Harmonic compliance assessment and mitigation design in renewable energy networks

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***Abstract*—The analysis approach for harmonic emission compliance studies in distributed generation systems is shaped by a regulatory framework that requires a priori resolution of several performance requirements. This approach is steeped in risk avoidance and, like most risk avoidance, results in conservative outcomes that are not necessarily in the best interest of the market. This article describes this analysis approach and demonstrates how the regulation and associated analysis result in increased rather than decreased risk to the stakeholders. A suggestion is made for a pragmatic approach that will result in better outcomes for network owners as well as generation proponents. The recommended approach provides for an initial risk assessment followed by field measurements that quantify the extent of compliance and assist in the design of mitigation systems.**

I. INTRODUCTION

The rate at which relatively large blocks of power electronic based generation are now being connected to the grid requires diligent application of the procedures set out in the standard [1] as expected in the regulatory legislation.

Connection agreements are negotiated between generator proponents and network operators within the prevailing regulatory framework. The resulting grid connection agreements require proponents to adhere to a set of performance standards ranging from reactive power capability to active power control [4] and includes quality of electricity generated, deemed to cover aspects of voltage fluctuations, harmonic distortion and voltage unbalance. This article explores important aspects of the compliance and mitigation system design requirements relating to generation of harmonic distortion.

Assessing compliance with harmonic emission limits as part of a grid connection study requires an understanding of the interaction between the external network and the proposed generator – especially relating to non-linear aspects of the generator. In its simplest form, a renewable energy source connected to an existing network can be represented as shown in the figure below. It is important to keep this representation in mind as each of the elements is in fact quite complex.

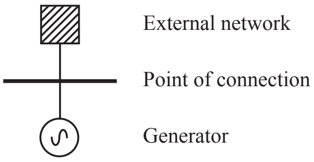

Fig. 1. Simplest representation of embedded generation

Harmonic assessment consists of estimating the effect of non-linearities within the generator on voltage distortion at the point of connection. Harmonic mitigation design consists of proposing solutions that will result in compliance with agreed (automatic or negotiated) access standards as documented in a grid connection agreement. The required ratings of proposed solutions are then determined according to the most onerous foreseeable operating conditions.

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At first glance the process is simple: the network service provider establishes an access standard that is quantified in terms of maximum voltage (and sometimes current) emissions by the proposed new generator. The generator must demonstrate that these limits are not exceeded under the range of operating conditions that the plant will be exposed to when connected to the network, either by virtue of the nature of the generators or due to mitigation measures. Once the generator is commissioned, performance tests verify compliance.

The diagram in figure 1 above includes a network element, essentially "everything above the point of connection." In reality the situation is complex: networks are not perfectly known and can operate in multiple configurations, the generator and network influence each other, and both will change over time. The considerable advances in analysis and measurement tools have been counter-weighed by rapid development of new generating technology, more sensitive loads and the demand for highly optimised, low loss operation. The high penetration of renewable, distributed generators demands careful consideration of the most appropriate approach to the voltage quality aspect of grid connections.

II. NETWORK MODELS

Power system engineers are acutely aware of the need for an accurate representation of the electricity network and improvements in computer technology now allow modelling of any aspect of the network, from basic load flows (important for efficient energy dispatch), fault levels (essential for effective protection coordination) and control system modelling (to safeguard system stability). Harmonic analysis tools are now able to perform detailed balanced and unbalanced harmonic load flows, and electro-magnetic transient analysis open up views on sub-microsecond events in the network. Such power demands the responsibility to construct accurate, robust models of the network, so that all stakeholders are aware of the assumptions, limitations and predictive accuracy of models.

Harmonic analysis essentially consists of load flows at multiple frequencies. The network impedance at each of frequency is critically important. Without an accurate representation of the frequency dependent impedance of the network, harmonic analysis is not of much practical use. Some aspects that bear consideration are:

Changes over time: No network is static, and planning engineers are continuously matching predictions of future load changes with requirements for equipment ratings and configurations. Despite this uncertain future, compliance is to be assured under all foreseeable future operating conditions. The graph below demonstrates some of the variations in network impedance that can occur as a result of four such variations: winter or summer loads, high and low load conditions.

Only a segment of the frequency range is shown for clarity. In most analyses, eight conditions are considered for each year under review: summer, winter, autumn and spring, high load and low load conditions.

