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Abstract

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Keywords

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THE APPLICATION OF IEC 61000-3-6 TO MV SYSTEMS IN AUSTRALIA

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ABSTRACT

IEC 61000-3-6 [1] comprises a number of stages and tests to determine harmonic emission allowances for customers connected to MV or HV networks. Of particular importance is the section concerning loads distributed along a feeder, each having a different fault level. Although a common situation, the treatment given in the IEC standard is poorly described, being largely illustrated by one atypical example. This allows simplifying assumptions to be made which are invalid in practical cases. This paper outlines a more general approach that is relatively easy to apply.

1 INTRODUCTION

Australia, as with many other countries, is gradually adopting IEC 61000 series Electromagnetic Compatibility standards as part of its undertakings under the GATT Agreement. Our harmonic and flicker standard over the last 25 years has been AS2279.2 [2], covering both domestic and industrial situations. The two domestic standards have been replaced [3-5] and the two industrial ones are due to be replaced by the corresponding IEC ones about the beginning of 2001.

This paper will concentrate specifically on the application of IEC 61000-3-6 which concerns harmonics in MV systems. The approach adopted in the standard is different to earlier ones where it is assumed that there is mainly one harmonic source whose parameters are well known allowing a rigorous approach to analysis. It is oriented to many harmonic sources, none known exactly in detail, combining together in an uncertain manner. The approach is statistical and attempts to model only the grossest features of customer loads.

IEC 61000-3-6 is an incomplete and imprecise document and is not classified as an international standard. It is a Type III technical report, one that provides guidance for engineering practice rather

than give a standard calculation procedure. It contains several alternative procedures with no clear specification as which one to use. Some of the methods involve new analysis procedures using parameters which have not been used before and which are unknown for many systems.

In preparation for the general adoption of this standard, Integral Energy and the Power Quality Centre at the University of Wollongong have attempted to apply it to a number of test cases and have encountered difficulties in interpretation. We will describe the analysis techniques we have developed in order to allow the spirit of the standard to be applied to practical situations. Three issues of importance are (i) the selection of harmonic orders to be studied, (ii) the choice of summation law and (iii) a practical approach to Stage 2, Test 3 analysis which examines the allocation of harmonic current to customers distributed along a feeder with significant changes in fault level.

2 OVERVIEW OF STANDARD

The standard is applicable to MV (1kV-35kV) and HV (35kV-230kV) power supply systems and covers harmonics up to the 40th. The aim is to limit harmonic voltages in power supply systems to the utility planning levels by limiting the contribution from individual loads. To account for time variation, customer harmonic contributions and utility harmonic levels are assessed generally by the 95% cumulative probability level, that is the level which is not exceeded for 95% of the time.

Customer installations are assessed in three stages. The first stage accepts installations which are sufficiently small in rating compared to the short-circuit level at the PCC (point of common connection). Three alternative tests are given. Only relatively small loads can pass Stage 1.

In Stage 2, a proportion of the planning level is given to each customer according to their share of the system capacity, with an allowance for the background contribution. There are 3 tests of increasing complexity. Test 1 assumes that all customers on the one supply have the same PCC and identical fault levels, as when a number of close industrial customers have a dedicated substation. Test 2 considers that there are also low voltage customers on the supply whose harmonic trend is significantly different to the MV customers. We consider that the concepts here are poorly defined and most utilities will have no idea of the diversity factor which is required. We intend not to use this test until circumstances have shown it to be necessary and the required diversity factor can be determined. Test 3 concerns customers spread along an MV feeder with significantly different fault levels. This is a very common situation and the main aim of this paper is to clarify this test.

It should be briefly mentioned for completeness that there is also a Stage 3 for customers who fail Stage 2. Acceptance is temporary on an "exceptional and precarious basis" in some special circumstances. This Stage is rarely applied and will not be considered further.

There are three guiding principles given in the standard

- (i) Allocation of harmonic emission levels are such that all emission rights are allocated when the system is fully loaded and the worst system voltage reaches the planning level. Emission rights have to be allocated for each harmonic up to the 40th.
- (ii) The "equal rights premise" - customers with equal maximum demand and with the same PCC are to be given equal emission rights.
- (iii) Contributions from different sources must take account of diversity. Two summation laws are suggested.

The main concerns of the present paper will be

- (i) Do all the harmonics up to the 40th harmonic have to be studied?
- (ii) Which summation laws should be used?
- (iii) What is a practical approach to Stage 2, Test 3?

