

ALLOCATION OF HARMONIC CURRENTS TO CUSTOMERS IN MESHED HV NETWORKS

T.J. Browne, V.J. Gosbell and S. Perera

Integral Energy Power Quality Centre
School of Electrical, Computer and Telecommunications Engineering
University of Wollongong, NSW 2522
Australia

Abstract

Use of the new harmonic standard AS/NZS 61000.3.6 to determine legally and technically defensible harmonic current limits for an interconnected transmission network ought to be feasible. But for various reasons, application of this standard to even a simple radial network, let alone a relatively complex meshed transmission system, is a highly non-trivial exercise. Further, the allocation procedure proposed by AS/NZS 61000.3.6 is shown to deliver harmonic current allocations that result in harmonic bus voltages which exceed utility planning levels. A new method has been developed, whereby harmonic voltages at network busbars are explicitly forced to be at or below utility planning levels when all loads are injecting their maximum permitted harmonic currents derived under the allocation. This new method is shown to give a suitable and strictly equitable harmonic allocation for a simple three-bus sample transmission network.

1. INTRODUCTION

For various reasons, application of the new harmonic standard AS/NZS 61000.3.6 [1] (hereinafter ‘the Standard’) to even a simple radial network, let alone a complicated meshed system, is a highly non-trivial exercise. This paper uses a simple three-node meshed transmission network model, detailed in Section 2, to illustrate in Section 3 the process given by the Standard. Section 4 proposes a possible solution to problems that have arisen.

The Standard prescribes a method that allocates harmonic currents to a load based on the maximum MVA demand of that load and on a weighted measure of the MVA capacity of the point of common coupling (PCC) between the load and the network. Weighting factors are discussed further in Section 3.2.1. The approach is unsatisfactory in that it fails to guarantee harmonic voltages at each busbar will be maintained below planning levels when all loads are utilising their full harmonic current allocations. Results in Section 3.3 demonstrate that this is the case.

However, Section 4 illustrates a new approach to the allocation problem, which removes the problems associated with the procedure given in the Standard. We designate the new procedure the ‘constrained bus voltage’ (CBV) method. Promising results are given in Section 4.3 for the three-node example network.

2. REPRESENTATION AND CALCULATION ISSUES

2.1 Nonlinear Summation

Arguably the key tenet of AS/NZS 61000.3.6 is the nonlinear summation law [2–4], which allows us to work with stochastic 95% values rather than absolute, deterministic limits; it also accounts for phase diversity between harmonic sources. As a result, it is an appropriate means of manipulating harmonic currents and voltages mathematically. It forms a basis both for the allocation method prescribed by the Standard, outlined in Section 3, and for the new allocation method given in Section 4.

The law, designated the ‘second summation law’ within the Standard, states that harmonic voltages V_i may, in general, be added as

$$V = \left(\sum_i V_i^{\alpha_h} \right)^{1/\alpha_h} \quad (1)$$

with h being the harmonic order and α_h being a summation exponent given by

$$\alpha_h = \begin{cases} 1 & , \quad h < 5 \\ 1.4 & , \quad 5 \leq h \leq 10 \\ 2 & , \quad h > 10 \end{cases} \quad (2)$$

That is, the 95% value of the h th harmonic voltage at a bus is not a direct sum of contributing 95% voltages due to sources taken one at a time, but rather a nonlinear sum

of such voltages. The analogous situation occurs for harmonic currents in a network element.

2.2 Three-Node Example Network

A transmission network is typically a relatively complex ring system. In order to demonstrate the application of the Standard and determine some of the subtler behaviour of harmonic allocations, we choose to work with a simple three-node example network, as given in Figure 1. All parameters are on a 100MVA base.

