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Experience in the application of IEC/TR 61000-3-6 to harmonic allocation in transmission systems

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Abstract

Technical report IEC/TR 61000-3-6 is widely used as a guide to harmonic management in HV and MV networks, assisting in coordination of harmonic levels between utility and customer. In 2001, Australia and New Zealand adopted the harmonic standard AS/NZS 61000.3.6, which closely follows the above IEC technical report. As a result, transmission utilities and connected loads are required by government regulations to abide by the harmonic allocations set by the standard. The technical report contains some useful general principles which can be applied to the harmonic management of power systems. However, unexpected difficulties can be found when attempts are made to apply them to large power systems. The formal procedure recommended by the standard for calculation of harmonic emission levels limits the voltage at the point of connection. There can be situations where the highest harmonic voltages are remote from the PCC. This can be accounted for by taking into account interactions between each injecting load and all other busbars in one single step. This leads to the development of a harmonic "allocation constant", which will apply to the entire transmission network, as a measure of the ability of the network to absorb harmonics without violating a set planning limit. At present, the allocation procedure given in the standard implies consideration of only a single network operation scenario. However, substantial variations have been identified in the harmonic behaviour of transmission networks, including harmonic absorption capacity, with changes in generator commitment and switching configuration. The proposed approach accounts for variations by taking data from multiple network scenarios. For the specification of an easily-measurable harmonic current emission level - rather than a harmonic voltage level - for a particular customer, the network harmonic impedance is necessary. This quantity can vary substantially at the one busbar in a transmission network. The application of a standardised hth harmonic impedance is proposed which is based on the fundamental frequency fault level at the PCC. IEC/TR 61000-3-6 gives no guidance as to methods of treating harmonic resonances in transmission systems. Resonances will occur in any transmission system with sufficient line lengths, and will impose substantial constraints on harmonic allocation if computer calculations are accepted without modification. It is unclear if these resonances are of practical importance, and it is proposed that resonance amplifications be limited to allow useful allocations until their importance has been established by field results.

Keywords

systems, transmission, allocation, experience, harmonic, application, 6, 3, 61000, tr, iec

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EXPERIENCE IN THE APPLICATION OF IEC/TR 61000-3-6 TO HARMONIC ALLOCATION IN TRANSMISSION SYSTEMS

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SUMMARY

Technical report IEC/TR 61000-3-6 is widely used as a guide to harmonic management in HV and MV networks, assisting in coordination of harmonic levels between utility and customer. In 2001, Australia and New Zealand adopted the harmonic standard AS/NZS 61000.3.6, which closely follows the above IEC technical report. As a result, transmission utilities and connected loads are required by government regulations to abide by the harmonic allocations set by the standard.

The technical report contains some useful general principles which can be applied to the harmonic management of power systems. However, unexpected difficulties can be found when attempts are made to apply them to large power systems.

The formal procedure recommended by the standard for calculation of harmonic emission levels limits the voltage at the point of connection. There can be situations where the highest harmonic voltages are remote from the PCC. This can be accounted for by taking into account interactions between each injecting load and all other busbars in one single step. This leads to the development of a harmonic "allocation constant", which will apply to the entire transmission network, as a measure of the ability of the network to absorb harmonics without violating a set planning limit.

At present, the allocation procedure given in the standard implies consideration of only a single network operation scenario. However, substantial variations have been identified in the harmonic behaviour of transmission networks, including harmonic absorption capacity, with changes in generator commitment and switching configuration. The proposed approach accounts for variations by taking data from multiple network scenarios.

For the specification of an easily-measurable harmonic current emission level – rather than a harmonic voltage level – for a particular customer, the network harmonic impedance is necessary. This quantity can vary substantially at the one busbar in a transmission network. The application of a standardised h^{th} harmonic impedance is proposed which is based on the fundamental frequency fault level at the PCC.

IEC/TR 61000-3-6 gives no guidance as to methods of treating harmonic resonances in transmission systems. Resonances will occur in any transmission system with sufficient line lengths, and will

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impose substantial constraints on harmonic allocation if computer calculations are accepted without modification. It is unclear if these resonances are of practical importance, and it is proposed that resonance amplifications be limited to allow useful allocations until their importance has been established by field results.