3 WHICH HARMONICS HAVE TO BE STUDIED?

Several overseas studies have suggested that at present the 5th harmonic dominates in MV systems [6-7]. We have carried out a harmonic survey over several weeks at a zone substation in suburban Sydney supplying a typical mixture of residential, commercial and industrial loads [8]. Instrument limitations restricted measurements to only a few harmonics and the 5th, 19th and 49th harmonic voltage and the voltage THD were recorded. Figure 1 is typical of several results taken involving the average of two line-line voltage readings.

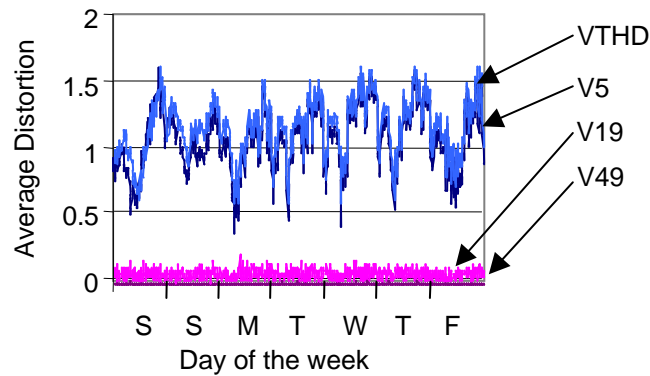


FIGURE 1: MV survey result over 1 week

We found at any site that all line-line voltage harmonic trends were similar and gave a similar 95% value. For the limited harmonics recorded, the harmonic voltage decrease with increasing harmonic order. Most significantly, the THD and 5th harmonic voltage were almost the same showing that other harmonics are considerably smaller. We have concluded that, in most cases, harmonic assessment can be made on the basis of the 5th harmonic alone. Three reservations need to be considered.

- (i) It is possible in the future that there will be a change in power electronic technology to give a spectrum of current emission different to today, for example if there is a significant shift from natural commutation to high frequency switching.
- (ii) IEC planning levels become smaller with increasing frequency and a relatively small high frequency harmonic can be the cause of a harmonic limit exceedance. Our calculations suggest that this will usually be accompanied by significant notching.
- (iii) Resonances caused by pfc capacitors without detuning reactors can cause amplification around a particular harmonic order giving prominence to a harmonic order in the range 10-20.

4 WHICH SUMMATION LAW SHOULD BE ADOPTED?

The first summation law involves the combination of different voltage contributions using a linear law. The constants to be used depend on the equipment rating relative to the short circuit level and to some extent on the type of load. For the 5th harmonic, 8 different constants are required to cover the range of relative equipment rating. The second summation law is expressed by the equation

$$U_h = \alpha \sqrt{\sum_i U_{hi}^2} \quad (1)$$

where α depends on the harmonic order and is 1.4 for the 5th. We consider that the second summation law seems more appropriate and is simpler for general applications. It is noted that harmonic calculations using the second summation law have a large sensitivity to the choice of α [9]. Investigations which can give more confidence in the choice of α will allow this standard to be applied with more confidence.

5 SUMMARY OF STAGE 2, TEST 1

We shall summarise some aspects of the standard's treatment of Stage 2, Test 1 as it is fundamental to our approach to Stage 2, Test 3. For a given harmonic h , the first step for all tests is to determine the acceptable global contribution, G_{hMV} , to the harmonic voltage from the combined MV supplied loads. This level will combine with the upstream contribution from the next highest voltage level to give a resultant voltage equal to the Planning Level L_{hMV} . It is suggested in the standard that the upstream contribution be taken as $T_{hHM}L_{hHV}$ with T_{hHM} generally taken as 1. Using the second summation law,

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

The allowed harmonic voltage contribution by customer "i" (E_{Uhi}) is proportional to their share of power supply system capacity. If the customer maximum demand is S_i and the supply capability is S_t , then guiding principle (i) can be satisfied with the law

$$E_{Uhi} = G_{hMV} \sqrt[\alpha]{\frac{S_i}{S_t}} \quad (3)$$

The allowed harmonic current contribution for customer "i" (E_{Ihi}) can then be determined using the harmonic impedance of order h at the customer's PCC.

$$E_{Ihi} = \frac{E_{Uhi}}{Z_{hi}} \quad (4)$$

6 LIMITATION OF THE TREATMENT GIVEN IN STAGE 2, TEST 3

A common situation for assessment is to have loads distributed along an MV feeder having significant variation in fault level. The problem with the approach of Stage 1, Test 1 is that while the harmonic voltage emission allocation remains the same for equal sized loads, the harmonic current allocation varies in proportion to the harmonic impedance. This results in two similar loads of equal size but located at different positions along a feeder receiving possibly very different harmonic current allocations, especially when cable lengths are greater than 10km or overhead line lengths are greater than 5km.

