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Development of an Aggregation Tool for PV Inverter Response to Frequency Disturbances across a Distribution Feeder

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***Abstract*—The rapid increase in distributed generation (DG), especially commercial and household solar PV systems in the distribution network necessitates the development of better tools that provide greater insights in the operation of the large numbers of DGs. This paper presents the development and preliminary use of an aggregation tool that allows modeling of DG response to frequency disturbances based on experimental data across a distribution feeder. By altering different RE penetration levels and/or composition of inverter models in a feeder the tool can model and observe a diverse range of responses to the same grid disturbance. The tool provides preliminary insight into whether a broader simplified model of DGs is possible in distribution networks and can assist network operators with managing systems with high renewable energy penetration.**

***Index Terms*—Inverters, ROCOF (Rate of Change of Frequency), Grid Support Functions (GSFs), Photovoltaics (PV), Distributed Energy Resources, Power Electronics**

I. Introduction

Global increase in renewable energy systems (RES) has led to a substantial uptake of solar PV systems at large-scale [1]–[3] and also as distributed generation (DG) for commercial (10 kW-1 MW) and residential (1-10 kW) systems. [4]. Due to its geography and residential landscape, Australia has one of the highest solar PV penetration levels in the world; a total capacity of 13.9 GW as of 2019 with approximately 2.1 million solar PV installations (or 95% of the total) sized below 10 kW, not directly controlled or monitored by utilities [2]. This poses a major challenge to the bulk power system operation, as millions of PV systems need to be managed without compromising grid stability. At low penetration levels, common load models, such as the ZIP model [5] or a constant power injection [5], are sufficient. However, at higher penetration levels, DG integration ceases to be a trivial issue and distributed energy resource (DER) behavior must be taken into account and accurately modeled.

During grid faults and frequency disturbances, DER has the potential to exacerbate grid disruptions if penetration levels are high, presenting a challenge for system operators. In order to support the grid during disturbances and abnormal operating regimes, solar PV inverters are equipped with advanced functionalities known as grid support functions (GSFs) [6]. Examples of GSFs include active [7] and reactive power control as a function of grid voltage and grid frequency, anti-islanding detection and fault-ride through (FRT) capability. On a local basis, the voltage management across a feeder is one of the main challenges in an effort to increase the hosting capacity of a network [8]–[10]. At network scale, the aggregate response of DGs as PV penetration increases has much broader implications. In fact, inverter requirements have become critical as international standards [4] become stricter and require higher FRT capabilities to allow PV inverters to withstand grid disturbances.

Although recent standards prescribe the general behaviour of grid connected inverters, it remains up to manufacturers to determine the implementation of the control strategies that provide these GSFs. This leads to a great variance on how inverters respond to faults or other disturbances. Such diverse behavior leaves the power system vulnerable to disturbances as the response of thousands or millions of PV inverters cannot be accurately anticipated.

Major power outages in the past have been exacerbated by the inability of renewable resources to ride through voltage and frequency disturbances. In Australia, examples of disturbances with direct implications to DG include *i)* the state-wide blackout in South Australia in September 2016 leading to a loss of over 1.8 GW of load [11], *ii)* a major separation event across the whole National Energy Market (NEM) in August 2018 that created three "islands" out of one single synchronised network [12] and *iii)* an islanding event of South Australia in November 2019 [13]. All of these events were caused by severe weather conditions that led to a loss in large-scale generation. The voltage and frequency disturbances propagated through the network and in many instances DER responded by disconnecting or reducing generation, which further exacerbated the issue and led to unexpected system behavior.

From a power system operation perspective, aggregation and modeling of DG behaviour at a feeder level is critical. Current tools used by system operators such as PSSE, PSCAD or even real-time simulation based tools, cannot account for the diverse behavior of millions of DGs across the network. By aggregating inverter responses, it is possible to account for a broad range of scenarios that include various penetration levels across different feeders and different irradiance levels allowing us to better understand how solar PV inverters may affect system stability during these events.

