# HARMONIC ALLOCATION CONSTANT FOR IMPLEMENTATION OF AS/NZS 61000.3.6

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## Abstract

Allocation of equal harmonic emission rights to MV customers having the same maximum demand is a key concept in the new Australian harmonic standard AS/NZS 61000.3.6 [1]. Some difficulty can arise with the application of the standard when customers are spread out along a feeder with significantly different fault levels. One proposed method of overcoming this problem is to reduce the allocation as the square root of the fault level [2]. This method requires the calculation of an allocation constant that is applied to all customers connected to the same zone substation. This paper gives a methodology for calculating the harmonic allocation constant when there is incomplete data, and discusses some simplifying assumptions that can be made to optimise calculations.

## 1. INTRODUCTION

In January 2001 Australia adopted a new harmonic standard governing emission limits of distorting loads in MV and HV power systems. The new standard AS/NZS 61000.3.6 is an adaptation of the international technical report IEC 61000-3-6 [3].

AS/NZS 61000.3.6 comprises a number of stages and tests to determine harmonic emission allowances for customers connected to MV or HV networks. Stage 1 has three tests that base acceptance on load size as compared to the short circuit level at the connection point. Stage 2 contains three tests of increasing complexity depending on the amount of information known about the system. There is also a Stage 3 where excessively distorting loads are allowed connection on a temporary and precarious basis. It is perceived that most distorting loads will be assessed under Stage 2 of the standard.

The Integral Energy Power Quality Centre has been involved in producing and implementing practical methods for applying AS/NZS 61000.3.6. Of particular importance is the section of the standard concerning loads distributed along a feeder having significant variation in fault level. AS/NZS 61000.3.6 briefly covers this section in Stage 2, Test 3. The application of the principles suggested by the standard for this section is poorly described and only a non-practical trivial example is provided. A more general approach follows.

## 2. PRINCIPLES OF AS/NZS 61000.3.6

The guidelines specified in the new standard are somewhat more difficult to apply than in the previous harmonics standard AS 2279.2 [4]. These guidelines attempt to ensure allocation of harmonic emission rights to customers is more equitable. A key concept is that customers with the same agreed power and the same Point of Common Coupling (PCC) are entitled to equal harmonic emission rights. The PCC is defined as the nearest point in the power system to which another consumer might be connected.

To account for time variation, customer harmonic contributions and utility harmonic levels are assessed generally by the 95% Cumulative Probability (CP) level. As the 95% levels are statistical quantities direct summation is inadequate for combining contributions from a number of customers. Two summation laws are proposed by the standard:

(i) The first summation law makes use of diversity factors that require knowledge of the load type and is suited to more individual cases.
(ii) The second summation law is a more general method that accounts for time diversity of the individual loads on a larger scale, and is given by Equation (1)

$$U_h = \sqrt[\alpha]{\sum_i U_{hi}^{\alpha}} \tag{1}$$

Where the exponent α depends on the harmonic order h. The recommended value for the 5th harmonic is 1.4.

The second summation law provides the basis for the proposed methodology for allocating harmonic emission rights to customers within an MV distribution system.

The standard encourages an equitable allocation of harmonic 'rights' to all customers having the same maximum demand. Where customers see different fault levels the question arises as to whether these 'rights' are to equal harmonic voltage, equal harmonic current, or some other right. It can be shown that allocating equal harmonic voltage rights allows greater use of the system's harmonic absorption capability, but customers towards the end of a weak feeder receive lower current. The allocation of equal current is fairer but underutilises the harmonic absorption capability. The standard recommends a mid-way policy of equal harmonic power, which can be shown to be equivalent to a harmonic current allocation varying with the square root of the fault level.

AS/NZS 61000.3.6 assumes that the harmonic voltage at the MV level is a combination of the emissions from the MV loads and the background distortion of the HV transmission system. Thus a fraction $T_{hMV}$ of the HV harmonic planning level $L_{hHV}$ must be included in the MV harmonic voltage planning level $L_{hMV}$. Using the second summation law the acceptable global harmonic contribution $G_{hMV}$ from the MV distribution system alone can be calculated using Equation (2)

$$G_{hMV} = \sqrt[\alpha]{L^{\alpha}_{hMV} - (T_{hHM} L_{hHV})^{\alpha}} \qquad (2)$$

The fraction $T_{hHM}$ is assumed here as unity.

For the purpose of this work only the 5th harmonic is considered as it has been shown to be the most predominant and problematic for most MV distribution systems [5-6]. A full description of the principles behind the proposed methodology can be found in [2].