Test 3 is intended to allocate harmonic emissions more fairly while still utilising the power supply system's capability to absorb harmonic currents. As discussed in the standard, one possible method of increased allocation to the customer at the end of the feeder is to allocate harmonic current rather than voltage as a function of load size. However, this gives a much greater voltage allocation to the far loads and greatly reduces the supply system's harmonic capability. The approach finally recommended, and adopted here, is a half-way policy of allocating harmonic power (more strictly harmonic VA). This is equivalent to allocating a current emission which varies as $1/\sqrt{Z}$ where Z is the impedance to the point of load connection.

The standard shows how this method can be applied to a study system. The problem with the example is that it is performed on an atypical homogenous system where each load is of identical size and each feeder has identical parameters.

It is suggested that each load is to be allocated a harmonic current of

$$E_{\text{hi}} = \frac{k}{\sqrt{Z_{\text{hi}}}} \quad (5)$$

where k is an "allocation constant" to be determined. There is no need to consider how E_{hi} should vary with load size in the particular example given. Secondly, the effect of the other feeder currents on the upstream harmonic current can be easily determined since their current will be the same as the study feeder. This gives an equation involving k which can be solved easily but ignores issues which have to be resolved in a more general situation.

7 PROPOSED STAGE 2, TEST 3

In our alternative approach we try as far as possible to adhere to the broad principles recommended by IEC 61000-3-6. As a compromise between maximising the system's harmonic absorption capability and a uniform allocation to all customers of similar demand, the approach of assigning $E_{\text{hi}} \propto 1/\sqrt{Z_{\text{hi}}}$ is maintained. To account for the load size, we generalise eqn (5) to

$$E_{\text{hi}} = \frac{kS_i^{\frac{1}{\alpha}}}{\sqrt{Z_{\text{hi}}}} \quad (6)$$

where k is taken to be constant for all feeders fed from the one supply point.

We shall discuss the selection of k with reference to the example radial MV power supply system shown in Figure 2. As k increases, the harmonic voltages increase (but not in proportion to k) with the greatest value occurring at the end of the weakest feeder, taken to be Feeder 1. Although "weakest feeder" can be defined strictly in this situation by a complex mathematical relationship, in most cases it will be the feeder having the lowest fundamental voltage at the far end when the whole system is loaded to its maximum intended supply capability. k is chosen to make the harmonic voltage at the end of the weakest feeder equal to the Planning Level. In general, it need be found for the 5th harmonic only.

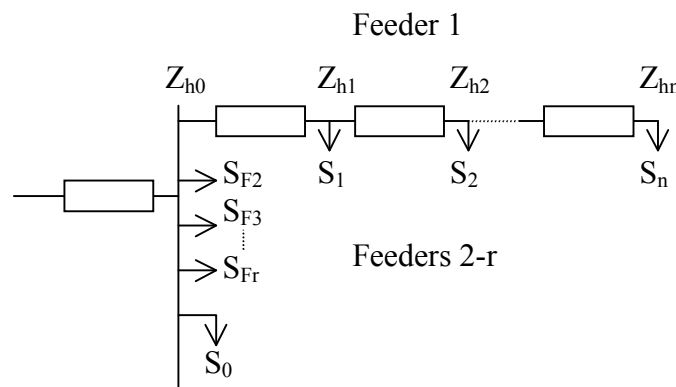


FIGURE 2: Example radial MV Distribution System
 $(S_n$ in Feeder 1 is maximum expected demand at each load takeoff point;
 S_{Fr} is the maximum expected loading on Feeder r)

The harmonic voltage at any point is found by combining several voltage contributions using the second summation law.

- (i) Upstream background level U_{hBG} (generally taken as $T_{hHM}L_{hHV}$)
- (ii) $Z_{h0}I_{h0}$ drop due to S_{h0} at the local busbar
- (iii) A drop due to each of the other feeder currents flowing through Z_{h0}
- (iv) Voltage drops due to each of the local loads on feeder 1: S_1, S_2, \dots, S_n

Voltage drops (iv) can be expressed in the form

$$U_{hr} = Z_{hr}I_{hr} \quad (7)$$

where Z_{hr} is the total impedance to the r^{th} take-off point on the weakest feeder and I_{hr} is the current.

