flows in distribution feeders at times of high solar energy availability, and substantial weather-induced load variation, among other impacts. In the event of a large loss of generation, under-frequency load shedding of these distribution feeders is one tool that network operators use to arrest the frequency decline. The penetration of distributed PV generation leads to low availability of load to shed, or the chance of inadvertently removing generation, which can lead to power system failure. This paper explores these effects on the largest power system in Western Australia and suggests methods to mitigate the impact of increasing DER penetration on under-frequency load shedding schemes.**

***Index Terms*—Reverse Power Flow, Back-feeding, DER, UFLS**

I. INTRODUCTION

A. Overview

The unprecedented uptake of rooftop photovoltaic (PV) panels has led to new challenges for power systems throughout the world. Where traditional power systems comprised mostly of centralised generators supplying power uni-directionally, distributed energy resources (DER) now contribute supply to a substantial portion of underlying demand. One impact of high DER penetration in distribution feeders is a reduction in the effectiveness of traditional under-frequency load shedding (UFLS) schemes. Such schemes aim to restore energy balance in a power system following an unplanned loss of generation by disconnecting portions of load if the system frequency drops below predefined thresholds, typically as a ”last resort” to avoid a system black-out [1]. As outlined in the Technical Rules in Western Australia [2], the intent of UFLS in the South West Interconnected System (SWIS) is to trip 15% of total load in each of five stages, with the remainder reserved for essential services. This arrangement is not dissimilar to systems in other parts of Australia, or in Europe [1]. However, as DER penetration increases, the actual load available to trip during sunlight hours reduces. Indeed, UFLS activation during times of reverse power flow would actually increase contingency size. Recent publications suggest that many power systems are starting to see signs of DER penetration affecting the availability of load for UFLS [3]–[5]. In the SWIS, there are already zone substations where distribution feeders experience reverse power flow at times of peak solar availability.

B. Problem Statement

Given a trend of increasing DER penetration and the difficulties already experienced, the existing SWIS UFLS scheme needs to be reviewed to ensure that sufficient load is available for tripping to meet the intent of the scheme, and to ensure that feeders are not tripped at times of reverse power flow wherever possible.

The existing SWIS UFLS scheme comprises of UFLS relays fitted to most distribution feeders, which are set to one of five stages (or off). It is of note that many of these relays are not remotely configurable, and hence cannot be changed more than a few times per year given labour limitations [6]. It is also of note that the UFLS scheme does not include ”transmission loads”, being those connected above the distribution network, which limits total load available to the UFLS scheme.

C. Literature Review

Others have proposed various techniques to implement UFLS schemes that cater for the challenges of increased DER penetration. A technique that has been mentioned in literature commonly is the use of directional relays [4]–[6], also known as dynamic arming [7]. Directional relays take current as an additional input to disarm the UFLS functionality if the feeder is back-feeding. While this does not do anything to make more load available, it is an effective way to stop generation being tripped. However, other ideas are also presented in literature to consider how feeders are allocated for UFLS schemes. One paper proposes a method of taking into account DER by using estimates of DER penetration to influence feeder allocation [5]. This method, however, uses long term averages and ignores intra-day changes in load availability. Another paper proposes taking measurements in shorter time spans to better allocate feeder preferences [4], but similarly ignores intra-day changes. Another paper proposes a clustering-based approach to allocate feeders to UFLS stages [3]. Whilst the method proposed in this paper would result in a more balanced set of UFLS stages based on feeder ”type” grouping, this paper does not address the challenges associated with low load conditions as experienced in the SWIS.

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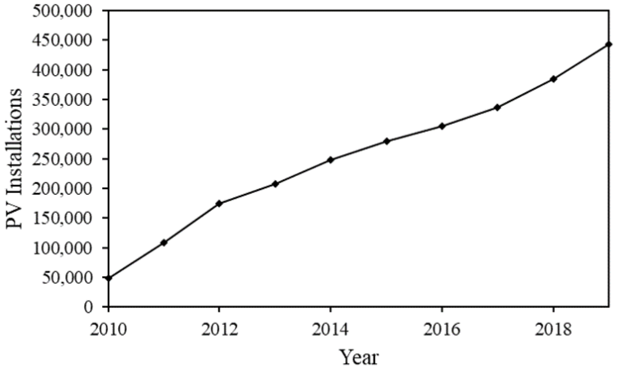