The objective of this paper is to present the preliminary development of a tool that aggregates experimentally measured individual inverter responses, in order to represent the combined response of DG in a feeder to specific grid disturbances. Such a tool allows for a more general study of aggregate inverter behavior that accounts for the diversity in inverter responses to common grid disturbances. The paper describes both the inverter testing procedure and aggregation methodology (Section II), as well as results for different cases and feeder configurations (Section III).

II. Methodology

The two main variables that define the inverter response to a grid disturbance are the voltage and the frequency at the point of common coupling (PCC). However, the voltage is a rather localised variable and its values depend on the characteristics of each individual feeder, making an accurate aggregate model quite complicated and requiring electromagnetic type transient simulations [14]. On the other hand, the grid frequency is a common variable across all inverters, so aggregation is more straightforward.

The steps for the creation of a feeder aggregation tool include comprehensive testing of individual inverters to grid disturbances and a combination of all responses considering variations in the fleet of inverters in a particular feeder. These stages are described in Section II-A and II-B.

A. Inverter Bench-Testing

Laboratory bench-testing of residential-scale solar PV inverters was performed in order to gain insights into their behavior under a range of grid disturbances. The inverters were all single-phase inverters rated between 2 kW and 5 kW. They are off-the-shelf models complying with Australian standards, either the current AS 4777.2:2015 [15] or the older AS 4777:2005 [16]. Twenty-five inverters have been comprehensively tested under a variety of grid disturbances that include *i)* start-up tests *ii)* reconnection behavior tests *iii)* voltage disturbances *iv)* frequency variation tests *v)* temporary cessation tests and *vi)* voltage phase-angle jumps. The PV inverters which have been tested so far represent about 20% of all rooftop PV capacity in Australia, however, in certain cases they represent a major proportion of the inverter fleet found in an individual state.

The testing setup, which includes a Regatron TC.GSS PV emulator rated to 16 kVA 600 V dc and a 50 kVA Regatron TC.ACS bidirectional grid emulator [17], is shown in Fig. 1. The process of testing each individual inverter typically involves:

- Adjusting the parameters of the AC grid emulator and PV emulator to the required set-points.
- Subjecting the hardware to a disturbance through the grid emulator software (ACS control).
- Capturing waveforms of grid voltage and current, and PV voltage and current.

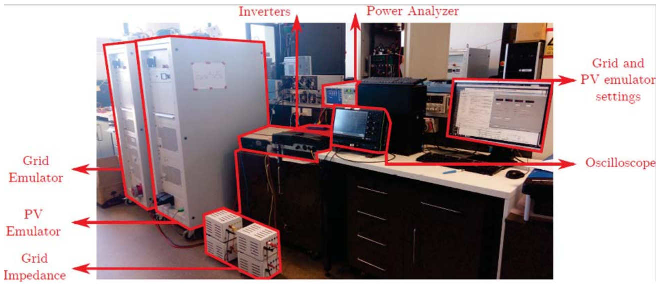

Fig. 1. Inverter bench-testing setup in the UNSW Power Electronics lab

Voltage and current waveforms are recorded by a digital oscilloscope, at 50 kHz sampling rate. The instantaneous active and reactive power is calculated at the post-processing stage, using single-phase PQ theory [18]. All results from the inverter testing are also made openly available[1].

