Solar power plant harmonic emission - design and commissioning case study

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***Abstract*— Harmonic emission limitation is a power quality compliance requirement under the Australian National Electricity Rules (NER). Many solar farms have been commissioned recently in Australia and much experience has been gained during commissioning tests. Unlike a conventional synchronous machine, solar PV power plants use inverter-based technologies which generate a wide range of harmonic frequencies. Total harmonic voltage distortion measured at the point of connection (PoC) depends not only on the harmonic current profiles of the inverter, but also the harmonic impedance of the external grid and the solar farm collector network impedance. the latter can be calculated from the Norton equivalent impedance of the inverter. Unfortunately, the information required for harmonic calculations is often difficult to obtain. This paper presents a harmonic filter design methodology, which has demonstrated during commissioning to reduce total harmonic distortion and individual harmonic voltages to allocated levels. Additional topics including IEC summation law, impacts of cloud shading and filter switching, and statistical measurement requirements are also discussed and illustrated with field measurements.**

Keywords-solar farm, harmonics, total harmonic distortion

I. Introduction

Australia is in the midst of an energy transformation. In 2018, more than AUD 20 billion has been invested in large-scale clean energy projects. More than 87 large-scale renewable energy projects are either under construction or financially committed at the beginning of 2019 [1]. The Australian Energy Market Commission (AEMC) reported that more than 50 GW of new wind and solar projects are currently in development, which is roughly equivalent to the National Electricity Market's (NEM) entire current capacity.

Any new generating system to be connected to the NEM needs to follow a connection process which include:

- Determination of a set of Generator Performance Standards (GPS) defining technical performance
- Generator registration based on evidence from power system studies that demonstrates the generator to be connected can meet with the agreed GPS
- Onsite commissioning tests to demonstrate GPS compliance and to validate simulation models

Power quality is one of the requirements of the GPS. Schedule S5.2.5.2 of the National Electricity Rules (NER)[2] refers to AS/NZS 61000.3.6:2001 [3], which is a modified adoption of the IEC technical report, type 3 IEC 61000-3-6, Electromagnetic compatibility (EMC) - Part 3 [4]. Using the harmonic emission indicative planning levels proposed by the AS/NZS 61000.3.6:2001 as the maximum allowable emission limits, the Network Service Provider (NSP) will allocate harmonic emission limits to each customer connecting to the point of common coupling (PCC). Table I shows a typical harmonic emission allocation at the 66kV point of connection (PoC) of a 100 MW solar farm. For even, triplen and higher order harmonics, the emission allocation could be as low as 0.1%.

TABLE I. Typical Harmonic Emission Allocation (100 MW solar farm)

h	Limit	h	Limit	h	Limit
(-)	(-)	(-)	(-)	(-)	(-)
		21	0.10	41	0.14
2	0.11	22	0.10	42	0.10
3	0.15	23	0.19	43	0.13
4	0.10	24	0.10	44	0.10
5	0.46	25	0.19	45	0.10
6	0.10	26	0.10	46	0.10
7	0.31	27	0.10	47	0.13
8	0.10	28	0.10	48	0.10
9	0.16	29	0.17	49	0.13
10	0.10	30	0.10	50	0.10
11	0.41	31	0.16		
12	0.10	32	0.10		
13	0.41	33	0.10		
14	0.10	34	0.10		
15	0.10	35	0.15		
16	0.10	36	0.10		
17	0.27	37	0.15		
18	0.10	38	0.10		
19	0.27	39	0.10		
20	0.10	40	0.10	**THD**	**0.59**

Harmonic emission has not been a compliance issue for generating systems in the past as most of the generators were of rotating machine types, which are not harmonic sources. However, it is observed that the connection of renewable energy systems, which are mostly based on power electronic inverter technologies, could increase the harmonic voltage emission. During the development of mitigating measures for harmonic emissions, the following challenges have been encountered:

1. Lack of power system frequency dependent impedance information
2. Inadequate information on solar inverter harmonic characteristics, including harmonic current profiles and Norton equivalent impedance
3. Inadequate solar farm harmonic assessment metering and methodology
4. Lack of harmonic filter design experience for solar farm developers