Thus:

$$L_{hMV}^\alpha = U_{hBG}^\alpha + (Z_{h0}I_{h0})^\alpha + Z_{h0}^\alpha (I_{hF2}^\alpha + \dots + I_{hFr}^\alpha) + \left\{ (Z_{h1}I_{h1})^\alpha + (Z_{h2}I_{h2})^\alpha + \dots + (Z_{hn}I_{hn})^\alpha \right\} \quad (8)$$

Each of I_{h1} - I_{hn} can be expressed using eqn (6). The determination of I_{hFr} strictly requires the summation of the currents at each take-off point on the feeder r . In practice, this requires a maximum supply capability figure for each take-off point supplied by the substation and we believe that in most cases this information will not be easily available. To simplify the expression for k even further we assume that the other feeders have zero harmonic impedance, i.e. that 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) 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 will overestimate the current in the remaining feeders and hence be pessimistic.

With this assumption, k can be approximated by

$$k \approx \frac{G_{hMV}}{\left(\sum_{i=1}^n S_i Z_{hi}^\alpha + S_0 Z_{h0}^\alpha + (S_{F2} + S_{F3} + \dots + S_{Fr}) Z_{h0}^\alpha \right)^{\frac{1}{\alpha}}} \quad (9)$$

Where several customers are connected to the same PCC the harmonic emission allocation for the aggregate load is first determined as described above. Suppose that a customer with the maximum demand S_i is connected to a load point having maximum capability S_M . If the allocation to the whole load point is I_{hM} , this application of the second summation law gives the allocation to customer "i" as

$$I_{hi} = \left(\frac{S_i}{S_M} \right)^{\frac{1}{\alpha}} I_{hM} \quad (10)$$

Various studies using the approximate value of k from eqn (9) has shown that this approach is most inaccurate when there are a number of weak feeders all of similar nature. This is illustrated below using the homogenous example from the standard. We have found that a good rule of thumb in this case is to halve the contribution from the other feeders, that is to halve the third component in the denominator of eqn (9).

7.1 Homogenous Example

The 20kV distribution network example given in IEC 61000-3-6 is shown in Figure 3. 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.

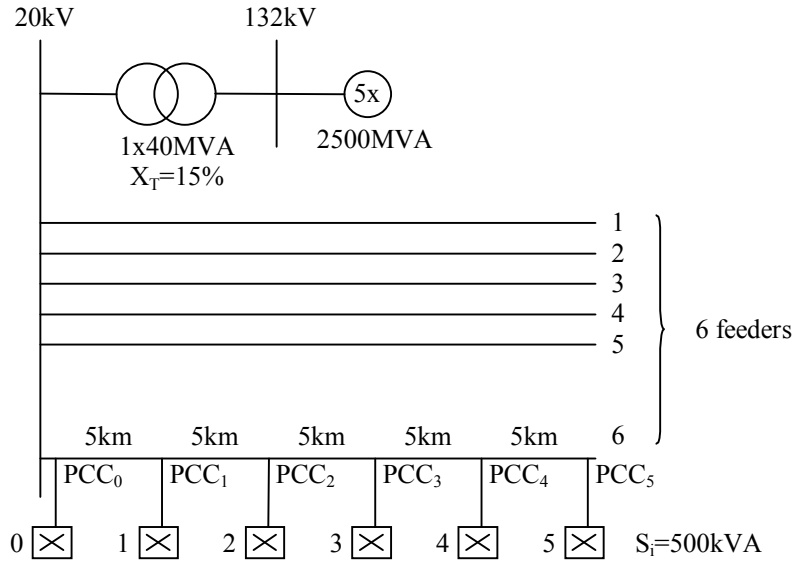


FIGURE 3: Homogenous MV distribution network with six feeders, six loads / feeder

The calculation is performed for the 5th harmonic. From IEC 61000-3-6 we obtain the recommended planning levels for the 5th harmonic as $L_{hMV}=5\%$ and $L_{hHV}=2\%$. Using these values and the recommended value of $\alpha=1.4$ we can calculate the global harmonic voltage emission, G_{hMV} , for all loads within the distribution system.

$$G_{hMV} = \sqrt[\alpha]{L_{hMV}^\alpha - (T_{hHM} L_{hHV})^\alpha} = \sqrt[1.4]{5.00\%^{1.4} - ((1.00)(2.00\%))^{1.4}} = 3.97\%$$

As all feeders in the example are identical, any feeder can be chosen for the calculation of k.