Based on the current tests completed on the inverters, the following responses can be currently aggregated as a single feeder:

1) Frequency step - 50 Hz to 51.95 Hz
2) Frequency step - 50 Hz to 47.05 Hz
3) Frequency ramp - 50 Hz to 51.95 Hz (+1 Hz/s RoCoF)
4) Frequency ramp - 50 Hz to 51.95 Hz (+4 Hz/s RoCoF)
5) Frequency ramp - 50 Hz to 51.95 Hz (+10 Hz/s RoCoF)
6) Frequency ramp - 50 Hz to 47.05 Hz (-1 Hz/s RoCoF)
7) Frequency ramp - 50 Hz to 47.05 Hz (-4 Hz/s RoCoF)
8) Frequency ramp - 50 Hz to 47.05 Hz (-10 Hz/s RoCoF)
9) Sine frequency modulation (0.5 Hz)
10) Sine frequency modulation (0.2 Hz)
11) Frequency "notch" -5 Hz for 1 s.
12) Frequency "notch" -5 Hz for 4 s.

B. Aggregation of Results

There are multiple challenges that need to be addressed when aggregating results from solar PV inverters to specific feeders. Firstly, market segmentation should be taken into account. Inverters that represent a majority in one region may not be popular in another region [19], so any tool should be able to accommodate for such variations between different locations. Secondly, the aggregation should consider both the capacity and the number of inverters. For these reasons, results are normalised to the rated power of each inverter.

The aggregate power response is taken as a linear combination of the different inverter weightings in a network, their rated power and their characterised bench testing responses to a common network disturbance, as shown in (1).

$$FR_{pu} = \frac{\sum_{n=1}^{x} \prod(IR_n, inv_n)}{\sum_{n=1}^{x} \prod(P_n, inv_n)} \tag{1}$$

where, FR_{pu} is the per unit feeder response, inv_n is the percentage weighting of inverter n on the feeder, IR_n is

[1]Bench-testing results can be viewed at http://pvinverters.ee.unsw.edu.au

Fig. 2. Feeder modelling tool

inverter n's power response to the disturbance, P_n is inverter n's rated power and x is the number of inverter models present on the feeder. The weighting of each inverter is set using sliders in a custom MATLAB GUI, shown in Fig 2. The remaining inverter weightings are calculated automatically satisfying the condition $\sum_{n=1}^{x} inv_n = 1$, or manually set to zero if the inverters are not present on a specific feeder.

To add to the complexity of practical inverter response aggregation, distribution networks typically include combinations of present generation as well as legacy inverters. For example in Australia there are at least 1.47 million inverters which were installed under the 2005 standard and represent 4.7 GW of capacity, while the remaining fleet (9.2 GW) is compliant with the modern AS4777.2-2015 standard [2].

III. RESULTS

The range of voltage and frequency disturbances in a grid is extremely broad and their combination effectively creates infinite possibilities. The bench-testing of inverters focused on worst-case scenarios (step-changes of the grid frequency) as well as more common disturbances in the form of frequency ramping (defined by the rate of change of frequency or RoCoF). Relating back to events observed in the grid, the results provided in the following section focus on RoCoF disturbances. From a standards perspective [15], [16], legacy inverters maintain their output power constant within the disconnection frequency limits whereas current inverter models linearly decrease their power output between 50.25 and 52 Hz [17].

A. +1 Hz/s Rate of change of frequency (RoCoF) event

A change in the frequency with a RoCoF of 1 Hz/s is considered as a general case. The frequency of the grid as a function of time during this disturbance when the frequency is increased from 50 Hz to 51.95 Hz (the disconnection limit is set to 52 Hz) is shown in Fig. 3.

For the 1 Hz/s RoCoF event, two feeders have been considered with three active inverter models. Here, three inverters have been selected so that the individual response of each

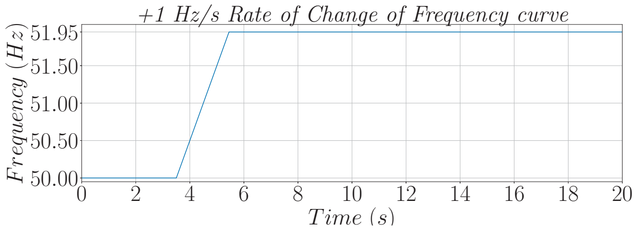

Fig. 3. RoCoF (1 Hz/s) curve

TABLE I
FEEDER COMPOSITION FOR +1 HZ/S ROCOF

Feeder 1		Feeder 2	
Inverter	**Weighting**	**Inverter**	**Weighting**
Inverter 4	37.33%	Inverter 13	33.33%
Inverter 6	23.33%	Inverter 14	39.33%
Inverter 7	38.33%	Inverter 16	26.33%

inverter and the combined feeder response can be shown in a single figure. The inverter models have been selected to highlight the different inverter responses that have been captured. The inverter weightings for these two feeders are given in Table I.