The authors have been actively involved in solar farm electrical system analysis and performance standard compliance tests in Australia. More than 1GW of solar farms have been successfully designed and commissioned during 2017-2019. This paper aims to present a harmonic filter design and commissioning experience of Coleambally solar farm (CSF) [5] which was successfully commissioned in 2018. The structure of this paper is as follows:

- Section II provides some background information of the project, including a high-level description of the solar farm, the harmonic emission issues and the mitigation method.
- Section III describes the challenges encountered during the design and commissioning stage of the harmonic filter, highlighting the need of CIGRE method for solar farm harmonic assessment and presenting a consolidated harmonic filter design methodology for solar farm.
- Section IV presents the harmonic measurements of Coleambally solar farm and discusses the challenges of demonstrating harmonic emission compliance statistically during commissioning.
- Section V further discusses other operational challenges for solar farm and identifies needs for revising the existing harmonic emission standards.
- Some recommendations are provided in Section VI.

II. Background

A. Coleambally Solar Farm

Coleambally solar farm, a 150 MW solar farm using photovoltaic technology, is located in Southwest of New South Wales. It is owned by NEOEN, an Independent Power Producer specialised in renewable energy projects with headquarter in Paris, France. The commissioning was performed by Bouygues Construction Australia Pty Ltd, the subsidiary of the worldwide industrial company Bouygues Group. Coleambally solar farm connects to the existing 132 kV substation of TransGrid, the Network Service Provider (NSP) of New South Wales. Two harmonic filters, one C-type and one damped harmonic filter were designed to reduce the harmonic voltage emissions of the solar farm.

B. Solar farm harmonic issues

Photovoltaic based solar farms use DC/AC inverters to convert the electricity generated by the PV panels into AC and feed into the main grid. Pulse width modulation (PWM), which controls the switching status (turn on/off) of semi-conductors (such as IGBTs) supplied by a dc source, is the fundamental principle for synthesising an AC current. PWM works by comparing a 50 Hz voltage reference with a high frequency modulation signal known as a carrier. There are many different topologies that have been developed to maximise some aspect of the inverter such as the efficiency or harmonic content, including multilevel designs. A reactor is connected to the output of the inverter to smooth the current at the output of the inverter.

C. Mitigation method

Various harmonic emission mitigation methods are available including active and passive harmonic filtering. An active power filter monitors the harmonic current profiles of the system and injects equal but opposite harmonic compensating counter currents to cancel out the harmonic currents. While it can effectively reduce harmonic currents, it may not necessarily be able to minimize the individual harmonic voltages which are amplified by the harmonic impedance of the solar PV plant. On the other hand, a harmonic filter can detune the harmonic impedance of the network such that voltages will not be amplified at the frequencies of higher harmonic current content. Figure 1 shows the design of a typical broadband C-type filter. It attenuates the targeted frequency, presents a low impedance to higher order harmonics, and minimizes the power loss at fundamental frequency. Coleambally solar farm has one C-type filter tuned to 170 Hz and one second-order damped filter to attenuate harmonics of higher frequencies.

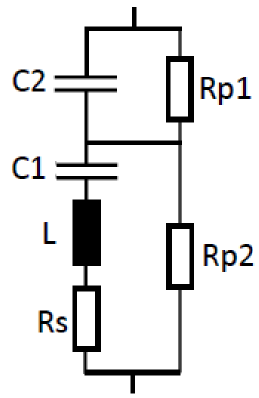

Figure 1. Typical C-type filter design

III. Design challenges

A. Frequency dependent network model

Accurate frequency dependent network model is needed for determining the harmonic impedance at the PoC. Prior to the connection of a new wind or solar farm, the NSP needs to compute the system harmonic impedances, which is a set of impedance polygons of different harmonic frequencies (typically up to 40th order) at the proposed connection point. A wide range of system operating conditions is examined to include variations caused by outages of single lines and transformers, plus numerous combinations of in-service shunt capacitor banks. Figure 2 shows an example of an impedance polygon for harmonic order 2. Statistical information can also be added to the harmonic polygon. For example, the harmonic polygons only encircle areas where the network operates 95% of the time.