KEYWORDS

Harmonics, Harmonic Allocation, Network – Transmission, IEC/TR 61000-3-6, AS/NZS 61000.3.6

1. INTRODUCTION

IEC/TR 61000-3-6 [1] concerns utility and customer harmonic responsibilities in MV and HV/EHV power systems. Although a Type 3 report (a collection of useful data and procedures), it has been adopted in Australia with slight modifications as a national standard [2]. The Australian distribution industry has found difficulties in applying this document, particularly in two areas: (i) determination of planning levels for specific power systems, and (ii) allocation under Stage 2 when there is significant feeder impedance. As the then National Electricity Code [3] (and now the National Electricity Rules [4]) required utilities to implement the standard [2], there was a need for more prescriptive procedures in the application to MV radial distribution systems. Consequently Standards Australia commissioned the writing of the Handbook HB 264-2003 [5].

Some of the Handbook's authors have since been involved in the determination of planning levels and Stage 2 allocation of harmonic current emission in transmission systems. The transmission systems under study (refer Section 3) are characterised by long, lightly loaded transmission lines with uncertainty as to the future loading of individual nodes. One system has predominantly hydro generation and there is a large variety of possible generator connection scenarios. These issues are not dealt with fully in the IEC document or its Australian equivalent. The paper will cover the analytical techniques developed in order to apply the principles of [1] to the study systems. It is anticipated that there might be other transmission systems with similar characteristics and thus the developed techniques might be of general interest.

2. PRINCIPLES OF IEC/TR 61000-3-6 [1]

Planning levels are the utility's internal objectives for harmonic voltage limits. They are used in the allocation of customer's harmonic current as explained below.

The main part of the document of concern is Stage 2, the allocation of harmonic currents to a particular customer. Four important principles are given:

1. All customers, both present and future, are to be allocated a share of harmonics.
2. Harmonics are to be allocated in proportion to customer maximum demand ("agreed power" is the term used in the document).
3. When all customers are taking their full share, the maximum harmonic voltage in the system will be limited by the planning level value.
4. Diversity is to be accounted for by the standard's second summation law, whereby voltages and currents A_i can be added according to

$$A_{NET}^{\alpha} = \sum_{i} A_i^{\alpha} \qquad (1)$$

where the diversity exponent α is unity for h<5, 2 for h>10, and 1.4 otherwise.

These principles are best illustrated with a simple distribution system example given in Figure 1, with LV loads being ignored for simplicity. It will also be assumed that harmonic voltages transfer from upstream to the MV system under study with no change.

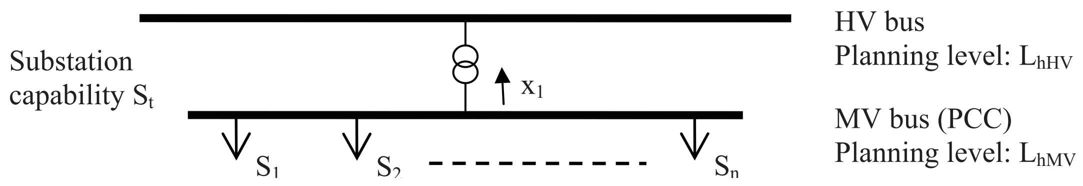

Figure 1: Simple distribution system example

Suppose the supply capability of the MV substation is S_t. Let the planning levels at the h^{th} harmonic for the HV and MV buses be L_{hHV} and L_{hMV} respectively. The global voltage available for MV loads is

$$G_{hMV} = (L_{hMV}{}^{\alpha} - L_{hHV}{}^{\alpha})^{(1/\alpha)} \quad (2)$$

Harmonic voltage is to be allocated to a customer with maximum demand S_i such that the sum of all allocated harmonic voltages is G_{hMV}. Making use of the diversity equation (1), this can be achieved by choosing the h^{th} harmonic voltage emission level of customer "i" to be

$$E_{Uhi} = G_{hMV} (S_i/S_t)^{(1/\alpha)} \quad (3)$$

Let the fundamental supply system impedance seen at the PCC (point of common coupling) be x_1. Assuming this impedance at the h^{th} harmonic is hx_1 gives a harmonic current emission level of

$$E_{Ihi} = E_{Uhi}/hx_1 \quad (4)$$

In transmission systems, every connected load can potentially affect the harmonic voltage, not just at the PCC, but at every other bus as well. [1] allows for this by increasing the assumed supply capability of the bus under study, effectively reducing the proportion available to local buses through (3).