$$k \approx \frac{G_{hMV}}{\left(\sum_{i=1}^n S_i Z_{hi}^{\frac{\alpha}{2}} + S_0 Z_{h0}^{\frac{\alpha}{2}} + (S_{F2} + S_{F3} + \dots + S_{Fr}) Z_{h0}^{\frac{\alpha}{2}} \right)^{\frac{1}{\alpha}}}$$

$$\approx \frac{3.97\%}{\left(0.01 \cdot 2.16^{\frac{1.4}{2}} + 0.01 \cdot 3.25^{\frac{1.4}{2}} + 0.01 \cdot 4.35^{\frac{1.4}{2}} + 0.01 \cdot 5.44^{\frac{1.4}{2}} + 0.01 \cdot 6.54^{\frac{1.4}{2}} + 0.06 \cdot 1.07^{\frac{1.4}{2}} + 0.30 \cdot 1.07^{\frac{1.4}{2}} \right)^{\frac{1}{1.4}}}$$

$$= 6.88\%$$

For the load at the far end (node 5) we have

$$E_{lh5} = \frac{k S_5^{\frac{1}{\alpha}}}{\sqrt{Z_{h5}}} = \frac{6.88 \cdot 0.01^{\frac{1}{1.4}}}{\sqrt{6.54}} = 0.10\% \text{ (on 50MVA base)} = 10.02\% \text{ (on own base)}$$

Table 1 shows the results from the proposed Stage 2, Test 3 method are slightly more conservative than the IEC Stage 2, Test 3 exact calculations. This should be the case for just about any system as long as the loads are of equal size.

As there are a number of feeders similar to that of the weakest feeder in this example, the rule of thumb of halving the contribution from other feeders when determining k can be utilised. This increases the harmonic emission allowances for each of the nodes by approximately 26% to levels comparable to that of the IEC Stage 2, Test 3 allocation. The resulting harmonic voltages at node 0

and node 5 are 3.9% and 4.8% respectively, very close to the standard's exact calculation results given in the fourth column of Table 1.

TABLE 1: Comparison of different allocation schemes for homogenous case

PCC node No.	Fifth harmonic impedance $Z_h=5$ Per Unit	Stage 2, Test 1 E_{lhi} (%) ¹⁾	Stage 2, Test 3 E_{lhi} (%) ¹⁾	Proposed Stage 2, Test 3 (%) ¹⁾
0	1.07	28.7	33.2	24.8
1	2.16	14.2	23.3	17.4
2	3.25	9.4	19.0	14.2
3	4.35	7.1	16.4	12.3
4	5.44	5.6	14.7	11.0
5	6.54	4.7	13.4	10.0
Resulting harmonic voltages using the above current allocations are given below				
Resulting U_{hi} at Node 1		3.1%	4.0%	3.4%
Resulting U_{hi} at Node 5		3.4%	5.0%	4.1%
¹⁾ % of load current of each single consumer of agreed power $S_i=500\text{kVA}$				

7.2 Extreme Example

To fully test the application of the proposed method, and highlight the deficiencies of the IEC 61000-3-6 method, we consider the system in Figure 4, containing one weak feeder, one strong feeder and a large load at the busbar.

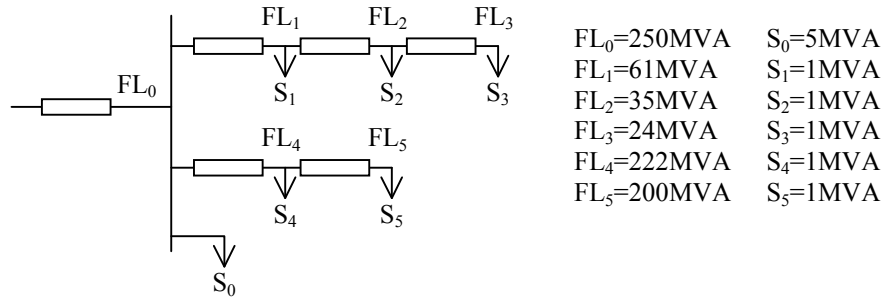


FIGURE 4: Extreme MV Distribution System Example

As the top feeder in Figure 4 is easily identifiable as the weakest feeder the calculation for k is

$$k \approx \frac{G_{hMV}}{\left(\sum_{i=1}^n S_i Z_{hi}^{\frac{\alpha}{2}} + S_0 Z_{h0}^{\frac{\alpha}{2}} + (S_{F2} + S_{F3} + \dots + S_{Fr}) Z_{h0}^{\frac{\alpha}{2}} \right)^{\frac{1}{\alpha}}}$$

