HARMONIC ALLOCATION TO MV CUSTOMERS IN RURAL DISTRIBUTION SYSTEMS

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Abstract

The harmonic management of power systems in Australia is governed by AS/NZS 61000.3.6. This document is limited to a discussion of principles with little advice on detailed calculation. A Standards Australia handbook shows how the standard can be applied to find customer harmonic allocations for city and urban power systems. This paper further extends this work to rural power systems having the features of isolated lumped loads and radials with spurs. A general harmonic allocation equation is developed containing an allocation coefficient which is required to be found for each MV system. It is shown that the computation to find this coefficient can be simplified so that a small spreadsheet can be used.

1. INTRODUCTION

International harmonic surveys show that THD voltages are generally increasing at about 1% per decade and there are many sites in Europe where harmonic levels already exceed limits, also known as Planning Levels, for some harmonics [1]. It is important that utilities have effective policies for ensuring that the harmonic loads being connected to their system do not exceed their system's capacity to absorb distortion.

At LV, equipment harmonic emission is controlled by equipment standards such as [2], while at MV, harmonic current is allocated to each customer's installation guided by the principles of AS/NZS 61000.3.6 [3]. Unfortunately, this document is unclear in places, and is particular difficult for occasional users. Standards Australia commissioned a handbook [4] to give a guide to applying the standard. This guide was limited in application to MV distribution systems with uniformly distributed loads and a simple radial topology, based on a correction factor as developed in [5].

With a growth in mining loads remote from towns, there is now a need to extend the procedure to rural systems having the following additional features of lumped loads and spur lines.

This paper proposes an approach which can be applied to rural systems and is illustrated with a particular test system which will be used to confirm the usefulness of the suggested approach. It allows the determination of the harmonic current to be allocated to an installation under Stage 2 of the standard.

It is assumed that pfc capacitors are fitted with series detuning reactors so that the harmonic impedance can be determined from simple fault level considerations. LV installations are ignored in this paper since their harmonic effects on MV systems are not usually of great significance [4].

The treatment of diversity given in Section 2.1 is based on a combination of experience and theory and is necessarily approximate. Hence little is to be gained by an attempt at an exact approach, especially as this leads to the need for an enormous amount of data. Engineering judgement need to be exercised in most harmonic allocations where the accuracy required is about 10%.

A list symbols is given after the References section.

2. STAGE 2 OVERVIEW

This section gives the main aspects of Stage 2 as given in [3, 4]. It identifies the basic principles that will be used in the paper for the development of analytical techniques which can address rural systems.

2.1 Representation of time-varying quantities

Under normal conditions, power system harmonics are due to the interaction of many time-varying distorting loads. The following principles are recommended for representing voltages and currents in this situation [3]:

1. Time-varying voltages and currents are represented by their 95% probability values.
2. The 95% values of voltages and currents can be found from the 95% value of the independent contributions using the Summation Law to account for diversity. This law is

$$V_{tot}^{\alpha} = V_1^{\alpha} + V_2^{\alpha} + \ldots + V_n^{\alpha} \quad (1)$$

where α varies with the harmonic order. A value of $\alpha = 1.4$ is used for $5 \le h \le 10$ and 2 for $h > 10$.

2.2 Allocation principles

The Standard adopts these principles for harmonic allocation under Stage 2:

1. The harmonic allowance to an installation increases with maximum demand.
2. The harmonic allowance should be such that the highest harmonic voltage in the local power system just reaches the Planning Level when the system is fully loaded and all installations are taking their maximum allocation.

[3] discusses the choice of quantity to be allocated. In distribution systems with long feeders, as is usually the case in Australia, harmonic VA is shown to be a more suitable quantity than voltage or current since it gives a useful allocation to customers at points of low fault level. This allocation quantity will be adopted here.

2.3 Interaction with other parts of the distribution system

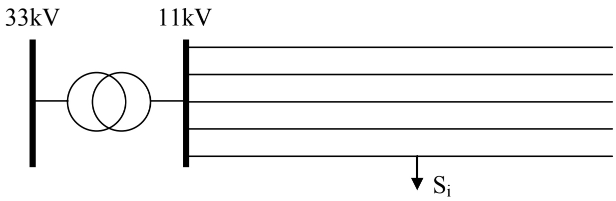

Figure 1 - 11 kV power system with study installation having maximum demand S_i

In the local power system shown in Figure 1, the harmonic voltages are influenced by loads connected elsewhere with harmonic effects propagating via the 33kV system. Similarly, the local power system influences harmonic voltages upstream. Assumptions need to be made which allow the user to avoid making any detailed study of upstream effects due to the 33kV system and other more remote interconnected parts.