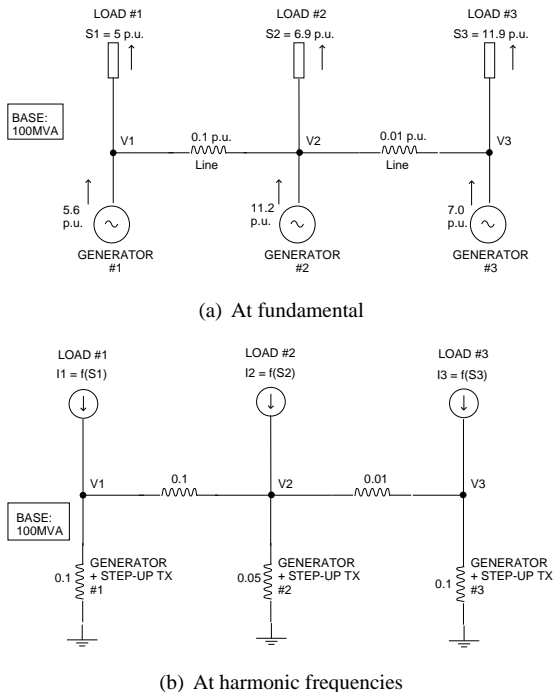


Figure 1: Network model under investigation

Lumped generation is represented at harmonic frequencies by an equivalent to a series combination of generator subtransient reactance and step-up transformer reactance. Lines are represented by pure reactances, while each load is treated as a harmonic current source corresponding to that load's allocated harmonic current, as discussed further in Section 2.3.

2.3 Network Modelling Considerations

The state of the network has the potential to affect harmonic allocations considerably. It would be desirable to cover all possible switch combinations, all possible generator operating ranges, and all possible load conditions. But such a goal is impractical. Instead, the harmonic allocation must be determined based on the worst case network conditions. Of course, actually finding the worst case is non-trivial, so we will – for the time being – assume that open points and outage conditions will not affect the allocation.

When a load is being assessed for compliance with its harmonic current allocation, compliance need only be checked for *normal* network operating conditions. But the

allocations themselves should be developed to ensure that, providing all loads comply with their limits, planning levels are not exceeded under any network conditions. That is, the condition of every load injecting its maximum permitted harmonic currents¹ must be the assumption used when determining harmonic limits. This means that for allocation – as distinct from assessment – purposes, *we can represent every load by a harmonic current source having a value equal to the harmonic current allocation prescribed to that load.*

Of course, it is unlikely that, for example, a large R-L load will inject its entire harmonic current allocation. But when allocating harmonic currents to other loads, this is beside the point: two loads of equal magnitude sharing a PCC should reasonably expect to be permitted equal harmonic current injections, regardless of the compositions of those loads.²

3. HV NETWORK ALLOCATIONS AS PROPOSED BY AS/NZS 61000.3.6

3.1 Background

This section details the results of strict application of the influence-coefficient-based harmonic allocation procedure prescribed in AS/NZS 61000.3.6 to the three-node example network of Figure 1.

A summary of the procedure is given in Section 3.2. Results presented in Section 3.3 will demonstrate, as per discussion in Section 3.4, that this allocation procedure fails to prevent planning levels from being exceeded.

3.2 Outline of the AS/NZS 61000.3.6 Harmonic Allocation Procedure

Three principal steps are required for the application of AS/NZS 61000.3.6 to a network:

1. Calculation of influence coefficients $k_{h,ji}$ to facilitate calculation of the MVA capacity of the PCC;
2. Use of the influence coefficients to determine the permissible harmonic voltage distortion attributable to a load at its PCC;
3. Use of the network harmonic impedance, as seen by the load, to convert the harmonic voltage allocation into a harmonic current allocation.

3.2.1 Calculation of Influence Coefficients

The Standard defines the influence coefficient $k_{h,jl}$ as the h th harmonic voltage observed at node l upon application

¹For 95% of the time - the condition is a statistical one.

²Possible future load changes is the primary reason behind this approach. A customer might wish to replace its large (say) R-L load with a nonlinear load of equal rating at some stage in the future. A reasonable harmonic allocation policy should allow for this possibility.

of a 1 p.u. h th harmonic voltage to node j . The definition requires that, when calculating influence coefficients, all loads be represented by deactivated harmonic current sources.