B. Inverter harmonic characteristics

For harmonic analysis, the solar PV inverter is typically modelled as a harmonic current source in parallel with the Norton equivalent impedance, which represents the output filter's capacitance, resistance and inductance [6]. Both harmonic current profiles and Norton equivalent impedance are generally available from the OEM. However, these harmonic currents are typically measured in a laboratory and experience shows the source impedance and background harmonic voltages and can have a significant impact in determining the currents and source impedance. It is challenging to calculate directly the Norton equivalent impedance from components of the inverter, and the value is typically derived from division of harmonic voltages measured at the inverter terminal by the harmonic currents. Uncertainty is introduced in the process.

Therefore, for harmonic assessment purpose, the worst-case harmonic current distortion for each harmonic order across all inverter loading levels from 10% to 100%, along with an assumption of infinite Norton equivalent impedance is used to estimate the higher harmonic voltage that the inverter can possibly produce.

C. Harmonic assessment methodology

Traditionally, harmonic voltage calculation is based on the recommendation provided in the IEC 61000.3.6. Equation (1) below is the general summation law used in IEC 61000-3-6 for calculating the resulting harmonic voltage due to multiple harmonic sources:

$$U_h = \sqrt[\alpha]{\sum_i^n U_{hi}^\alpha} \qquad (1)$$

where:

U_h = magnitude of the resulting harmonic voltage (order h),
U_{hi} = magnitude of the various individual harmonic emission sources (order h) to be combined,
α is an exponent depending mainly upon 2 factors:

- The chosen value of probability for the actual value not to exceed the calculated value;
- The degree to which individual harmonic voltages vary randomly in terms of magnitude and phase.

The IEC recommended summation exponents are summarized in Table II.

The CIGRE brochure 672 "Power quality aspects of solar power" [7], which was published in 2018, challenges the IEC recommendation. The technical brochure highlights:

Harmonic magnitudes and phase angles (phasors) are important for realistic studies of cancellation effects between PV inverters / PV installations and other installations. If larger PV plants are built using multiple individual PV inverters of the same model, the harmonic currents of individual PV inverters add up arithmetically up to higher harmonic orders. The standard summation exponents (e.g. according to IEC 61000-3-6) are not suitable in this case.

The brochure further concludes:

Summation exponents and prevailing ratios are both close to one, which confirms that the current emission of the PV inverters adds up virtually arithmetical without any considerable cancellation.

Measurement results from our recent solar farm commissioning tests support this CIGRE finding. As a result, a summation exponent of 1 is applied to all harmonic orders for study purposes to represent the worst-case scenario.

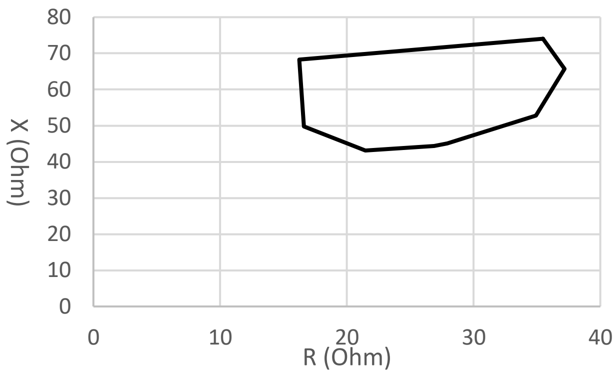

Figure 2. Example harmonic polygon (n=2)

TABLE II. IEC SUMMATION EXPONENTS FOR HARMONICS

Harmonic order	α
H < 5	1
5 ≤ h ≤ 10	1.4
H > 10	2

D. Harmonic filter design methodology

Referring to Figure 1, the following filter design methodology was developed:

1. Confirm capacitor size based on reactive power requirements at PoC (In the CSF case, two 19 MVAr filters are needed in order to meet the NER reactive power capability at the point of connection PoC (not PCC)).
2. Convert the required reactive power to the capacitance $C_{2.}$
3. Choose Q (quality factor) which is the "sharpness" of the filter frequency response.
4. Select the tuned frequency. Multiple filters may be required. (In CSF case, one C-type and one second order damped harmonic filter were designed and tuned to different frequencies).
5. Calculate L based on the tuned filter frequency as for single-tuned designs.
6. For the C-type filter, choose C_1 so that L and C_1 are series resonant ($Z \approx 0$) at the power frequency.
7. Rp1 is normally set to infinity, i.e. open circuit.
8. Adjust Rp2 to provide desired high(er) frequency damping.
9. Check filter design by evaluating the new harmonic voltages at the PoC iterate if required.
10. Perform sensitivity studies of the selected L and C parameters (which may vary due to changes in ambient temperature) to ensure design robustness.

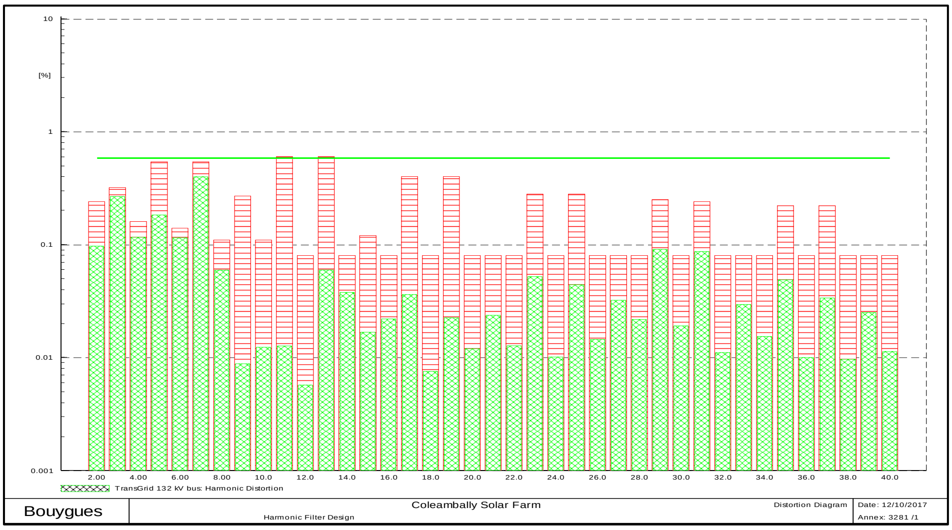

Figure 3. Harmonic distortion diagram

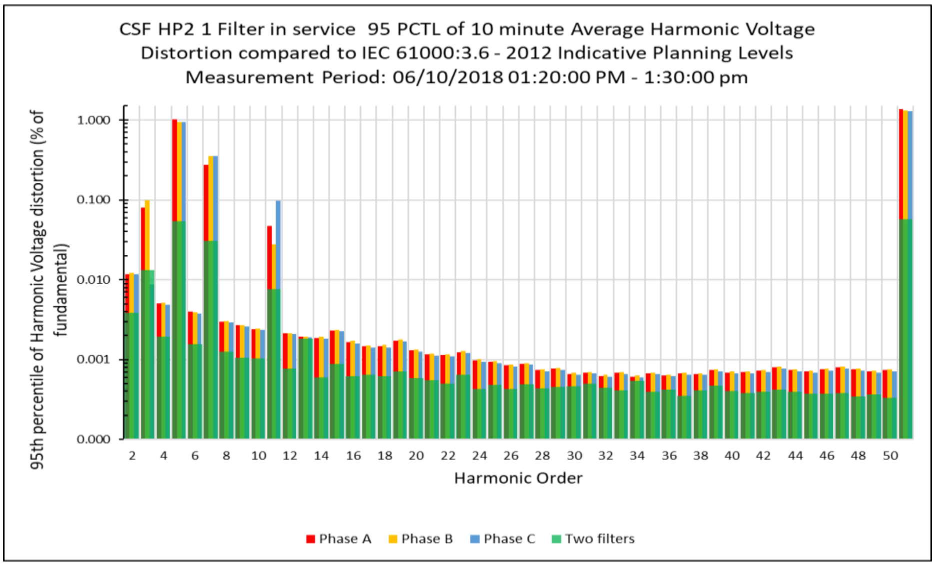

Figure 4. Comparison of measured harmonic emission levels with and without the harmonic filters