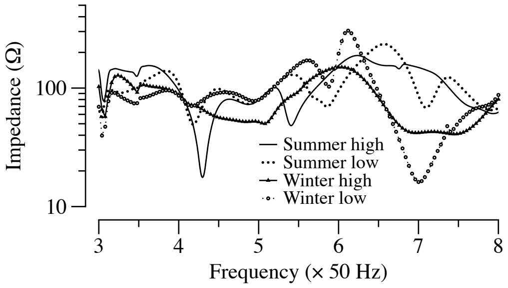

Fig. 2. Subset of network impedance depending on time

Contingencies: Each of the above time-based variations will be subject to several network contingencies. The ability of the generator to remain functional despite, for example, the loss of one or more feeders in the surrounding network, the status of bus couplers, or the loss of transformers, is a key requirement of connection agreements. These contingencies have a marked effect on network impedance, as shown in the example below for only two possible operating modes.

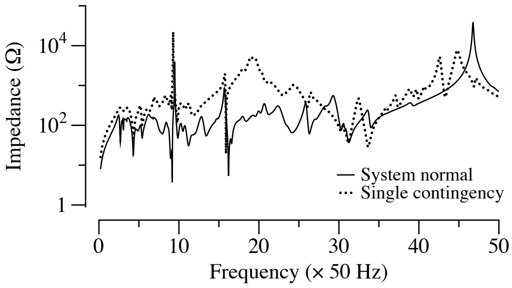

Fig. 3. Subset of network impedance depending on contingencies

Basic network uncertainty: Network operators are surprisingly unaware of the status of their own network, specifically relating to parameters that determine frequency dependent impedance. It can be a considerable hurdle to obtain, for example, the tuned frequency of existing capacitor banks, or the correlation between the switched status of such banks in the various time-based variations (for example, whether any particular capacitor bank is connected or disconnected during a high load period) and uncertainty in these parameters can only be modelled as a set of possible values.

Other, normal changes need to be considered as well, such as the effect of temperature variation on capacitance, resistance and loads, normal fundamental frequency deviations, and the impact of voltage fluctuations.

Loads and generators Most harmonic studies assume that the network impedance (everything in the network element) is independent of the impedance of the generator. This is generally true in conventional systems where the short circuit ratio (the ratio of the total system fault current to the load/generator current) is relatively high. In most renewable and distributed generation systems that are located in weak networks this assumption does not hold: the frequency dependent impedance as measured at the point of connection is significantly impacted by the generator impedance. This is demonstrated in the graph below, and has important consequences for harmonic studies as each of the several hundred possible network scenarios now also needs to consider the many possible variations in generator configurations, most of which will almost certainly not be known until detail design of the generator is complete.

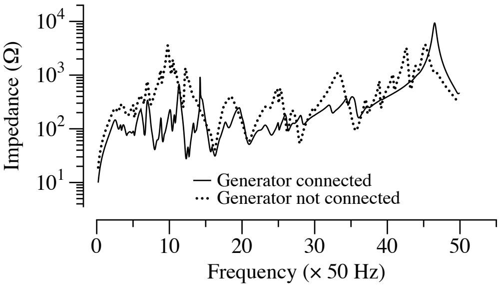

Fig. 4. Subset of network impedance depending on generator connection

It is clear that the network may take on any of a number of possible states and it is tempting to allocate probabilities to these with descriptors such as “unlikely”, “rare” or “usually,” but that would be misleading. The conditions listed here have a uniform probability distribution — it is equally likely for the network to operate for extended periods of time in any of these states, and others that cannot be quantified.

The large number of possible network operating modes is commonly represented as impedance ranges: an area in the R/X impedance plane for each individual harmonic order that contains all the possible values of network impedance at that frequency, and around which a circumscribing polygon in the form of a convex hull [8] is then constructed. When transferring the values at integer (or fractions of integer, in the case of inter-harmonics) it is important to record a representative and realistic set.

Subsequent analysis can then focus on traversing the edges of the polygon between vertices, rather than considering each of the (possibly thousands of) constituent members.

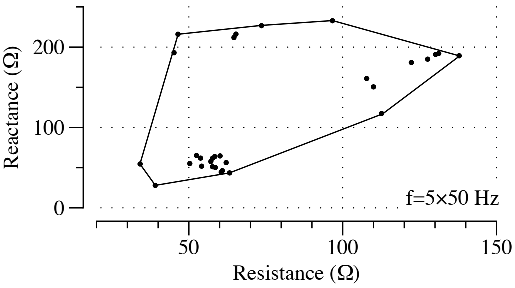

Fig. 5. Example of construction of an impedance polygon

Harmonic analysis is based on determining the point on each frequency polygon (not only the vertices) that results in the highest harmonic distortion at that frequency. This is a relatively fast, comprehensive and reasonably conservative approach. The drawback of this approach is that once a polygon is traversed there is no way any specific result can be traced back to a specific network configuration, and since the harmonic distortion is calculated for each harmonic order independently the concept of total harmonic distortion (a key feature in the compliance evaluation) is effectively lost.