Influence coefficients from bus j to other buses can be calculated from the harmonic bus impedance matrix $Z(h)$. Matrix partitioning and Kron reduction permit all of the unknown harmonic bus voltages to be expressed in terms of the known harmonic voltage source (1 p.u. at bus j , as above) and known harmonic current sources (zero at all buses), producing the influence coefficients $k_{h,jl}$.

3.2.2 Calculation of Harmonic Voltage Limits

Let S_{tj} be the linear sum of the fundamental³ MVA exiting bus j , on a maximum demand day, that is not proceeding directly to another network bus within the area under examination; all fundamental MVA being imported to bus j is to be ignored⁴. The Standard claims that the measure S'_{tm} of network MVA capacity at bus m , which we shall designate the PCC, is appropriately described by

$$S'_{tm}(h) = \sum_j k_{h,jm} S_{tj} \quad (3)$$

where the $k_{h,jm}$ are the influence coefficients found as per Section 3.2.1. Then, if S_i is the maximum MVA demand for the customer in question and L_h is the planning level set by the utility for the h th harmonic, the Standard specifies the maximum permissible voltage distortion attributable to the customer at its PCC as

$$E_{Uhi} = L_h \left(\frac{S_i}{S'_{tm}} \right)^{1/\alpha_h} \quad (4)$$

where α is the summation exponent accounting for nonlinear summation, as given in Section 2.1 and in the Standard.

3.2.3 Calculation of Harmonic Current Limits

When the voltage distortion E_{Uhi} allocated to the customer and the network harmonic impedance $Z_{ii}(h)$ seen by the customer are both known, the current limit E_{Ihi} can be calculated as

$$E_{Ihi} = \frac{E_{Uhi}}{Z_{ii}(h)} \quad (5)$$

at each harmonic order h .

3.3 Results of Application to Three-Node Example Network

Applying the procedure described in the Standard and summarised in Section 3.2 to the three-node sample net-

work of Figure 1 leads to a set of harmonic current allocations for the three loads. When all the loads are injecting their full allotted harmonic currents⁵, voltages at each bus for each harmonic are as given in Figure 2.

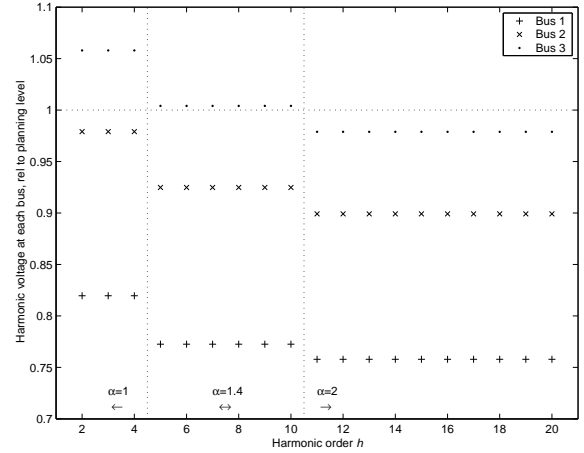


Figure 2: Harmonic voltages (relative to planning levels) at each bus for each harmonic order, when all loads are injecting their full harmonic current allowances, as determined by applying the Standard

Some comments relating to Figure 2 are in order:

1. α is the summation exponent of Eqn. (2).
2. Current allocations and bus voltages are directly proportional to planning levels. As the planning levels are at the discretion of the utility, the figure shows the bus voltages relative to the planning levels.
3. *Bus 3 exceeds the planning level* by around 6% for low-order harmonics (2nd through 4th) and marginally for the 5th through 10th. As the intent of the Standard is to deliver a harmonic allocation that will allow planning levels to be met, this situation is unacceptable and demonstrates that the Standard does not provide a reliable outcome.
4. The method prescribed by the Standard does not make full use of the network harmonic capacity at the higher-order harmonics.