## 3. THE ALLOCATION CONSTANT k

When loads are spread out along a feeder and connected to points having different fault levels, allocation of harmonic current emissions becomes difficult. To achieve the constant harmonic power policy recommended in Section 2, the harmonic current emissions need to be allocated in proportion to agreed power $S_i$ and inversely proportional to the square root of the harmonic impedance $Z_{hi}$ at the PCC. A suitable strategy from [2] is to allocate harmonic current emissions $E_{Ihi}$ using Equation (3)

$$E_{Ihi} = \frac{k S_i^{\frac{1}{\alpha}}}{\sqrt{Z_{hi}}} \qquad (3)$$

Where k is called the allocation constant. The same value of k is used for all loads supplied from a common substation. Its value is chosen such that when the substation reaches load saturation, and all loads are contributing their maximum permitted harmonic contribution, the magnitude of the considered harmonic voltage will have a value not exceeding the limits suggested by AS/NZS 61000.3.6. It is easy to show that this voltage will occur at the far end of the 'weakest' feeder.

Exact calculation of k is possible but complex and requires an enormous amount of data. To illustrate this process we consider a distribution system with each non-linear load modeled as an equivalent harmonic current source. At harmonic order h, the resulting voltages are related to the currents as shown in Equation (4)

$$[V_h] = [Z_h][I_h] \qquad (4)$$

Where [$\mathbf{V}_h$] is the unknown harmonic voltage vector, [$\mathbf{Z}_h$] is the harmonic impedance matrix, and [$\mathbf{I}_h$] is the harmonic current vector. For a system with N nodes the expanded form of Equation (4) is as follows

$$\begin{bmatrix} V_{h1} \\ V_{h2} \\ \vdots \\ V_{hi} \\ \vdots \\ V_{hN} \end{bmatrix} = \begin{bmatrix} Z_{h11} & Z_{h12} & \cdots & Z_{h1j} & \cdots & Z_{h1N} \\ Z_{h21} & Z_{h22} & \cdots & Z_{h2j} & \cdots & Z_{h2N} \\ \vdots & \vdots & & \vdots & & \vdots \\ Z_{hi1} & Z_{hi2} & \cdots & Z_{hij} & \cdots & Z_{hiN} \\ \vdots & \vdots & & \vdots & & \vdots \\ Z_{hN1} & Z_{hN2} & \cdots & Z_{hNj} & \cdots & Z_{hNN} \end{bmatrix} \begin{bmatrix} I_{h1} \\ I_{h2} \\ \vdots \\ I_{hj} \\ \vdots \\ I_{hN} \end{bmatrix}$$

Using direct addition the harmonic voltage at node i is given by Equation (5)

$$V_{hi} = \sum_{j}^{N} Z_{hij} I_{hj} \qquad (5)$$

As we are combining 95% CP level voltages using the second summation law Equation (5) must be rewritten to include the exponent α as shown in Equation (6)

$$V^{\alpha}_{hi} = \sum_{j}^{N} Z^{\alpha}_{hij} I^{\alpha}_{hj} \qquad (6)$$

Note that the phase of the harmonic currents and voltages are not considered in Equation (6) but are assumed to be included in the summation law exponent α.

Evaluating Equations (3) and (6) and assuming the maximum harmonic voltage to be less than the global harmonic contribution $G_{hMV}$ the value of k can be determined from Equation (7)

$$k = \frac{G_{hMV}}{\max_i \left( \sum_j^N \frac{Z_{hij}^{\alpha} \cdot S_j}{Z_{hjj}^{\frac{\alpha}{2}}} \right)^{\frac{1}{\alpha}}} \tag{7}$$

Evaluation of Equation (7) requires the projected agreed power and system harmonic impedance at each PCC along every feeder within the local MV distribution system. To reduce the need for an extensive amount of data some assumptions can be made to determine an approximate value of the harmonic allocation constant k.

## 4. INCOMPLETE DATA APPROACH

Although the 'weakest' feeder is strictly defined by Equation (7) in most cases it will also be the feeder with the lowest fundamental voltage when the system is loaded to the fullest extent. Knowledge on the 'weakest' feeder allows an approximation to k to be obtained when other data is not readily available. Three methods of approximating k when limited data is available are provided here:

(i) A pessimistic approach assuming all loads other than the 'weakest' feeder loads are connected to zone substation busbar (equivalent to assuming all other feeders to be of zero length).
(ii) An approach when all feeders are similar, i.e. all feeders are assumed to have the same loading and fault level distribution as the 'weakest' feeder.
(iii) The use of (i) incorporating correction factors.