Fig. 1. Number of small-scale PV installations in Western Australia

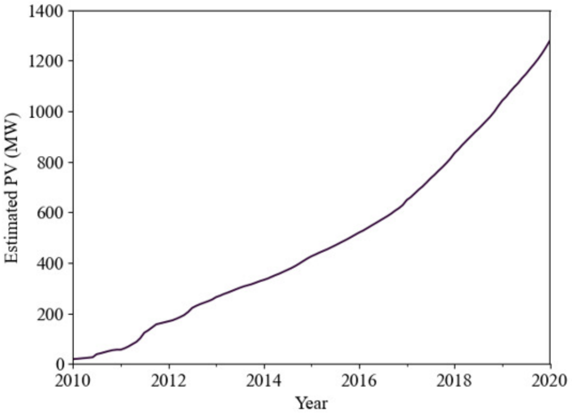
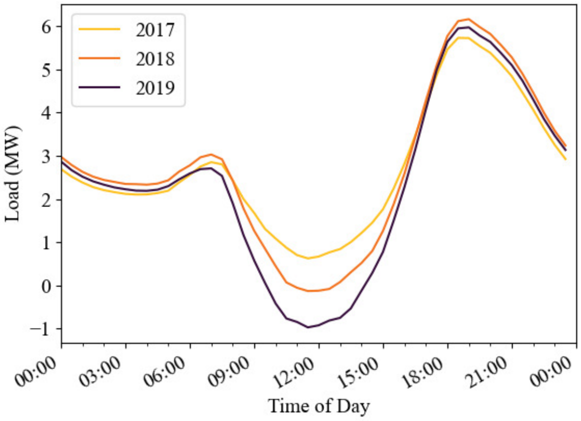


Fig. 2. Estimated PV capacity installed on the SWIS (2010-2020)

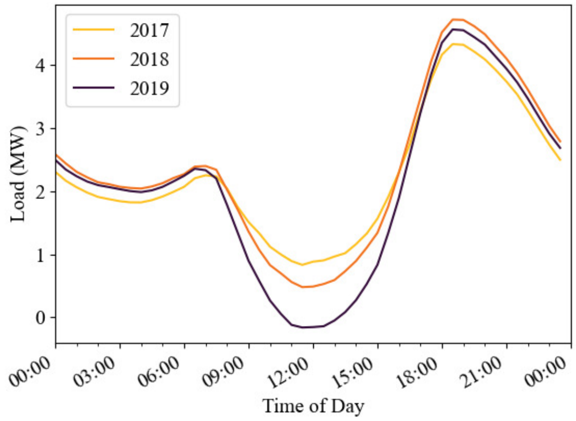
II. CHANGING NETWORK

A. DER Trends

According to Clean Energy Regulator (CER) data, the quantity of small scale PV installations in Western Australia has increased tenfold over the past ten years, as can be seen in Fig. 1. Furthermore, the average size of small scale installations are also increasing, from 3.75 kW before 2019 to an average size of 6.61 kW in 2019 [8]. Whilst there are various technical and practical limitations to the amount of DER permissible on the network, this trend of increasing DER penetration is expected to continue for the foreseeable future. The total installed capacity of small scale PV on the SWIS reached more than 1.2 GW as of October 2019 according to CER data [8]. On a power system with a generation capacity of 4.9 GW in the market [9], 1.2 GW of small scale PV represents a significant portion of generation that does not respond to market price signals. Furthermore, the time-of-day change in PV between day and night require increased flexibility in market generators. This also means that at different times of day the generation fuel composition changes significantly, from high levels of DER in daylight hours to high levels of non-renewable generation overnight.