It is not overly surprising that allocations can arise where planning levels are exceeded even when all customers comply fully. Nothing in the Standard explicitly prevents this case from occurring. But a new allocation method which overcomes this problem has been developed, as Section 4 describes.

³Note that S_{tj} is independent of frequency.

⁴FACTS devices are beyond the scope of this paper.

⁵Again, in a 95% sense.

3.4 Assessment of the Merits of the Allocation Procedure Prescribed by the Standard

As established in Section 3.3, the allocation procedure prescribed by the Standard fails to guarantee customer harmonic current limits that will allow the utility to comply with its own planning levels. Despite this, there are merits to this approach warranting attention:

1. The method is reasonably, but not strictly, equitable: two customers of equal MVA rating connected at the same PCC will receive the same harmonic current allocations. But two customers of equal MVA rating connected at *different* PCCs will not necessarily receive equal allocations.
2. Larger loads will, in general, be permitted larger harmonic current allocations, although the extent of this effect diminishes at higher frequencies as a consequence of the nonlinear summation law (Section 2.1).

However, these benefits cannot compensate for the fact that the allocation procedure does not work.

4. PROPOSED CONSTRAINED BUS VOLTAGE APPROACH

4.1 Preamble

Strict application of the Standard has been shown in Section 3 to produce an unacceptable harmonic current allocation. A new ‘constrained bus voltage’ (CBV) method is proposed, which continues to utilise the nonlinear summation law of Eqn. (1) but which explicitly prevents the harmonic voltages at any busbar from exceeding planning levels when all customers are injecting their maximum permitted harmonic currents.

4.2 The Proposed Allocation Method

Our proposed alternative allocation method bypasses voltage distortion allocation and determines harmonic current limits⁶ directly. We suppose that, at any harmonic order h , every load i can be represented by a harmonic current source whose current allocation is E_{Ihi} , given by

$$E_{Ihi} = k_h \cdot S_i^{1/\alpha_h} \quad (6)$$

where k_h is a frequency-dependent (but not bus-dependent) allocation coefficient yet to be determined, S_i is the per-unit load at the bus, and α_h is the harmonic-dependent summation exponent described in Section 2.1 and in AS/NZS 61000.3.6. Making the current allocation proportional to S_i^{1/α_h} , instead of just S_i , follows directly

⁶As with the allocation method prescribed by the Standard, the ‘limits’ are actually 95% values, that is, a load will be expected to be within its harmonic current allocation 95% of the time.

from the nonlinear summation law summarised in Section 2.1, allowing us to lump together multiple loads at the one bus easily.

We determine k_h by using the nonlinear summation law of Eqn. (1) to determine the bus voltages $V_j(h)$ in terms of k_h . We then select the maximum value of k_h such that

$$V_j(h) \leq L_h \quad (7)$$

that is, no harmonic bus voltage is permitted to exceed the relevant planning level when all loads take their full harmonic current allocations in a stochastic 95% sense.

This new method eliminates the key problem, discussed in Section 3.3, of non-compliant allocations.

An implication of Eqn. (6) and the requirement that k_h be bus-independent is that the new allocation method is strictly equitable: two loads of equal maximum MVA demand will always receive equal harmonic current allocations, regardless of their locations in the network. In contrast, the allocation method prescribed by the Standard is only partially equitable, ensuring that two loads of equal maximum MVA demand will receive equal harmonic allocations if they are connected to the same PCC.

4.3 Application to Three-Node Example Network

Voltages arising at each bus when this procedure is applied to the three-bus, three-load example network of Figure 1 are shown, again relative to utility planning levels, in Figure 3.