Of the four principles articulated above, the first and third are straightforward to interpret under steady state conditions. Both are difficult to apply, however, to a transmission network, which is continually evolving and in which the future load is neither well-known nor well-defined. Some proposed techniques for accounting for these difficulties are presented in Section 6.

3. CHARACTERISTICS OF THE SYSTEM UNDER STUDY

The developed analytical techniques have been applied to two existing transmission networks in Australia. As similar conclusions have been obtained for both networks, only one is considered here in detail.

The longest transmission lines in this network are around 200 km long and require detailed representation at harmonic frequencies as elaborated in Section 4. The substantial capacitance exhibited by some of the long lines can mean that harmonic current injected at one extremity of the network can lead to substantial harmonic voltage at other extremities. It is thus necessary to study the transmission network [6] as one entity. The transmission system has both 220 kV and 110 kV voltage levels, each having generation and individual loads connected. It is impossible to distinguish between the two levels in a functional sense. As will be demonstrated in Section 6, this has significant implications for harmonic allocation.

In the network under investigation, the peak load is around 1600 MW and more than 50% of this is connected at a single substation, quite remote from the bulk of the generation.

4. MODELLING PRINCIPLES

Development of a model for the study system is largely based on [7], with some additional contributions from [6].

As harmonic orders 2 through 40 are all of concern and numerous long lines exist within the study system, detailed modelling of transmission lines has been required. That is, a model incorporating distributed parameter equations, including both series impedance and shunt admittance, has been used. Skin effect was also taken into account using the recommendations from [7].

Extensive simplification of the system was not possible due to sensitivities of the Particular features of the study system meant that, as suggested by [6], the entire primary transmission network needed to be included in the model. These features included numerous generator scenarios (it is a predominantly hydro system with extensive reserves), complex connections of multiple transformer secondaries, and meshed systems connected via multiple voltage levels. However, loads and generators connected at MV buses were modelled referenced to appropriate HV buses.

Transformer, line, capacitor and generator models were combined to form the admittance matrix ($\mathbf{Y}_h$) and resulting impedance matrix ($\mathbf{Z}_h$) of the entire study system for each relevant harmonic. Harmonic impedance of the system varies with time due to the inclusion of switched capacitors, generator connections and changing network configurations. All of these scenarios have been taken into account to determine the worst-case harmonic impedance, as discussed in Section 6.6.

It was also found during the modelling that small changes in harmonic voltages at one of the major loading sites were amplified significantly at some very remote sites. The inclusion of network damping was thus considered important, however rather than adjusting the already included load impedances it was decided to simply cap these amplifications for the purpose of developing planning levels and allocation strategies. Detailed treatment of this subject is given in Section 6.4.

5. PLANNING LEVELS

Harmonic voltage planning levels selected were based on IEC/TR 61000-3-6 [1], incorporating the principles of the Handbook HB 264 [5] which was developed for interpreting AS/NZS 61000.3.6 [2] on MV systems. Planning levels are profiled across the various voltage levels. Application of the method in [5] had the perceived advantage of ensuring that internal planning levels set within a distribution network were appropriate for the external planning levels set for the distribution utility by the transmission network.

The recommended planning levels were adjusted partially for the study system for two reasons:

(i) The system contained numerous interconnections between the 220 kV and 110 kV networks. Both generation and load were relatively evenly distributed between the 220 kV and 110 kV networks. Since loads are potential harmonic sources and generators are harmonic current sinks, the 220 kV harmonic voltages would not be expected to be markedly different from those on the 110 kV system. Thus harmonic planning levels for the 220 kV system have been taken as equal to those for the 110 kV system.

(ii) Generator buses would be expected to have lower harmonic levels than for load buses at the same voltage level. Specifying an unduly high planning level here will impose a high harmonic immunity level which will increase generator cost. After considering generator subtransient reactances and generator transformer impedances in the study system, generator bus planning levels were set at half the transmission bus planning level values.