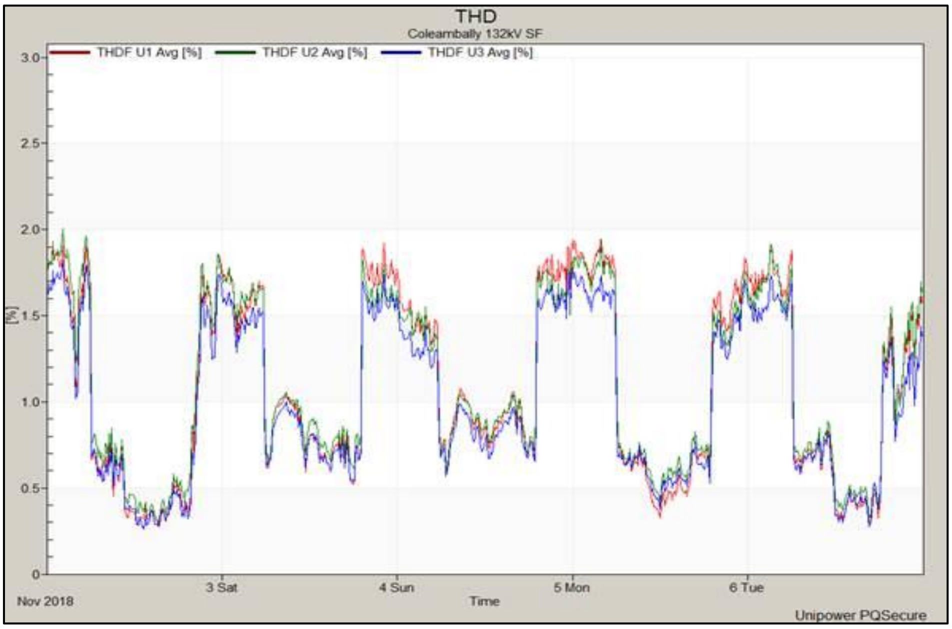

Figure 5. THD measurement plot from TransGrid

Additional sensitivity tests considering variation in filter component design tolerance, and uncertainty of network components are performed the ensure robustness of final filter design and optimize losses.

E. Calculated vs measured harmonic voltages

The harmonic load flow calculation function in PowerFactory is used for assessing the harmonic emission at the PoC of the solar farm. An in-built harmonic impedance loci script was used to transverse through each harmonic polygon and to determine the worst-case harmonic voltage distortion. Figure 3 shows the predicted harmonic voltage distortion at the PoC after the connection of the two harmonic filters through simulation. It demonstrates that the emission of each harmonic voltage is lower than the allocated limit and the THD is less than the allocation. Figure 4 shows the measured harmonic voltages with and without the two harmonic filters. The test result showed a reasonable level of similarity with the simulated responses, which could only be achieved by the combination of (a) good input data, (b) accurate simulation and (c) effective filter design.

IV. COMPLIANCE TEST RESULT

Figure 5 shows the total harmonic voltage distortion measured at TransGrid's Coleambally substation for five consecutive days. The results show that the THD was lower during daytime when the harmonic filters were switched in when the solar farm was operating, despite the generation of additional harmonic current. The filters effectively reduce the system harmonic voltages.

To demonstrate the solar farm meets the statistical harmonic emission requirements, testing and measurement techniques specified in AS/NZS 61000.4.7:2012 [8] were used. AS/NZS 61000.3.6:2012 requires the minimum measurement period to be 1 week of normal business activity, but the monitoring period should include some time of expected maximum harmonic levels. In addition, two performance indices are required:

- 95-percentile of the 10-minute harmonic voltage emission measurements over 1 week should not exceed the planning level; and
- 99-percentile of the 3-second harmonic voltage emission measurement of one day should not exceed the planning level.