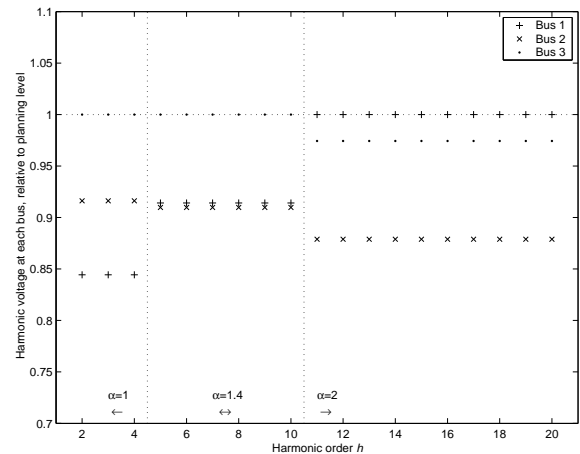


Figure 3: Harmonic voltages (relative to planning levels) at each bus for each harmonic order, when all loads are injecting their full harmonic current allowances, as determined by applying the new constrained bus voltage method

There are two critical distinctions between Figure 3 and the equivalent graph for the allocation method prescribed by the Standard, Figure 2:

1. The new method has eliminated the key problem of the method prescribed by the Standard, namely utility planning levels being exceeded despite all loads complying with their allocations. Thus, we have developed a method that delivers an equitable harmonic current allocation and guarantees that all planning levels will be observed, provided all loads comply with their allocations.
2. The harmonic capacity of the network is better utilised (that is, harmonic bus voltages are closer to planning levels when loads are at their full allocations) at higher harmonics under the new method than under the method prescribed by the Standard.

Figure 4 shows the differences, relative to planning levels and each load's own base, between the current allocations derived for each load by the CBV method and the current allocations derived for each load by following the Standard directly. Only load 2 appears to be adversely affected in any significant way by the CBV method, and even then only at the lower-order harmonics. Considerable increases in current allocations can be observed for load 1, while the discrepancy between the two methods for load 3 is minimal.

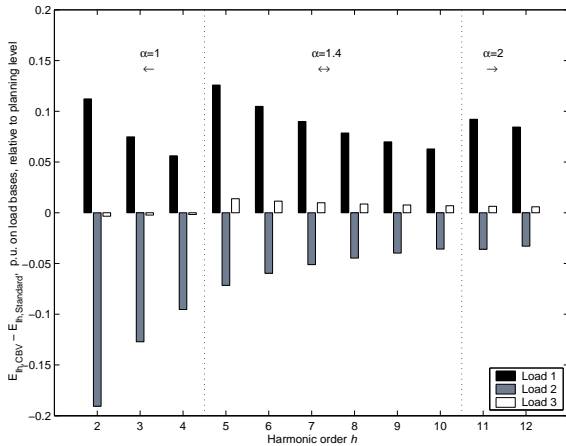
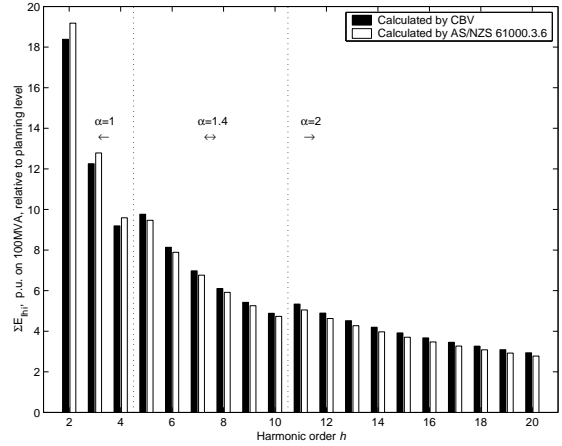