### 4.1. A pessimistic approximation to k

To illustrate how we can reduce the amount of data required to calculate the value of the allocation constant k we consider the radial MV distribution system shown in Figure 1.

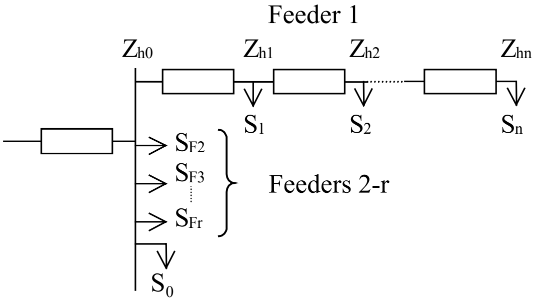

Figure 1: Example radial MV distribution system
($S_n$ in Feeder 1 is maximum expected demand at each takeoff point; $S_{Fr}$ is the maximum expected loading on Feeder r)

To simplify the expression for k given by Equation (7) we assume that all feeders other than the 'weakest' feeder have zero harmonic impedance, i.e. all loads from the other feeders are connected at the supply busbar. This assumption simplifies the amount of data required considerably and in addition can be justified as follows:

(i) The harmonic impedance at the zone substation busbar $Z_{h0}$ is generally the smallest of all the impedances and this term will not be a major part of the overall voltage drop.
(ii) The assumption overestimates the current on the remaining feeders and hence will be pessimistic.

Assuming that the highest harmonic voltage level will occur at the end of the 'weakest' feeder we can estimate the value of k using the Equation (8)

$$k \approx \frac{G_{hMV}}{\left( \sum_{i=1}^{n} S_i Z_{hi}^{\frac{\alpha}{2}} + S_0 Z_{h0}^{\frac{\alpha}{2}} + (S_{F2} + \ldots + S_{Fr}) Z_{h0}^{\frac{\alpha}{2}} \right)^{\frac{1}{\alpha}}} \tag{8}$$

The approximation to k consists of three terms in the denominator. These terms are the harmonic contribution from the 'weakest' feeder, the harmonic contribution from any local load at the zone substation busbar and the harmonic contribution from the loads on the other (2-r) feeders.

This approximation requires the projected agreed power of each customer ($S_i$) and the system harmonic impedance ($Z_{hi}$) at all PCC points along the 'weakest' feeder, and also an estimate of the total maximum agreed power from the other feeders ($S_{F2}$, $S_{F3}$, .., $S_{Fr}$). Further, the approximation will always ensure a slightly pessimistic result for the value of k since it underestimates $Z_{hi}$ for the other feeders and therefore allocates too much current following Equation (3).

### 4.2. Approximation to k when all feeders are similar

Various studies using the approximate value of k from Equation (8) have shown that this approach is most inaccurate when there are a number of weak feeders all of similar nature. In the case where all feeders are similar in loading and impedance a less pessimistic approximation to k may be calculated.

In this case the harmonic contribution at the zone substation busbar due to each of the other feeders will be equal to that of the 'weakest' feeder. To reflect this the third term in the denominator of Equation (8) is modified to give Equation (9)

$$k \approx \frac{G_{hMV}}{\left(\sum_{i=1}^{n} S_i Z_{hi}^{\frac{\alpha}{2}} + S_0 Z_{h0}^{\frac{\alpha}{2}} + (r-1)\sum_{i=1}^{n} S_i \frac{Z_{h0}^{\alpha}}{Z_{hi}^{\frac{\alpha}{2}}}\right)^{\frac{1}{\alpha}}} \qquad (9)$$

Less data is required to calculate k using Equation (9) than is required for Equation (8) but the application is useful only when all feeders are of similar nature.

### 4.3. Correction factors for the pessimistic approximation of k

By considering the relationship between the harmonic allocation constant and ratio of impedance at either end of a feeder we have been able to slightly correct the pessimistic value of k from Equation (8) if additional data is known.

A good rule of thumb to optimise the value of k is to divide the contribution from the other feeders, the 3rd component of denominator in Equation (8), by the correcting factor given by Equation (10)

$$F_{hr} = \sqrt[2\alpha]{\frac{Z_{hn}}{Z_{h0}}} \qquad (10)$$

If the system impedance ($Z_{hn}$) at the end of each of the other feeders is not known a value of √2 for $F_{hr}$ is usually suited to most systems.