(a) Feeder A



(b) Feeder B

Fig. 3. 2017 - 2019 Time of Day Average Feeder Load

B. Feeder Trends

The average daily load profile of two specific SWIS distribution feeder with high DER penetration are shown in Fig. 3. Over the past three years, the average morning and evening peak loads remained relatively constant, but the load during sunlight hours decreased substantially. For Feeder A, on average, reverse power flow was observed between 9am and 3pm in 2019, but it is noted that reverse power flow can also be observed outside of these hours, or on specific days in prior years. Data from the CER [8] supports that this load profile change is most likely the result of increasing DER penetration. It is known that this feeder was part of the first stage of the UFLS scheme as recently as 2018, and was set to trip at 48.75 Hz. Whilst this may have offered some benefit in 2017 and 2018, it is likely that a daytime trip during 2019 would inadvertently increase load and further destabilise the power system. Feeder B is a similar example in a geographically different area within the SWIS (i.e. approximately 40 km away). The trends shown in 3 are occurring throughout many feeders on the SWIS. Across all of the feeders measured over 2018 and 2019, approximately 4.4% of the feeders showed consistent back-feeding for at least one half-hour period in at least one month of 2018; and in 2019 this percentage increased to 7.4%. With the average size of small scale PV installations increasing [8], the back-feeding phenomenon is expected to increase in the coming years. Likewise, the many other feeders that do not back-feed will continue to show lower demands due to the impact of small scale PV.

III. IMPACT OF HIGH DER PENETRATION ON UFLS

A. UFLS Load Availability

Prior to high penetrations of DER, the relative proportion of load available to trip was typically always higher than the 75% required in the SWIS and similar systems. However, as DER penetration has increased, the relative proportion of residential and light industrial/commercial feeder load has decreased substantially during sunlight hours. Consequently, it has become more difficult to make 75% of load available to trip without including loads that were not previously subject to UFLS, such as transmission loads and borderline essential services.

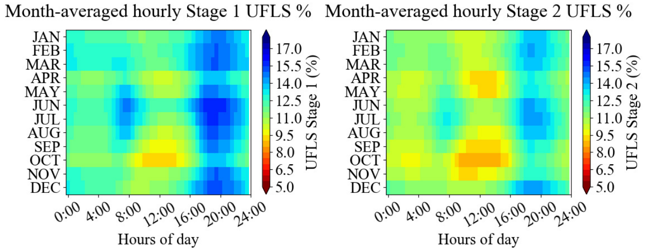
B. Relative Feeder Load

Prior to high penetrations of DER, the load profiles of distribution feeders were relatively consistent, and it was reasonably practical to group feeders into UFLS stages in such a way that approximately 15% of system load was tripped at any time, and in any season. However, it is noted that the uptake of DER has not been consistent on all feeders, for reasons such as socioeconomic constraints and existing network infrastructure age. Differences in relative DER uptake results in differences in the sensitivity of feeders to weather. Consequently, a given UFLS feeder configuration may achieve the target 15% load reduction on a a given day (e.g. cloudy), but much less on the following day (e.g. sunny). Similarly, a given UFLS feeder configuration may achieve the target 15% load reduction in a given hour (e.g. partly cloudy over some suburbs), but substantially less in the following hour (e.g. partly cloudy over other suburbs). As such, higher penetrations of DER are making it more difficult to define a static UFLS configuration appropriate for long periods of time.

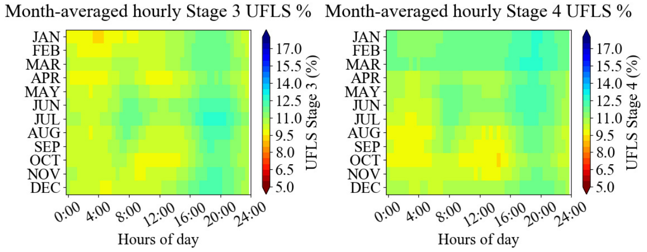
C. 2019 UFLS Availability

The percentage of total load configured to trip for each stage at a given time of year can be visualised in the month-averaged time-of-day heat-maps in Fig. 4. These figures are based on the UFLS settings known in 2018 and power flow data collected in 2019.

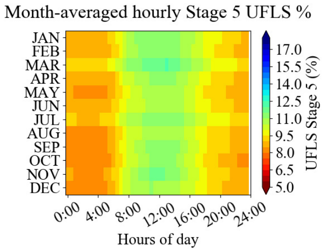
The impact of DER on the availability of load for UFLS can be seen in the lack of load during daylight hours, and large variability on days with intermittent cloud. Furthermore, while Fig. 4 depicts month-averages, the day-to-day changes in availability result in a lack of consistency in the available load to shed. The net result is that there are times when less than the required 15% of load would not be tripped by the first stage of UFLS. This would mean that additional stages may be triggered, resulting in a longer period of frequency instability and the potential disconnection of more customers than necessary. Conversely, there are other times when greater than the required 15% of load would be tripped, possibly leading to an overshoot/over-frequency event and a similar disconnection of more customers than necessary.