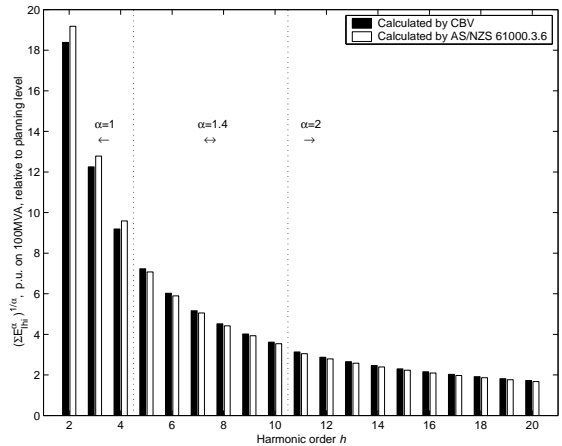
Figure 4: Difference between current allocations derived under the CBV approach and the approach given in the Standard, relative to the planning level and to loads' own bases, for each load at each harmonic

Figures 2 and 3 indicate that the allocation method specified by the Standard can cause utility planning levels to be exceeded and that this is not so for the CBV method. It thus might be expected that some measure of the total current injection permitted by the loads into the network, at any low-order harmonic, would be higher for the Standard-based allocation than for the CBV allocation. We can consider two such performance measures: the direct sum, which best represents the combined current allocation permitted to the loads, and the sum according to the non-linear summation law of Eqn. (1), which might be better suited as a basis for comparisons between individual loads.

These measures, both of which are useful only to gauge the performance of the two allocation procedures and are not physically meaningful, are shown in Figures 5(a) and 5(b) respectively for the two allocation methods. In both cases the Standard does, as expected, permit a greater summated harmonic current into the network at low-order harmonics. However, Figure 5 also shows that the reverse is true at higher harmonics, indicating that forcing bus voltages to be constrained to utility planning levels does not necessarily result in reduced current allocations.



(a) Linear summation



(b) Nonlinear summation, as per Section 2.1

Figure 5: Performance measures of total current injections into the network permitted under allocation derived by CBV method, compared with strict application of the Standard, at each harmonic order

Consequently, we can readily draw two conclusions from Figure 5:

1. As would be expected, at low-order harmonics the CBV procedure provides loads with smaller allocations than does the method prescribed by the Standard, the benefit being that utility planning levels are not breached when all loads are injecting, for 95% of the time, their full harmonic current allocations.

2. At higher-order harmonics, the CBV method allows the harmonic capacity of the network to be better utilised. That is, higher combined harmonic current allocations can be obtained, for any given higher harmonic order, by the CBV method than by strict application of the Standard.

5. CONCLUSIONS

Evidence presented in Section 3.3 has shown that the harmonic allocation method prescribed by the Standard produces unacceptable results: when all customer loads inject their full harmonic allocations determined by this method, harmonic voltages may exceed planning levels at some busbars.

Results from the new CBV method in Section 4.3 indicate that proper application of the Standard's nonlinear summation law (detailed in Section 2.1), coupled with an upper bound on harmonic bus voltages, forms a superior alternative method: the key problem of the approach required by the Standard is removed. Allocations made by the new method are strictly equitable, being based upon the relative sizes of the loads involved and upon the harmonic capacity only of the constraining bus.

Future work is likely to focus on two primary issues: the extent of the network that needs to be included in the model to give reliable results, and the effects of including or excluding line and power factor correction capacitance from the model. Both of these factors may have a significant impact on results; work is in progress to deal with them.

6. ACKNOWLEDGEMENT

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7. REFERENCES

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8. LIST OF SYMBOLS

α_h	Nonlinear summation exponent
E_{Uhi}	Voltage distortion at PCC allocated to load i
E_{Ihi}	Current allocation for load i
h	Harmonic order
$k_{h,jl}$	Influence coefficient, bus j to bus l
k_h	Allocation coefficient (§4.2)
L_h	Utility planning level at h th harmonic
m	Load i 's point of common coupling
S_i	Maximum MVA demand of load i
S_{tj}	Sum of fundamental MVA exiting bus j
S'_{tm}	Weighted network MVA capacity at PCC
$V_j(h)$	Bus j voltage under full current injection
$Z(h)$	Network harmonic impedance matrix
$Z_{ii}(h)$	Network impedance seen by load i