It is assumed that that the whole power system is harmonically fully loaded so that the 33kV bus reaches its Planning Level. The 33kV bus is represented as a constant voltage source equal to the Planning Level for each harmonic being studied. This is an approximation because some part of the 33kV bus harmonic voltage is due to downstream effects of the local power system and it is incorrect to use a voltage source representation for this contribution. However the assumption is pessimistic and gives some safety margin for the allocation calculation. If L_{MVh} is the MV Planning Level and L_{USh} the Planning Level at the next voltage level upstream, the harmonic voltage available to local MV loads is, making use of (1),

$$G_{hMV} = \sqrt[\alpha]{L_{MVh}^{\ \alpha} - L_{USh}^{\ \alpha}} \qquad (2)$$

3. HARMONIC ALLOCATION IN RURAL DISTRIBUTION SYSTEMS

3.1 Overview

The system of Figure 2 will be used to discuss the details of the allocation process. It has been chosen because it is simple but has all the features which need to be treated to apply to rural system harmonic allocations:

- Feeders 1 and 2 with distributed loads.
- Feeders 2 and 3 with lumped loads.
- Feeder 3 with spurs 3A and 3B.

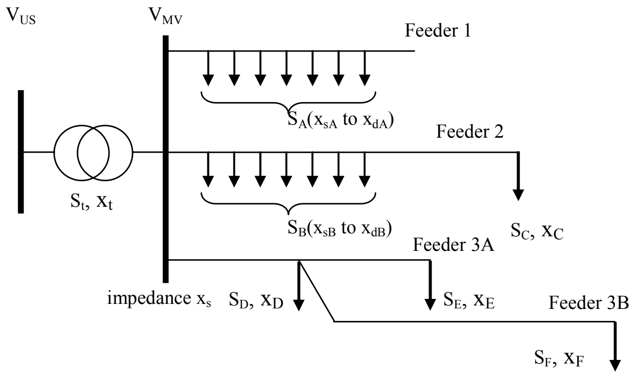

Figure 2 - Example system

One has to consider future as well as present loads in the allocation process (Section 2.2, point 2), hence not all the loads shown in Figure 2 need be connected at present. In some cases, the position of future loads is uncertain and engineering judgment needs to be made.

The allocation principles lead to an allocation law given in Section 3.2. The harmonic current drawn by MV loads is determined as shown in Sections 3.3, 3.4. Harmonic voltage can then be calculated as shown in Section 3.6, however this calculation need only be done for the weakest feeder as defined in Section 3.5. The value of k_h is then determined by simple proportion as given in Section 3.7.

3.2 The allocation equation

A load with maximum demand S_i is connected to the system at a point where the harmonic impedance is x_{ih}. It is shown in [6] that the principles of harmonic allocation are followed if the load S_i is given the following current allocation:

$$E_{Ihi} = \frac{k_h S_i^{\ 1/\alpha}}{\sqrt{x_{ih}}} \qquad (3)$$

k_h is the allocation constant for all MV loads in the local power system and varies with the harmonic order h.

3.3 Lumped MV loads

If resistance is small at harmonic frequencies, the harmonic impedance at the point of connection of load S_i is given closely by

$$x_{ih} = hx_{i1} \quad (4)$$

where x_{i1} is the fundamental reactance determined from fault level considerations. The harmonic current for installation "i" is taken as its full allocated emission from (3)

$$I_{hi} = \frac{k_h S_i^{1/\alpha}}{\sqrt{x_{ih}}} \quad (5)$$

3.4 Uniformly distributed MV loads

The methodology requires that all loads are represented as lumped quantities. We have shown in Appendix A that uniformly distributed MV loads drawing equal harmonic VA can be replaced with adequate accuracy, for harmonic calculations, by a lumped loads having a somewhat increased value of total MVA and situated at the appropriate pcc using (A.9, A.10). The loads S_A, S_B are replaced by:

- Feeder 1: S_{Aeq} is concentrated at x_{Aeq}.
- Feeder 2: S_{Beq} is concentrated at x_{Beq}.