The individual responses for inverters 4, 6 and 7 are shown in Fig. 4. All three inverters reduce their output power with a similar time-constant in response to the increase in the grid frequency. The last figure demonstrates the aggregated response of these three inverters as a single feeder. As the response is quite similar and the weightings are close, the feeder closely matches the individual inverter response.

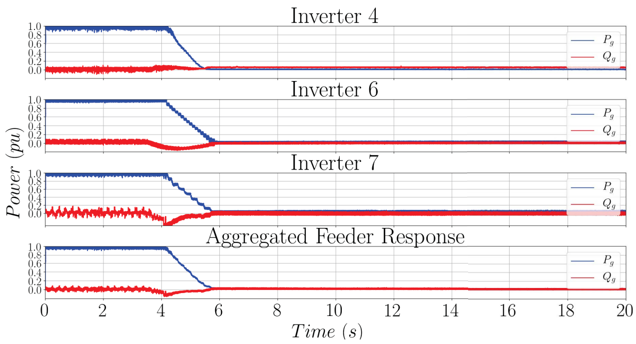

Fig. 4. Individual inverter responses and aggregate feeder response for Feeder 1 under a +1Hz/s frequency disturbance

As a contrast to the previous feeder, Fig. 5, shows three inverters that exhibit different responses to the same over-frequency with 1 Hz/s RoCoF disturbance. In this case, Inverter 14 does not ride through the RoCoF disturbance, and disconnects from the grid, as highlighted by its output power decreasing to zero abruptly. On the other hand, Inverter 13 and Inverter 14 both ride through the RoCoF disturbance, however the former inverter reduces its output power much more slowly then the latter. When looking at the combined feeder response, we see a behavior that does not match any individual inverter. The value of the aggregation becomes evident as it demonstrates that system operators have to manage a very broad range of possible responses to different grid disturbances.

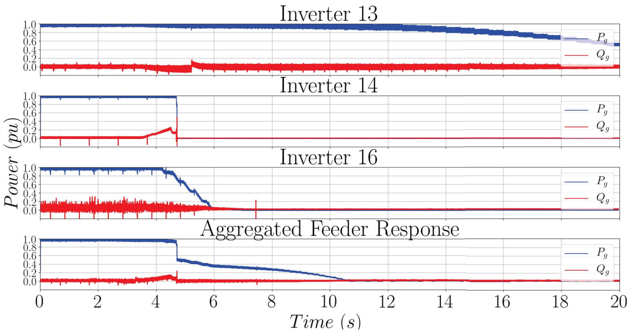

Fig. 5. Individual inverter responses and aggregate feeder response for Feeder 2 under a +1 Hz/s frequency disturbance.

B. -4 Hz/s Rate of change of frequency (RoCoF) event

The second frequency disturbance is selected as a -4 Hz/s RoCoF event. High RoCoF values were observed during the 2016 South Australian blackout and are expected to become more common as the overall system inertia decreases across power networks with the reduction of synchronous generation. The frequency is ramped down from 50 Hz to 47.05 Hz as shown in Fig. 6. The lowest value of 47.05 Hz is selected as current Australian standards require inverters to disconnect once frequency drops below 47 Hz [15].