III. GENERATOR

The new generator proponent naturally has more detailed information on the nature of the power sources. Most renewable generators that apply for grid connections are based on a distributed set of generators that are interconnected and combined at one or more collector substations, from where the grid connection is made.

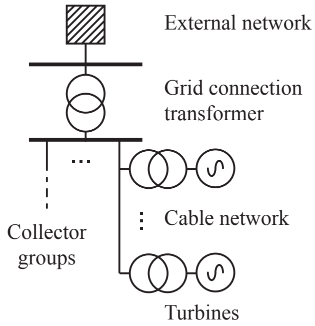

Fig. 6. Slightly expanded view of embedded generator

Most of the information in this distributed network is well-defined: transformer impedance, cable construction and length, location and number of generators.

The fact that most distributed generation is based on inverter technology (be that solar PV, wind, battery or stabilising system) and that these inverters generally have high switching frequencies make careful consideration of distributed cable capacitance a key aspect of any analysis. Information relating to the frequency dependent impedance of cable parameters can be difficult or impossible to obtain from manufacturers' data sheets and even if such information is available the site-specific influence of factors such as how screens are connected and the geometry of the cables when laid can have a significant and critical impact on the overall model. It is essential to verify the parameters as presented in cable data sheets against calculations based on the actual geometry, materials and manner of laying employed in each case. Figure 7 illustrates some components of a single core medium voltage cable that is used in the cable model.

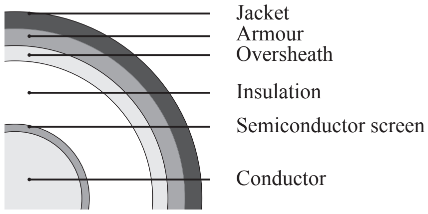

Fig. 7. Typical cable construction

Despite the relatively high degree of certainty in the generator network parameters there are several variables that will influence the overall frequency dependent network, such as the tap position (and hence impedance) of transformers, the actual installed cable lengths and parameters and the number of collector groups that are connected to the collector busbars. These are all independent of the upstream network variations, and can result in the requirement to traverse the network impedance polygons several dozen times, each time with a different generator configuration, in order to obtain comprehensive information.

IV. HARMONIC SOURCES

The characteristics of the generators themselves are at the heart of this complex network model.

Detailed models of inverters using time domain analysis tools can provide useful insight into the expected harmonic emissions of specific generators, but these idealised models need practical verification in the form of measurements to be useful. Changes in connection details (specifically the source impedance) also requires re-modelling of the equivalent impedance and emission spectra for individual applications. This approach to modelling generally includes (and requires) use of the Norton-equivalent impedance of the generator, and the accurate determination of this equivalent impedance is problematic [9].

The existing standard IEC 61400-21 [2] provides a robust framework for measuring, recording and reporting emissions from wind turbines. and the same standard is commonly used for determining emissions from solar PV inverters. The outcome of the process is a table as exemplified below that summarises emissions (in percentage of inverter rated current) at all relevant harmonic orders and at various power output levels.

Table 1. Extract from harmonic current measurement report

	Power output bins			
n	0–10	10–20	…	90–100
2	0.33	0.26		0.36
3	0.17	0.25		0.54
⋮				
40	0.11	0.16		0.12

The advantages of this approach is that emissions are presented in a standardised manner and are based on measurements according to prescribed methods and accuracy over a realistically long period, and the effect of the Norton equivalent impedance that is characteristic of the inverter is included in the measurement. This allows the inverter to be modelled as a current source. The approach has been criticised for resulting in overly conservative outcomes [3]. The current standard allows for power quality measurements to be conducted provided the voltage total harmonic distortion remains below 5%, and does not require the voltage harmonic spectrum to be recorded prior to or during the emission measurements. Given that most modern IGBT based inverters exhibit current emissions with the same or lower current total harmonic distortion, it is reasonable to suggest that some or most of the recorded emissions in fact originate in the network, not in the inverter.

As a comparison earlier generation wind turbines based on driven asynchronous motors had significantly higher emissions than most current generation IGBT inverter systems, due mainly to pole salience effects.