$$\approx \frac{3.97\%}{\left(0.02 \cdot 4.10^{\frac{1.4}{2}} + 0.02 \cdot 7.14^{\frac{1.4}{2}} + 0.02 \cdot 10.42^{\frac{1.4}{2}} + 0.10 \cdot 1.00^{\frac{1.4}{2}} + (0.02 + 0.02) \cdot 1.00^{\frac{1.4}{2}} \right)^{\frac{1}{1.4}}}$$

$$\approx 7.97\%$$

For example, for the load at node 3 we have

$$E_{lh3} = \frac{kS_3^{\frac{1}{3}}}{\sqrt{Z_{h3}}} = \frac{7.97 \cdot 0.02^{\frac{1}{3}}}{\sqrt{10.42}} = 0.15\% \text{ (on 50MVA base)} = 7.56\% \text{ (on own base)}$$

TABLE 2: Comparison of different allocation schemes for extreme case

PCC node No.	Load Size MVA	Fifth harmonic impedance $Z_{h=5}$ (pu)	Stage 2, Test 1 E_{lhi} (%) ¹⁾	Stage 2, Test 3 E_{lhi} (%) ¹⁾	Proposed Stage 2, Test 3 (%) ¹⁾
0	5	1.00	24.2	5.9	15.4
1	1	4.10	9.3	14.4	12.0
2	1	7.14	5.4	10.9	9.1
3	1	10.42	3.7	9.1	7.6
4	1	1.13	34.0	27.6	23.0
5	1	1.25	30.6	26.2	21.8
Resulting harmonic voltages using the above current allocations are given below					
Resulting U_{hi} at Node 0			4.2%	2.9%	3.7%
Resulting U_{hi} at Node 3			4.9%	5.0%	5.0%
¹⁾ % of load current of each single consumer of agreed power S_i relative to own base					

In this example we can see the disadvantages of the previous IEC 61000-3-6 methods. In the first approximation, Stage 2, Test 1, it can be noted that the harmonic emission allowance for the far end load on the weakest feeder is quite small and the loads on the strong feeders receive a much larger allowance. In Stage 2, Test 3 the allocation for the loads at the end of the weakest feeder is seen as being fairer. However, the emission allocation is not determined by load size, and thus the allowance given to the local load on the busbar is small considering the load is half the system capacity.

The proposed method is a good compromise between the other two methods in that the local load at the busbar receives a larger proportion of the harmonic emission allowance as it represents a large proportion of system capacity. At the same time the loads at the end of the weakest feeder are receiving a considerable emission allowance.

8 CONCLUSION

It is proposed that analysis need be performed for the 5th harmonic alone in most circumstances.

The second summation law has shown to be both simpler to use and more appropriate in the allocation of harmonic emission levels within MV distribution systems.

The situation of loads distributed along a feeder, each having a different fault level, is a common occurrence. The treatment given in the IEC standard is illustrated by an atypical example which allows simplifying assumptions to be made which are invalid in practical cases. The exact solution of this problem requires an impracticably large amount of data. This paper outlines an approximate approach that requires complete data only for the weakest feeder. The approach has been shown to be significantly accurate to allow development of an effective harmonic emission policy for MV distribution systems.

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10 List of principal symbols

Where possible symbols used in this paper remain consistent with those used in the IEC 61000-3-6 document

α	exponent of the second summation law	PCC	Point of Common Coupling of the customer
E_{thi}	allowed harmonic current emission limit of order h for consumer (i)	r	number of parallel feeders with power supply system
E_{Uhi}	allowed harmonic voltage emission limit of order h for consumer (i)	S_i	apparent agreed power of the individual customer (i)
G_{hMV}	global harmonic voltage emission of order h for all loads supplied at MV	S_t	total available power at saturation of the supply system capacity
h	harmonic order	S_{Fj}	total capacity of all loads along feeder (j)
i	single customer or load	T_{hHM}	HV/MV harmonic voltage transfer coefficient of order h
I_h	harmonic current of order h	U_h	harmonic voltage of order h
k	harmonic emission allocation constant	U_{h0}	background harmonic voltage of order h
L_{hHV}	harmonic voltage planning level of order h for HV	U_{hi}	harmonic voltage of order h for customer (i)
L_{hMV}	harmonic voltage planning level of order h for MV	Z_{hi}	harmonic impedance of order h of the distribution system at the PCC (i)
n	number of customer PCCs along the weakest feeder only		