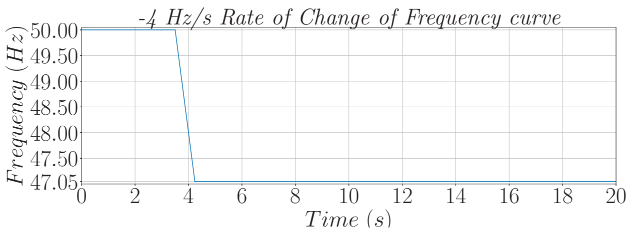

Fig. 6. RoCoF (-4 Hz/s) curve

1) Two-inverter feeder:

This feeder is selected as a direct demonstration of a system dominated by two inverters, as shown in Table II. As the frequency does not drop below the minimum value for inverter disconnection, the inverters continue to inject constant power to the grid. However, as Inverter 1 does not synchronise to the change of frequency as fast as the RoCoF of the disturbance, we observe an increase in the reactive power injected to the grid. This gradually reduces to zero as the voltage and current synchronise to the 47.05 Hz grid frequency.

The individual inverter responses to a -4 Hz/s frequency disturbance as well as the aggregate feeder response are shown in Fig. 7.

TABLE II
FEEDER 3 FOR -4 HZ/S ROCOF

Inverter	Weighting
Inverter 1	31.33%
Inverter 2	66.67%

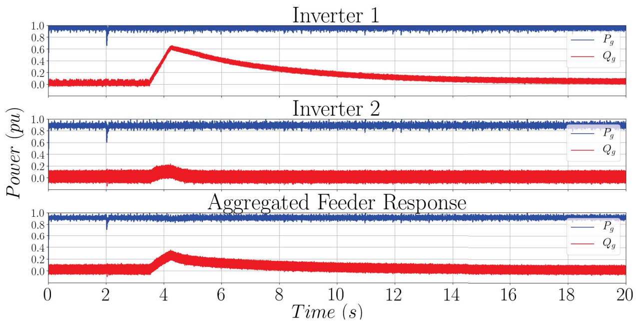

Fig. 7. Individual inverter responses and aggregate feeder response for Feeder 3 under a -4 Hz/s frequency disturbance.

2) Three-inverter Feeder:

Here we revisit feeder 2 from Table I. Inverters 13 and 16 remain connected to the grid with their active and reactive power remaining constant. However, Inverter 14 disconnects from the grid and the power reduces to 0 instantaneously. The aggregate feeder response is also shown in Fig. 8.

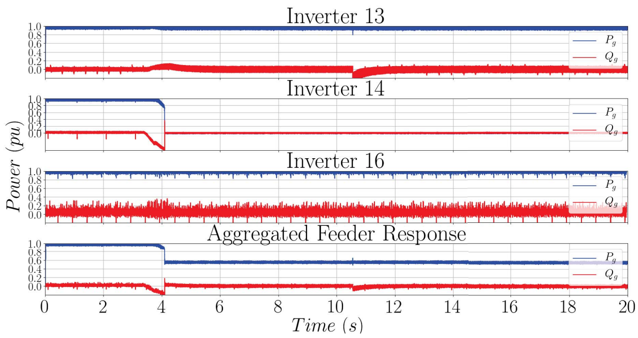

Fig. 8. Individual inverter responses and aggregate feeder response for Feeder 2 under a -4 Hz/s frequency disturbance

In this case, Inverter 14 disconnects from the network when the RoCoF disturbance occurs while Inverter 13 and Inverter 16 ride through the disturbance. The real power drops from 1 pu to 0.5 pu.

3) Fourteen-inverter feeders:

The previous feeders were used to highlight both the individual responses of different inverters as well as the process of their aggregation. In a normal feeder, it is expected to have PV inverter models from different manufacturers and different ratings. To illustrate this case, we present the aggregate results of 14 different inverters at different ratios within a random feeder. The feeder responses are obtained for the following cases, where the presence of each of the 14 inverters is varied:

- Feeder 4: inverters distributed with equal weighting;
- Feeder 5: one inverter dominating the feeder;
- Feeder 6: inverters distributed with random weighting.