6. ALLOCATION UNDER STAGE 2

6.1 Overview and objectives

The overall purpose of the Stage 2 allocation procedure of IEC/TR 61000-3-6 [1] is to ensure that the harmonic voltage level at each bus remains no higher than the planning level. To ensure that the allocation is equitable in some sense, allocated harmonic emission level should be an increasing function of load magnitude. Taking account of the diversity relationship expressed in (3), an emission quantity needs to be allocated in proportion to the term $S_i^{(1/\alpha)}$. Candidates for the allocated quantity are harmonic voltage, current and VA. Since transmission systems have buses with widely varying impedances (fault levels), the use of current would lead to the limiting of current generally based on the impedance of the weakest supply point. Harmonic voltage is considered to be the most suitable allocation quantity. Thus, for each load S_i,

$$E_{Uhi} = k_h S_i^{(1/\alpha)} \tag{5}$$

is the harmonic voltage allocated to that load at the PCC. The interpretation of coefficient k_h, the "allocation constant" at the h^{th} harmonic, is explained in sections 6.2 and 6.3.

6.2 Requirement for global allocation

As outlined in Section 4, in a transmission network with long lines, a harmonic injection at one bus can give rise to substantial harmonic voltages at many remote buses. The allocation task is to find k_h in (5) such that no bus voltage exceeds the planning level. Therefore the proposed allocation procedure must take account of all loads (both present and projected) and the harmonic voltages at all buses.

6.3 Influence coefficients

The formal Stage 2 allocation procedure recommended by IEC/TR 61000-3-6 may require the calculation of influence coefficients. An influence coefficient $k_{h,ij}$ (noting that the harmonic order h is suppressed for clarity) is defined as the harmonic voltage arising at bus i when a 1 pu h^{th} harmonic voltage is applied at bus j. It should be noted that the syntax used here is somewhat different from that in IEC/TR 61000-3-6. If $Z_{h,ij}$ is the ij^{th} element of the network h^{th} harmonic impedance matrix then it is possible to show that

$$k_{h,ij} = Z_{h,ij} / Z_{h,jj} \tag{6}$$

At any particular harmonic, the matrix composed of the $k_{h,ij}$ is designated as the "influence matrix".

IEC/TR 61000-3-6 proposes a simplified use of the influence coefficients to calculate a "corrected total available power" at a busbar. Our previous work [8] has shown that this approach is equivalent to limiting the harmonic voltage at the PCC only and can lead to excessive harmonic voltages in some cases. It is proposed to limit the harmonic voltage at all busbars. Combining (5), (6) and (1) to give an expression for the harmonic voltage at every busbar enables k_h to be determined from

$$k_h = \frac{L_{hHV}}{\max\left(\sqrt[\alpha]{\sum_j {k_{h,ij}}^{\alpha} S_j}\right)} \tag{7}$$

6.4 Resonances and capping of influence coefficients

On the test network described in Section 3, a significant number of influence coefficients greater than unity was noted, indicating large voltage amplifications. Figure 2 demonstrates such amplifications, at selected harmonics, for one typical network case.

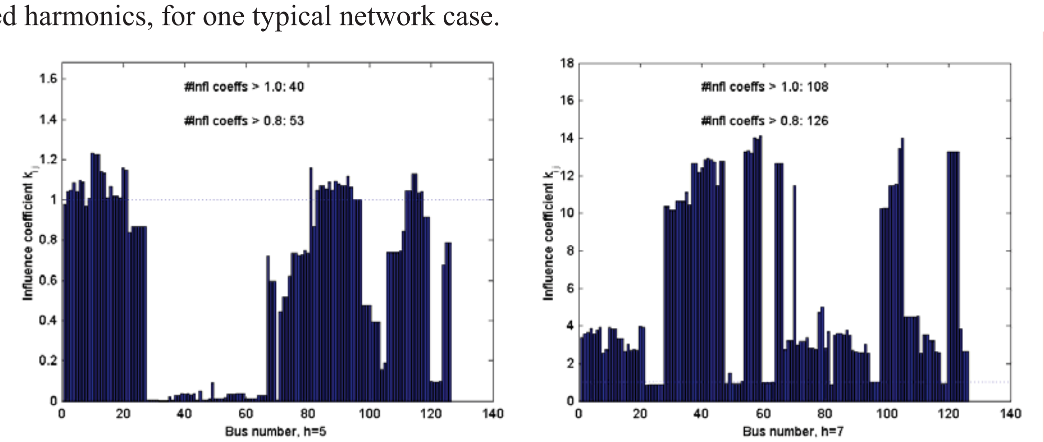

Figure 2: Influence coefficients calculated from a particular busbar to all busbars in study system at selected harmonics

Whilst the impact of resonances on the network harmonic impedance at the PCC is treated by [1], the bus-to-bus amplifications shown in Figure 2 have not been reported in the literature. It is believed that they have not been observed experimentally because many of the resonances are sharp and occur over short timeframes as the power system moves through its various operating states, made up of varying combinations of loading, generator commitment and transmission line and transformer switching conditions. Their existence has the potential to reduce the harmonic emission levels available for all loads to values too small to be practicable.