## 5. CASE STUDY EXAMPLE

To illustrate the application of the harmonic allocation constant k, we apply each of the above described methods to the example distribution system provided in Appendix I of AS/NZS 61000.3.6. The 20kV distribution network example is shown in Figure 2.

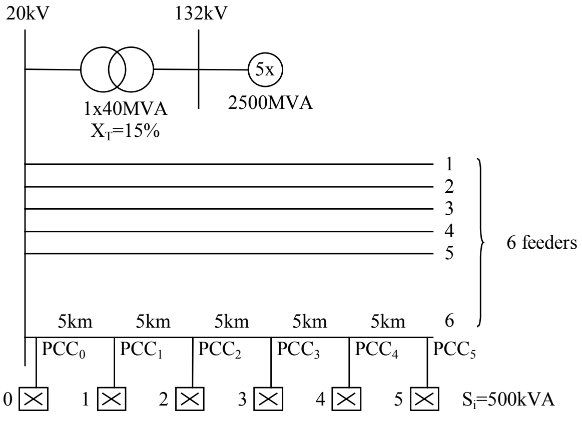

Figure 2: Homogeneous MV distribution network with six feeders and six loads per feeder.

The system consists of six 20kV overhead feeders of 25km length fed by one HV/MV 40MVA transformer. We will assume that all loads are directly supplied at MV and the system is at full capacity.

The example calculations are performed only for the 5th harmonic. The planning levels for the 5th harmonic are $L_{hMV}$=5% and $L_{hHV}$=2%. Using these values and the recommended value of $\alpha$=1.4 for the 5th harmonic the resulting value for the global harmonic voltage emission $G_{hMV}$ from Equation (2) is 3.97%.

All feeders in the example are identical, thus any feeder can be chosen as the 'weakest' feeder for the calculation of k. Table 1 shows the results from an exact calculation of k, and the three approximation methods described previously. As all feeders are identical in this example the approximation using the assumption of similar feeders produces the same value as the exact value of k.

Table 1: Allocation constant k using different calculation methods

| Calculation method | Allocation constant k |
|---|---|
| I. Exact value | 9.20% |
| II. Pessimistic value | 6.88% |
| III. Similar feeders value | 9.20% |
| IV. Adjusted pessimistic value | 9.09% |

From Table 1 we can see that the adjusted pessimistic value gives good results as compared to the exact value of k. The adjusted pessimistic approximation should be used when feeders are not all similar and only limited data is available.

The resulting harmonic current allocations of each load along the feeder are shown in Figure 3 for the different methods of calculating k.

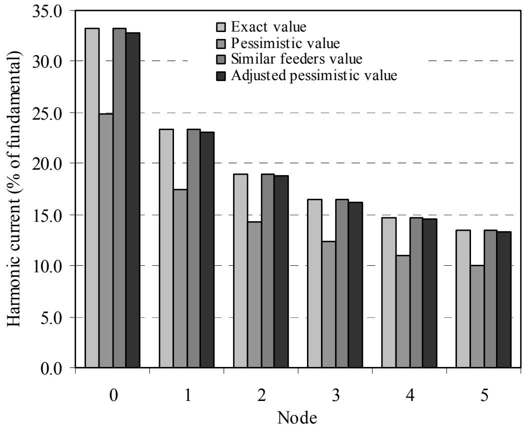

Figure 3: Harmonic current allocations using methods I-IV from Table 1 to calculate k

As can be seen in Figure 3 each approximation method provides a suitable value for k. The voltages arising from the allocated harmonic currents calculated using the second summation law are shown in Figure 4.

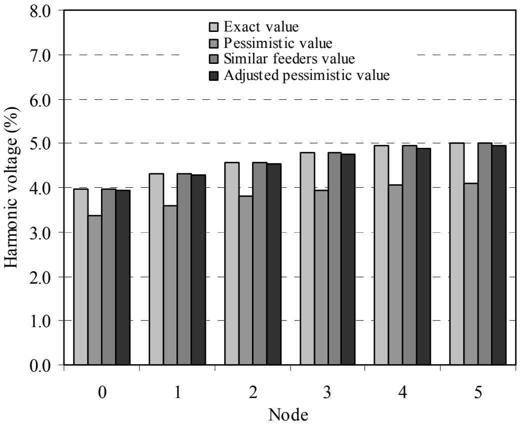

Figure 4: Harmonic voltages arising at each node using methods I-IV from Table 1 to calculate k

## 6. CHOICE OF ALLOCATION POLICY

To demonstrate the effect of applying the different allocation policies to customers along a feeder we analyse the results of applying equal harmonic current, equal harmonic power and equal harmonic voltage policies for the example distribution system in Section 5.