The Australian Energy Market Operator (AEMO) requires the generator to demonstrate performance compliance at three to four hold points stepping from minimum to maximum output. The generator cannot advance to the next hold point unless all performance criteria are met. One week of harmonic measurement will significantly delay the commissioning process and any non-compliance in harmonic emission may stall the whole commissioning program. As a compromise, the one-week test is only performed at full load and 4-hour tests are taken for the other hold points of lower active power. Instead of comparing the overall harmonic voltage emission against the planning level, the NSPs require comparing the harmonic voltage introduced by the solar farm against the allocated emission limit. This creates even more challenges to demonstrate compliance as it requires the reverse application of Equation (1), where the solar farm contribution is being interpreted as the vector change rather than the arithmetic difference between the background and the measured values. With an effective harmonic filter system, Coleambally solar farm was allowed to use 4 hours of measurements to demonstrate the generating system was likely to be compliance.

V. DISCUSSIONS

Other operational challenges relating to harmonic assessment, filter design and operations are briefly as follows. Some recommendations are provided.

A. Harmonic voltage emission allocation

There has not been a transparent process for harmonic emission allocation from the NSP. As seen from Table I, tight emission limits were allocated. It is especially difficult for solar farm connecting directly to the distribution system without a step-up transformer. For example, for a solar farm connecting to a 33 kV connection point, the high frequency components are likely to be strongly attenuated by the NSP's substation transformer and is unlikely to impact on any customers at the transmission level. The PoC is also used for assessment rather than the PCC. Some NSPs allocate tight emission limits to the connecting solar farms and in some occasions, required a substantial payment for unspecified damages to a transformer because some individual harmonic harmonics were higher than the allocation (but lower than the planning level) even though the THD was well below the allocation. Although the AS61000.3.6 has made allowance for acceptance of higher emission levels on a conditional basis (e.g. Stage 3 evaluation process), the system operator / NSP show no willingness to negotiate.

B. Filter induced high voltage

A harmonic filter injects reactive power into the network, causing system voltage rise at night when the inverters are off. Two remedial strategies have been deployed:

1. Switching – Filters can be switched off when the solar farm is out-of-service. While reactive power injection into the network can be avoided, this solution has two shortcomings: a) filters will be switched in/out twice a day which will reduce the lifetime of the switchgear and potentially cause transient over voltage (TOV) issues; b) the solar farm collector network impedance may cause amplification of existing (background) harmonics [9].
2. Night mode – some solar inverters have the night mode option – they can be used to inject/absorb reactive power like a STATCOM, but the inverters will consume active power.

C. Triplen harmonics

For electric network with passive elements only, triplen harmonics are zero-sequence in nature. The zero-sequence current circulates within the delta LV winding of transformer and therefore is not present in the HV transformer terminal. However, triplen harmonic currents generated by active network component like the solar inverter are of positive and negative sequence nature. This is demonstrated from on-site measurements where significant amount of triplen harmonics have been observed at the transformer HV terminal. To take the triplen harmonics into account, software which offers unbalanced harmonic loadflow calculation is needed. Alternatively, triplen harmonic source currents shall be treated in the same way to other order harmonic currents (e.g. 4th and 5th) irrespective of the vector groups of transformers within the generating system.

D. Specifications of harmonic measurements

As mentioned above, the requirement for one-week measurement for solar farm creates significant delay for commissioning. In fact, even a one-week measurement period may not capture the worst-case harmonic emission as some of the worst-case scenarios occur during outages, which may not appear during the measurement time frame. On the other hand, reducing the measurement timeframe may lead to underestimating the harmonic impact. For example, it is shown that the harmonic emission of the solar farm is generally lower at peak output [10], and higher at reduced output. Cloud shading which triggers the maximum power point tracking (MPPT) system may also introduce higher than normal harmonics. In addition, the time when the inverters and harmonic filters switch in/out will also transiently create higher harmonics. A better compliance measurement process and requirements should be considered.