As evidenced by the discussion on the "envelope impedance curve approach", [1] recognises that limits on resonances are necessary for network impedance calculations and suggests amplification factors at a single MV bus would typically not exceed two to five. At HV/EHV, in the absence of any further understanding of the particular system, it is proposed that the influence coefficients be conservatively limited to a value of two in such a way that their relative values are maintained. This can be achieved by the use of (8) for influence coefficients greater than unity. Field test results are required to verify the applicability of such limits.

$$k_{h,ij(capped)} = \frac{2k_{h,ij(old)}}{1 + k_{h,ij(old)}} \tag{8}$$

The modification of influence coefficients is shown graphically in Figure 3.

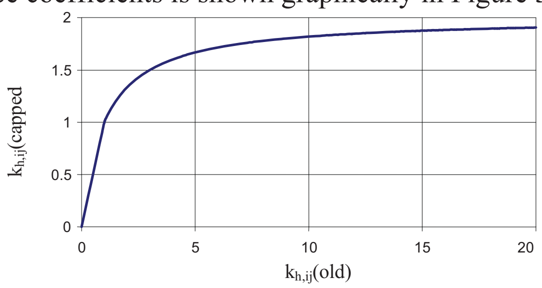

Figure 3: Relationship between uncapped and capped influence coefficients

6.5 Variations in network configuration and parameters

Load, and thus generator unit commitment, is continually changing in a transmission network. It is necessary to select a representative range of network operating conditions and to determine k_h for each scenario from (7), with the smallest value typically being chosen. If appropriate, a weighted average can be selected instead in order to reflect the expected proportion of time the network is to spend in each state.

In fact the quantity k_h does not vary too much with scenario due to its definition in terms of voltage emission in (5). This can be seen by considering the largest load S_{max} in the network. The ratio $k_h.S_{max}^{(1/\alpha)}$ / L_h (that is, the proportion of the planning level L_h allocated to the largest load) will be unity in a system where no influence coefficient is greater than one and other loads are relatively small. The modification of (8) may give a value as small as 50% and this can be reduced even more if there are other loads with maximum demand close to S_{max} connected nearby. Investigations have found that the ratio lies in the range 10-90% for the system under study.

6.6 Network harmonic impedances

IEC/TR 61000-3-6 observes that the conversion of a harmonic voltage emission level into a current, via division by the network harmonic impedance at the PCC, may well be desirable. However, analysis has found the network harmonic impedance to be highly variable, depending upon the network state under investigation. Figure 4 shows, for a single bus in the test network, the range of variation in Z_h. Based on these results it is suggested that the maximum value of the impedance be approximated by

$$Z_h = 2 \,.\, h \,.\, FL_1^{-1} \qquad \text{for} \qquad 1 < h \leq 20 \tag{9a}$$

$$Z_h = 2 \,.\, 20 \,.\, FL_1^{-1} \qquad\qquad h > 20 \tag{9b}$$

where FL_1 is the fundamental per-unit fault level at the PCC.

The approximation of (9) is not a strictly worst-case approach, but is expected to be adequate in most instances. It should be noted that the breakpoint may need to be altered, depending on typical and maximum transmission line lengths in the particular network.