The harmonic current allocations from applying the equal harmonic current, power and voltage policies are shown in Figure 5.

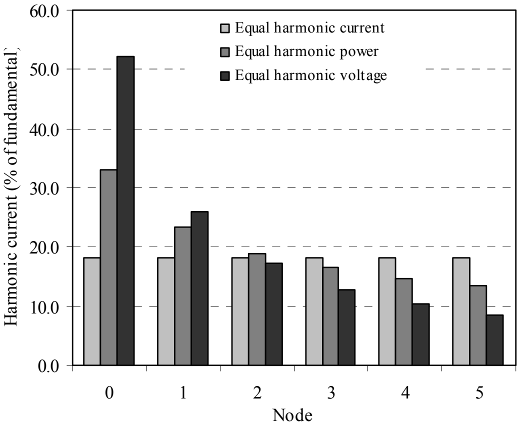

Figure 5: Harmonic current allocations using equal harmonic current, power and voltage allocation

Summing the total allocation of harmonic current from all loads in the system provides a measure of how well the distribution system's absorption capability is being utilised. For the case study example in Section 5 the use of equal harmonic power and equal harmonic voltage policies increase the amount of total harmonic current allowed to be injected into the system by 10% and 15% respectively.

Taking the increase in total harmonic current into consideration and comparing the different values in Figure 5 we have found that the allocation using the equal harmonic power policy has provided a suitable increase in the systems harmonic capacity without unduly penalizing customers at the end of the feeder. The voltages arising from the different current allocations are shown in Figure 6.

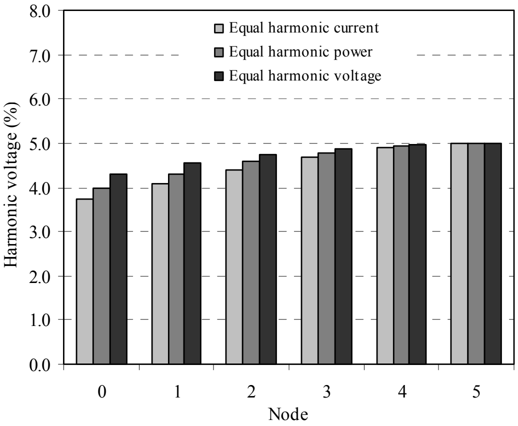

Figure 6: Harmonic voltages arising at each node using different allocation policies

## 7. CONCLUSION

The harmonic allocation constant k has been shown to be a practical method for allocating acceptable harmonic emission levels to distorting loads in radial MV distribution systems. Although a large amount of data is required to calculate the exact value of k alternative methods have been proposed that allow an estimate of k to be determined when only limited data is available.

The allocation of harmonic emission levels using the equal harmonic power rights policy has shown to be the most useful method of assessment from AS/NZS 61000.3.6 when loads are spread out along a feeder having significantly different fault levels.

The example provided in this paper to illustrate the use of the harmonic allocation constant did not include power factor correction capacitors. It is perceived that the installation of such capacitors may necessitate detailed design when allocating harmonic emissions rather than the global allocation described here. This is an area for further work.

## 8. REFERENCES

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## 9. LIST OF SYMBOLS

| | |
|---|---|
| $\alpha$ | Exponent of the second summation law |
| $E_{Ihi}$ | Allowed harmonic current emission limit of order h for customer i |
| $E_{Uhi}$ | Allowed harmonic voltage emission limit of order h for customer I |
| $F_{hr}$ | Allocation correcting factor at order h for feeder r |
| $G_{hMV}$ | Global harmonic voltage emission limit of order h for all loads supplied at MV |
| h | Harmonic order |
| i | Single customer or load |
| k | Harmonic emission allocation constant |
| $L_{hHV}$ | Harmonic voltage planning level of order h for HV |
| $L_{hMV}$ | Harmonic voltage planning level of order h for MV |
| PCC | Point of common connection of the customer |
| $S_{Fj}$ | Total capacity of all loads along feeder j |
| $S_i$ | Apparent agreed power of the individual customer I |
| $T_{hHM}$ | HV/MV harmonic voltage transfer coefficient of order h |
| $U_h$ | Harmonic voltage of order h |
| $U_{hi}$ | Harmonic voltage of order h for customer i |
| $Z_{hi}$ | Harmonic impedance of order h of the distribution system at the PCC i |