E. Instrumentation accuracy

In many cases, harmonic measurements are taken from revenue meters which typically have a 0.2% tolerance [11]. Proper demonstration of less than 0.1% emission limit for individual harmonic requires the use of Class 0.1 current transformers (according to IEC 61689-2) which are typically used for laboratory test only. Accuracy of the complete measuring system is a challenge for these low allocations.

VI. Recommendations

The Australian Standards AS/NZS 61000.3.6 and the corresponding IEC standards have been using the same emission planning level that was developed a few decades ago based on a limited set of well-established harmonic current sources. The allocation of harmonic limits (especially of the higher frequency), the summation law, and the limit allocation process need review in light of the changes in the power system, and proliferation of power-electronic based inverter technologies.

Some quantitative analysis on the impact of harmonics to the modern power system should be performed. For example,

- What damage do high order harmonics cause on transmission systems?
- Is any plant susceptible to damage from harmonics if at the current planning levels?
- What are best practice ways to design plant to survive harmonic levels without loss of life?

In additional, better guidance on how to meet with the Standards requirements is needed. For example, how measurements should be taken and compared with allocations (e.g. comparing the measurement against planning level or the solar farm contribution only against the emission allocation which requires the vectorial subtraction from previously measured background harmonics), and whether per-phase harmonic measurement is needed for compliance demonstration purpose.

The Joint Working Group CIGRE / CIRED C4.40, has therefore been established to consider what revisions are needed to ensure the standards remain adequate. The areas of focus include the evaluation of suitability of:

- general limit allocation process in systems containing distributed resources
- existing indices and limits (e.g. 95-percentile) for use in reconfigurable systems
- existing approach for allocating harmonic limits for higher frequencies (above, say, 1 kHz)

VII. Conclusions

This paper presents the challenges of connecting power electronic based inverters to the NEM in terms of harmonic emission compliance. It demonstrates with field measurement results how harmonic filters can be designed to reduce the harmonic voltage emissions at the PoC. This paper further discusses other operational issues regarding switching in/out the solar farms and harmonic filters, treatment of triplen harmonics and measurement requirements for compliance purpose. A review into the existing standards on harmonic emission is recommended with the increasing penetration of renewables into the grid.

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References

[1] Clean Energy Council, "Clean Energy Australia Report 2019" [Online].Available: https://assets.cleanenergycouncil.org.au/documents/resources/reports/clean-energy-australia/clean-energy-australia-report-2019.pdf [Accessed 07 08 2019]

[2] AEMC, "National Electricity Rules", Version 123, 1 July 2019.

[3] AS/NZS 61000.3.6, "Electromagnetic compatibility (EMC) Part 3.6: Limits—Assessment of emission limits for distorting loads in MV and HV power systems", Standards Australia/Standards New Zealand, 2001.

[4] TR IEC 61000. Electromagnetic compatibility (EMC) – part 3-6: Limits – Assessment of emission limits for the connection of distorting installations to MV, HV and EHV power systems.

[5] [Online] https://coleamballysolarfarm.com.au/ [Accessed 07 08 2019]

[6] E. C. Aprillia, "Modelling of Photovoltaic (PV) Inverter for Power Quality Studies", University of Technology Eindhoven Thesis, August 2012.

[7] CIGRE JWG C4/C6.29, Technical Brochure 672, "Power quality aspects of solar power", December 2016.

[8] AS/NZS 61000.4.7, "Electromagnetic compatibility (EMC) Testing and measurement techniques - General guide on harmonics and interharmonics measurements and instrumentation, for power supply systems and equipment connected thereto", Standards Australia/Standards New Zealand, 2012.

[9] R P D Ross, M P De Carli, P F Ribeiro, "Harmonic distortion assessment related to the connection of wind parks to the Brazilian transmission grid", CIGRE Paper C4-101, 2016 Paris Session.

[10] J Schlabbach; A Gross, "Harmonic current emission of photovoltaic inverters", 19th International Conference on Electricity Distribution Vienna, 21-24 May 2007.

[11] ABB, "Instrument Transformers Application Guide", 2015.