(a) Stage 1 (b) Stage 2



(c) Stage 3 (d) Stage 4



(e) Stage 5

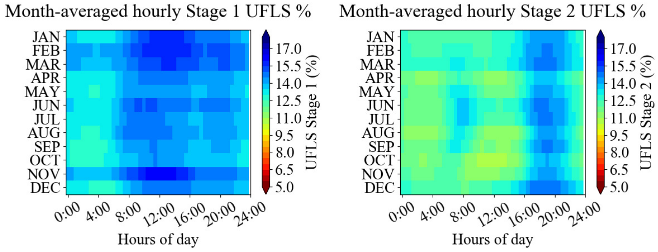
Fig. 4. 2019 UFLS availability based on original settings

IV. PROPOSED UFLS RE-BALANCING

On the basis that many existing UFLS relays are manually adjusted, it is proposed that UFLS settings are adjusted with the following principles:

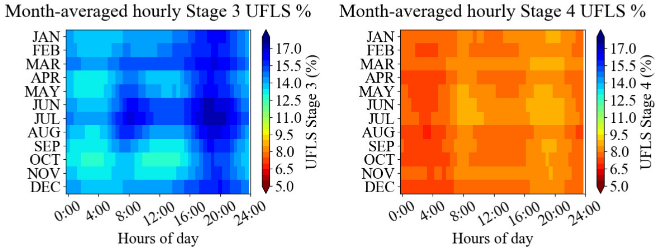
- turn off UFLS for feeders with high variability and frequent reverse power flow, to improve average load availability; and
- redistribute the remaining feeders to improve load availability and reduce load variability as far as practical. This involves moving many of the residential feeders to later stages and several commercial feeders to earlier stages.

This approach was applied to the SWIS, and the results are shown in Fig. 5. Such re-balancing ensures that the first stages of UFLS provide the intended 15% load reduction a much larger proportion of the time. A comparison is provided in Fig. 6, where the Stage 1 available load is compared between original settings and re-balanced settings on a sunny spring day



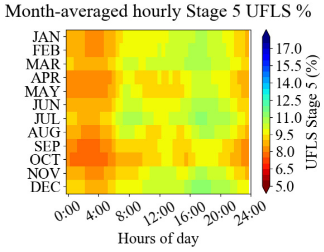
(a) Stage 1

(b) Stage 2



(c) Stage 3

(d) Stage 4

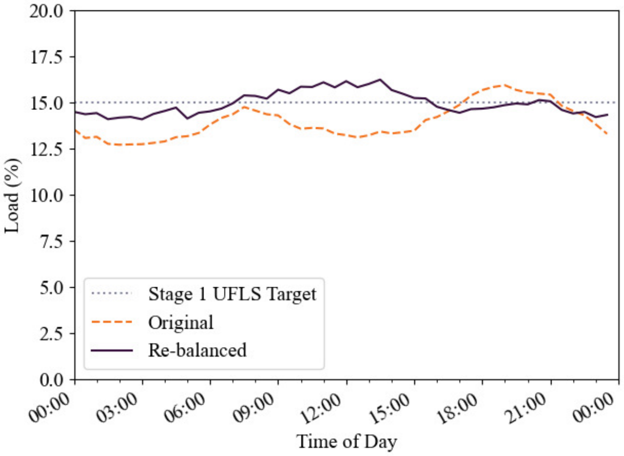


(e) Stage 5

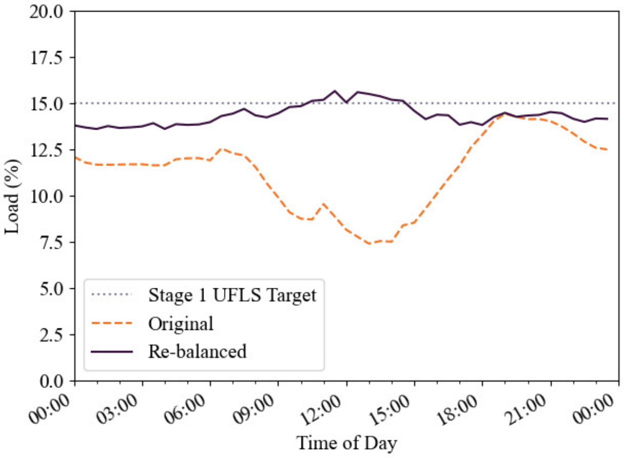
Fig. 5. 2019 UFLS availability based on re-balanced settings

and a cloudy winter day. It is clear that the re-balanced settings provide a more consistent availability of load and avoids the fast change, particularly from 15:00 to 18:00, in the outcome of an UFLS event on the sunny spring day. However, various difficulties are noted with this approach:

- The later stages of UFLS schemes are typically associated with heavy commercial and inner city areas due to their higher proportion of critical or important loads. These feeders have relatively high daytime use (business hours) and relatively low DER penetration, and hence offset the profile and variability of residential feeders identified previously. However, the proposed rearrangement generally requires that these load types are moved to earlier stages of the UFLS scheme, and such users would therefore experience a reduction in their reliability of supply.
- The total load in the UFLS stages may still be insufficient to meet the requirement. In the SWIS, the reduction in average distribution feeder load caused by high DER penetration, and the removal of feeders with regular reverse power flow from the UFLS scheme, means that only three out of five UFLS stages could be arranged to meet the 15% requirement in each stage. Where it is not possible to achieve high levels of UFLS availability in power systems with high DER penetration, it would be of benefit to include other sources of load, such as those connected to the transmission network directly.



(a) Stage 1 on cloudy winter day



(b) Stage 1 on sunny spring day

Fig. 6. Stage 1 comparisons between original settings and re-balanced settings

V. RECOMMENDATIONS

With the improvement of load availability in the SWIS after re-balancing, it is recommended that re-balancing of feeders be used to flatten the load available for UFLS stages in power systems where high DER penetration leads to low load and unbalanced UFLS stages. However, it was noted that the current SWIS target of 75% load available to shed over five stages is not achieved with the current settings, nor could it be reliably achieved in any combination of settings with existing equipment and loads. This report recommends alternative methods of achieving UFLS are investigated where the total load available to trip does not meet requirements. These include, but are not limited to:

- Dynamic arming of UFLS relays to disarm the feeder when it is back-feeding. This would ensure that reverse power flow feeders are never tripped, thus increasing the average UFLS load availability whilst still taking advantage of the load available during peak load times.
- Installation of remotely controlled UFLS relays to enable remote updating of UFLS relay settings from a centralised location. This would allow operators to dynamically assign feeders to UFLS stages based on shorter time periods, or even near-real-time, to ensure that UFLS stages meet the target load availability at all times. While the methodology used for the manual UFLS relay adjustments was based on the re-balancing principles outlined earlier, an automated system to remotely update relays would allow for the use of an algorithm to determine the best UFLS scheme arrangement.
- The addition of transmission-level loads to to the UFLS scheme. This would increase load available to the UFLS scheme, and these loads would typically have lesser variability associated with DER penetration.
- The consideration of seasonally distributing feeders which have UFLS relays that may be remotely configured, as this would likely assist in further flattening seasonal changes in load.

It is also suggested that that UFLS target load is reconsidered in the context of target reliability of supply. In events that require minimal response, a full trip of an UFLS stage results in more load tripped than required. A 2020 paper [10] showed that by taking into account available ancillary service response, the frequency can be shown to not require additional stages of load shedding. This method provides great benefits in preventing both the unnecessary tripping of additional loads, and the potential over-response due to multiple stages tripping. It is suggested that a further partitioning of the several large stages into many small stages, combined with a method to prevent unnecessary tripping of UFLS stages, would improve the system frequency response and reduce the number of load customers disconnected. One paper [11] simulated various UFLS schemes on the Slovenian power system and explored differences between schemes with six and twelve stages. They noted small differences in total load disconnected during most cases, but found examples of improved frequency response by limiting the instantaneous load tripped off. One case study found that while the existing Slovenian UFLS scheme tripped 25% of available load and resulted in an over-frequency event, a twelve-stage UFLS scheme tripped only 10% and prevented an over-frequency event.

VI. CONCLUSION

This paper investigated the impact of a widespread uptake of distributed rooftop PV on the UFLS scheme of a medium-sized islanded power system. It was found that rooftop PV eroded the availability of UFLS during the day, particularly in the first few stages as they were traditionally allocated to residential feeders. By changing the UFLS allocation philosophy and mixing in commercial CBD feeders (which has a counter-balancing demand profile with high daytime loading), while also removing residential feeders that potentially back-feed during peak sun hours, the UFLS scheme can provide more uniform availability throughout the day.

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