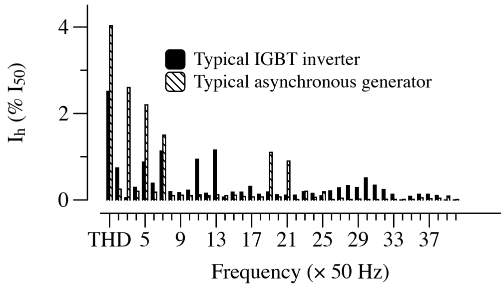

Fig. 8. IGBT and induction generator harmonic current spectra

It is believed that a new revision of the standard (now in CDV stage) will include recommendations on addressing the quite major drawback of the influence of background harmonic distortion on measured turbine emissions.

V. ANALYSIS FOR COMPLIANCE

The above approach to the network model establishes a range of impedance values at various harmonic orders and quantifies the harmonic emissions that are to be applied to the embedded generators. The analysis requires calculation of the voltage drop caused by currents emitted by the various generators across these impedances. The compliance process involves two stages: in the first, the network owner establishes a set of compliance levels for contributions to emissions, usually in accordance with the process outlined in the common standard IEC 61000-3-6. The emission limits can be based on automatic access (compliance with which requires no further permission to connect) or more relaxed, negotiated access limits, and the overall purpose is to ensure that all existing and future network connections are treated fairly and equally and that the long term integrity of the network is maintained.

The second stage requires the proponent to estimate whether the emissions of the generator will exceed compliance limits, and if necessary, to design and implement mitigating measures that will ensure compliance.

This approach and the associated design must also take into consideration the extreme levels of uncertainty involved in the design process. Many of the generator performance expectations can be clearly separated from the connected network behaviour, or at least the relevant network parameters are relatively simple to understand: the expectations of being able to withstand and remain connected when the network experiences transient conditions, or the ability to generate or absorb a certain amount of reactive power, or produce specific control system response in reaction to a variety of external inputs, are all comparatively simple because the lines of responsibility are very clear.

The surrounding network and the wind farm interact strongly in terms of harmonic performance. The responsibility of the wind or solar farm is to adhere to emission limits, but it has no control over the frequency dependent impedance of the network. It can be said that the network owner is equally responsible for harmonic emissions from the wind farm as arbitrarily small current emissions from the generator can interact with high network impedance. To compound matters, in a priori analysis there are any number of such possible interactions which means the wind or solar farm is required to design and implement mitigation systems that are essentially universally able to limit harmonic current emissions from any harmonic order to reach the network. And despite the fact that the generator has no way of knowing or controlling the external network, is also expected to install mitigation systems that will not result in any adverse effects such as harmonic amplification through parallel resonance in the surrounding network.

It is a very onerous design expectation and tends to result in complex filter configurations such as the typical configuration of a multi-branch, damped filter.

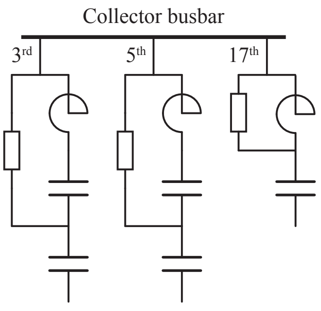

Fig. 9. Multi-branch, damped harmonic filter configuration

The impedance characteristic of this filter combination is designed to ensure compliance under all conditions, and require significant and specific damping and tuned frequencies and unusually tight manufacturing tolerances to achieve this goal.

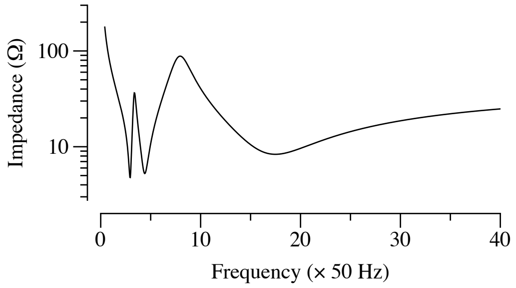

Fig. 10. Multi-branch, damped harmonic filter impedance

The typical outcome of a study and filter design is demonstrated graphically in the spectra in figure 11. Without mitigation harmonic emissions exceed acceptable limits across a wide range of harmonic orders. When the required filters are implemented all harmonic orders are at or below emission limits, for all the many operating scenarios considered.