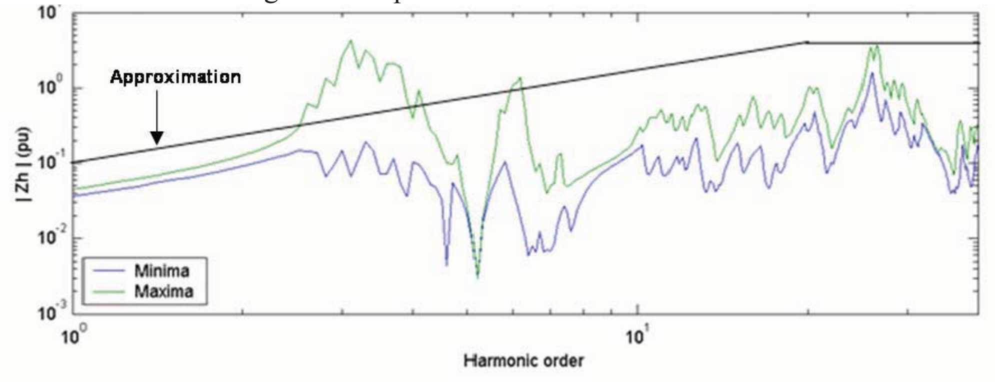

Figure 4: Harmonic impedance variation and approximation of (9)

7. OTHER ISSUES

7.1 Area-based allocation [9]

Existing work has assumed that loads at buses are known into the future with a reasonable degree of certainty. This assumption is difficult to justify, and – if reasonable estimates of worst-case future loadings are used for every bus – can lead to excessively small emission levels being prescribed. Area-based allocation is presently under investigation as a means of reducing the impact of errors in the estimate of future load connected at any particular bus and of increasing the emission levels given to individual loads.

In contrast to the future load at individual buses, annual load increases are generally well-known for an entire network, and moderately well-known for some groups of buses (areas) within the network. It is reasonable to expect that the worst-case load in an area will be less than the sum of the worst-case loads at individual buses. Thus by dividing the network into discrete areas and estimating the future load within each area, allocations can be made to the areas which will result in higher emission levels and a fuller use of the capacity of the network to absorb harmonics.

7.2 Network reduction

Techniques at present are suitable for allocating at only one planning level for any harmonic order; development of solutions to this constraint is an item of future work. Further, the calculations required to perform an allocation over a full network are highly computationally intensive. Both of these factors suggest that it is desirable to perform the allocation on a reduced form of the network. Only buses operating at the highest voltages (that is, those having the smallest planning levels) would normally remain in the reduced-order network model. For loads connected at lower voltages, either the IEC/TR 61000-3-6 medium voltage procedures or – in Australia – the Handbook [5] for distribution networks would typically be applicable, but such loads must still be referred to suitable higher-voltage locations for the purposes of calculating the allocation constant k_h.

8. CONCLUSIONS

The paper has discussed application of IEC/TR 61000-3-6, via its Australian equivalent AS/NZS 61000.3.6, to Australian state transmission systems. The major focus has been on the determination of planning levels and Stage 2 harmonic emission levels. Because the systems have uncertain future loadings and transmission lines are sufficiently long that capacitance needs to be modelled, new analytical techniques have been developed to allow the principles of IEC/TR 61000-3-6 to be implemented.

The determination of planning levels requires an understanding of the load and generator connections. In the study system the extensive meshing between the 220 kV and 110 kV networks, with approximately equal generation and equal loading at the two voltage levels, warrants their receiving identical planning levels, equal to the indicative values proposed by IEC/TR 61000-3-6 for HV and EHV buses. If instead the generation were to be connected solely at 220 kV, with load being connected only at the lower voltages, reduced planning levels on the 220 kV network than on the 110 kV network would be appropriate.

The determination of an allocation constant across the whole system needs to account for the influence on the study node of the distorting load at all other nodes. Computer simulation, based on recommended CIGRE models, shows that this influence can be large, with nodes widely separated having a strong influence on each other at certain harmonic frequencies. If true, this would greatly reduce the allocation available to a given customer. Experimental work needs to be carried out to confirm whether these magnifications apply, and if not, suitable system simulation models having the required damping need to be developed. Until this issue is resolved, it is suggested that these resonance amplifications be limited in order to determine useful allocations.

The harmonic voltage allocated to a customer needs to be converted to an equivalent harmonic current since this is more meaningful. A value for the harmonic impedance at the point of connection is thus required, but this can vary widely in transmission systems and is very sensitive to assumed network operation. A review of several scenarios suggest that the worst case limiting value is twice the equivalent fault current value up to the 20th harmonic, and then constant for higher frequencies.

Analytical techniques have been developed for applying IEC/TR 61000-3-6 principles to harmonic management in transmission systems typical of Australia. It is important to study a wider variety of transmission systems to help find techniques that are of general applicability for the further development of international standards.

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