TABLE III
FEEDER COMPOSITIONS WITH 14 INVERTERS

Inverter	Feeder 4	Feeder 5	Feeder 6
Inverter 1	10.67%	3.69%	11.65%
Inverter 2	6.87%	3.69%	3.04%
Inverter 3	6.87%	3.69%	12.55%
Inverter 4	6.87%	3.69%	0.57%
Inverter 6	6.87%	3.69%	4.92%
Inverter 8	6.87%	3.69%	0.82%
Inverter 9	6.87%	3.69%	1.73%
Inverter 11	6.87%	3.69%	14.64%
Inverter 13	6.87%	3.69%	12.35%
Inverter 14	6.87%	52.00%	5.64%
Inverter 17	6.87%	3.69%	16.89%
Inverter 20	6.87%	3.69%	0.61%
Inverter 22	6.87%	3.69%	7.80%
Inverter 23	6.87%	3.69%	6.78%

The feeder composition from different inverters for these three cases is given in Table III.

The aggregate feeder response is shown in Figure 9, where the active power injected by inverters to the feeder reduces from 0.95 pu to 0.62 pu (-35%) as inverters either reduce their power or disconnect from the grid. The reactive power also instantaneously increases to 0.23 pu as not all inverters are able to maintain unity power factor during the RoCoF event. Eventually, once the frequency reaches its new steady state, the reactive power also reduces to zero.

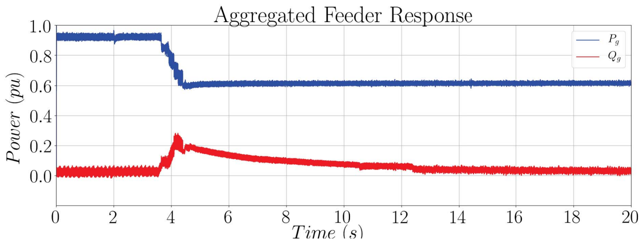

Fig. 9. Feeder response with 14 Inverters and even inverter weighting (Feeder 4).

For the second case, we select a dominant inverter across the feeder. Here, Inverter 14 represents 52% of all inverters in a feeder and also corresponds to an inverter that under a -4 Hz/s RoCoF disturbance undesirably disconnects from the grid. The inverter response in Figure 10 shows that the total active power from all inverters to the grid is reduced from 0.97 pu to 0.3 pu (-69%). The reactive power momentarily increases to 0.11 pu, as explained earlier, after which it reduces back to 0 pu.

The third case assumes a random inverter distribution across the feeder by allocating a random percentage weighting for all 14 inverters. Under the same RoCoF disturbance, the active power from the inverters decreases from 0.95 pu to 0.84 pu (-12%) as shown in Figure 11. The reactive power follows a similar pattern to the previous cases.

Referring back to the case of +1 Hz/s RoCoF but for a case with 14 inverters, the results for Feeder 6 are shown in Fig. 12.

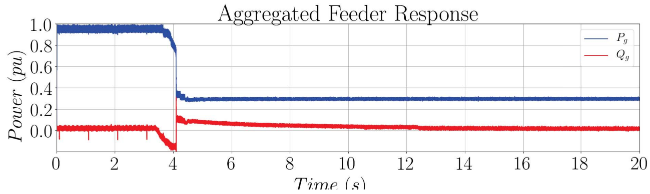

Fig. 10. Feeder response with 14 Inverters and one dominant inverter (Feeder 5).