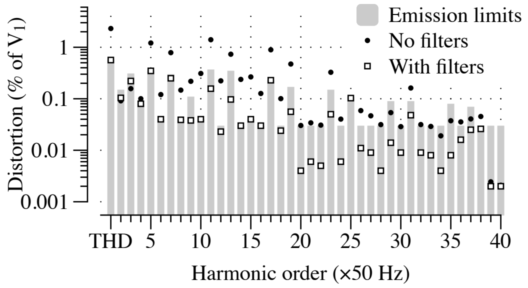

Fig. 11. Effect of harmonic filters on voltage distortion

At the conclusion of generator commissioning, the Australian regulator requires performance testing of the generator to validate compliance with the requirements of the generator performance standard. This testing is generally referred to as “R2” testing, and includes measurements of harmonic emissions. A guideline has been developed to assist proponents to perform these tests [7].

It is only at this testing level that any verification of assumptions on emissions, generator network or upstream transmission / distribution system is done under the formal approach described above.

VI. A PRAGMATIC APPROACH

The process described above is rigorous and provides the necessary level of risk mitigation to give comfort to both the network owner and generator proponent that compliance to harmonic emission limits have been addressed in the design stage, and that proposed mitigation measures will not have any detrimental effects on the network.

When the generator proponent is responsible for ensuring that a wide range of uncertainties in existing network conditions is modelled correctly, and is responsible for requesting all the necessary and appropriate information on the network that will allow appropriate modelling, it is clear that responsibilities are not allocated appropriately and that risk and the cost of risk mitigation is skewed towards the generator proponent.

The following practical approach is suggested:

- The network owner must take responsibility for providing frequency dependent impedances at the point of connection, either in the form of frequency scans of impedance, or impedance ranges for each individual harmonic order that is of interest in the connection agreement. This information must include all the network variations that the generator will realistically be exposed to for periods of time that are relevant to the connection agreement, such as contingencies, existing capacitor bank status and network topology changes.

This is contrary to the existing situation, where network information is generally provided with disclaimers distancing the provider of the information and the owner of the network assets from responsibility for the accuracy and completeness of the information, and explicitly shifts the risk of any errors, incompleteness or lack suitability to the generator proponent. Responsibility for the accuracy of this information cannot be passed to the generator proponent.

- The network owner is responsible for setting emission limits, and for providing information on the prevailing harmonic distortion in the network prior to the generator being connected. This is vital information for the generator proponent as it allows correct ratings of any required mitigation equipment and allows for future evaluation of harmonic emissions contributing to prevailing harmonic distortion.
- Using this set of information, and the additional information available on the generator network and inverter emissions, the proponent is responsible for a harmonic compliance assessment. This includes identifying the need for mitigation measures such as harmonic filters. The proponent is responsible for providing sufficient infrastructure in the facility (in terms of available space, civil benching, switchgear, etc) to allow for these measures to be implemented.
- During “R2” measurements, the actual emissions from the generator are to be established, and if voltage distortion levels exceed those set out in the emission limits, then mitigation is installed on the basis of the earlier assessment as modified by actual measurements. The “R2” measurement template unfortunately does not address the issue of measurement error and uncertainty, suggesting only that measurement equipment should have valid calibration certificates. Magnetic voltage transformers typically in use in medium and some high voltage applications can exhibit unacceptable errors above approximately 1 kHz [6]. In general, the recommended guidelines in IEC TR61869 [5] suggests that any application that uses capacitive voltage transformers commonly applied at HV and EHV cannot be used in any way as the basis for voltage harmonic measurements, and that current technology restricts useful voltage measurements to resistive shunts, capacitor voltage dividers, or optical voltage transformers. Current measurement is less problematic, with reasonable bandwidth possible with a variety of technologies, including the commonly used inductive type.

  The common absence of calibration certificates including frequency response tests for transmission or distribution level instrument transformers, and the inherent difficulty in measuring low amplitude harmonic voltages and currents using existing instrument transformers should be taken into consideration not only during post-commissioning measurements, but also when setting the emission limits.

  Another shortcoming of the “R2” measurement template is that no guidance is provided on how to identify contributions to harmonic distortion at the point of connection in the presence of existing background harmonic distortion. The measurement plan should identify how this will be done once background harmonic measurements are made.
- The proponent is to guarantee a fixed time period within which emissions will be made compliant once generation has commenced.

VII. Conclusion

The pragmatic approach to harmonic compliance assessment suggested in this article reduces the risk to the network owner, as any errors in the original network information are detected and corrected in the subsequent measurement process. It reduces the risk to the proponent of having to design and install mitigation measures that may be unnecessary, expensive and due to lack of accurate network information, ill suited to the application. The final outcome is a generator that is integrated correctly into the local network with least-cost, reliable and robust harmonic emission performance.

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