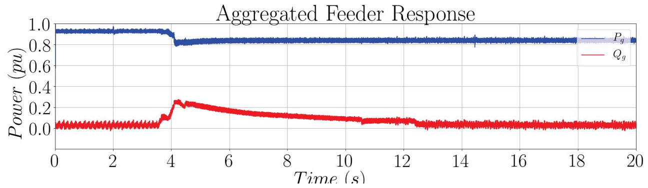

Fig. 11. Feeder response with 14 Inverters and random inverter weighting (Feeder 6)

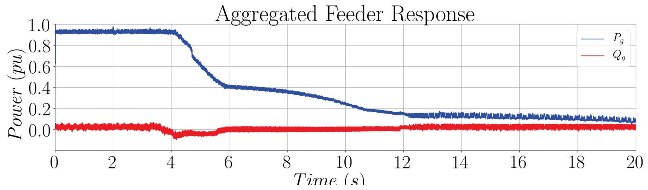

Fig. 12. Aggregate feeder response for Feeder 6 under a +1 Hz/s frequency disturbance

IV. Discussion

Based on the results that were presented in Section III and additional results from the extensive inverter testing, the challenge in modeling transient responses for PV inverters across multiple feeders becomes apparent. This challenge is a result of both complexity and scale which leads to certain choices when designing the experiments and testing the inverters:

- **Number of inverters tested:** This should be selected as a representative sample of inverters in the network (as a proportion of installations) as well as the market (as a proportion of manufacturers).
- **Representative feeders:** Considering current levels of DG, future growth as well as possible expansions in hosting capacity to account for current and future operations.
- **Grid disturbances:** Worst-case scenarios (i.e. frequency steps) help create an envelope of performance for inverters and feeders, but tests and aggregation should also consider past events and expected values (e.g. the choice of RoCoF values).

The results in Section III-A demonstrate that the models of inverters can substantially alter the aggregate response of the feeder. In some cases, the aggregate disturbance response of the feeder does not resemble the response of any individual inverter. Similar behavior is seen in many other tests (See Section II) and for different inverter combinations.

Considering a feeder hosting multiple inverter makes and models, as in the results of Section III-B, we observe that the composition of inverters in a feeder significantly affects the aggregate response. This is clearly shown by comparing the results in Fig. 13, which also shows the diversity of response caused by the change in inverter composition.

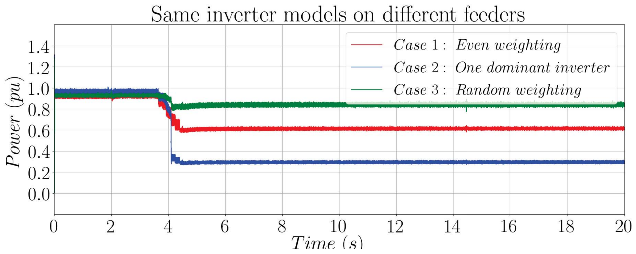

Fig. 13. Feeder responses for 14 Inverters with different weightings.

Finally, an important issue emerging from this study and the inverter bench-testing is that the fleet of legacy inverters will continue to influence aggregate feeders' behavior, in spite of evolving standards and uptake of new installations.

V. Conclusions

The growth of DG has led to the installation of millions of inverters in distribution networks. Laboratory bench-testing demonstrates that these inverters exhibit a broad range of responses to the same power system disturbance. This can be attributed to manufacturer implementation of a particular grid connection standard, and whether the inverter follows current or legacy standards. Additionally, despite compliance with standards, some inverters have shown to unexpectedly disconnect in response to grid disturbances, increasing volatility in the aggregate feeder response.

This paper has presented a tool for aggregating experimentally captured responses of inverters to grid disturbances at a feeder level. Using the tool, envelopes of different behavior can be developed by studying the effect of different combinations of inverter makes and models on a feeder, using information such as PV penetration levels at single-feeder, area or state level to help predict aggregate DER behavior. When grid disturbances occur, inverters are subjected to both voltage and frequency variations. Voltage disturbances tend to be localised and propagate through the network, usually at a smaller scale, while frequency disturbances uniformly affect the network. At this stage, the tool developed in this paper can be used for frequency disturbances while the work also demonstrates the complexity of making a similar tool for voltage disturbances because of their more localised nature.

Acknowledgement

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