The system of Figure 2 becomes transformed to that of Figure 3, which also shows node numbers for future reference.

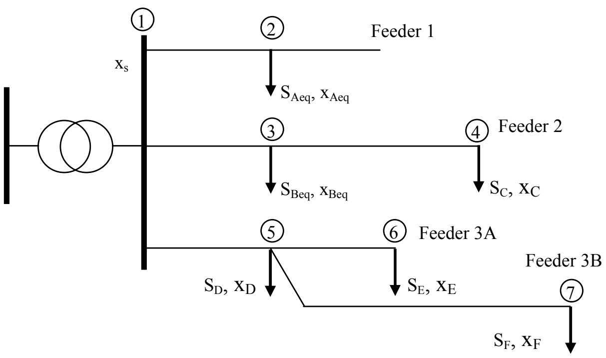

Figure 3 - Lumped model equivalent of Figure 2

3.5 Determination of weakest feeder

It is not necessary to calculate the highest voltage at the end of each feeder. Harmonic loading is related to fundamental loading since harmonic currents relate to maximum demand and harmonic impedance is related to fundamental impedances as given in (4). It is usually only necessary to determine the value of harmonic voltage at the end of the feeder with the highest fundamental loading.

The fundamental loading can be estimated for each feeder by computing the sum $\Sigma x_i S_i$ and finding the one having the largest value – see Table I for the calculations for the system in Figure 3. Uniform loads are given an impedance value corresponding to the average connection point. This is not exactly the same as the impedance of the equivalent lumped load used for harmonic calculations (A.10).

Table I - Fundamental loading for each feeder in Figure 2

Feeder 1:	$x_{Aav}S_A$
Feeder 2:	$x_{Bav}S_B + x_C S_C$
Feeder 3A:	$x_D S_D + x_D S_F + x_E S_E$
Feeder 3B:	$x_D S_D + x_D S_E + x_F S_F$

Notice that for Spur 3A, it is necessary to allow for the impact of the load on Spur 3B at the common impedance x_D. A similar remark applies to the impact on Spur 3B of the load on Spur 3A. Where there is uniform construction throughout the local system (either overhead open-wire, ABC or underground), reactances can be replaced by line lengths.

3.6 Determination of harmonic voltages

We determine the harmonic voltage appearing at the end of the weakest feeder as identified in Section 3.5. The following steps are necessary:

(a). Harmonic currents are determined for MV loads (5) with k_h initially set to unity.

(b). Harmonic impedances are chosen for each load at the pcc with the weakest feeder. For the Figure 2 example, if Feeder 3A is the weakest, impedances are chosen as
Load S_{Aeq}: the supply impedance x_{sh}
Load S_F: the impedance to D, that is x_{Dh}
Load S_E: the impedance to E, that is x_{Eh}

3.7 Determining the allocation constant

The harmonic voltage contribution of MV loads to the harmonic voltage at the end of the weakest feeder, with k_h equal to unity, can be found by summing the separate contributions using the Summation Law (Section 2.1). For other values of k_h, linearity applies and the MV contribution will be

$$V_{hMV.weakest} = k_h \times V_{hMV.weakest}' \quad (6)$$

where the dash ' indicates a value determined for $k_h = 1$. Hence,

$$k_h = \frac{G_{hMV}}{V_{MVh.weakest}'} \quad (7)$$

3.8 Extension to other frequencies

We note that that k_h in (7) is the ratio of two quantities. The numerator, G_{hMV} will need to be determined for each frequency. The denominator quantity only needs to be determined in detail at two harmonic frequencies as discussed below.

The weakest feeder has been defined in terms of fundamental quantities (Section 3.5) and will not change with frequency. The harmonic voltage is determined using the Summation Law as the sum of terms such as $(I_h x_h)^\alpha$ with k_h initially at unity. From the allocation law (3), these terms are of the form $Sx_h^{\alpha/2} = Sh^{\alpha/2} x_1^{\alpha/2}$. When the resultant V_h is then found by taking the α root, we find

$$V_h' \propto \sqrt{h} \quad (8)$$

Hence
$$k_h \propto \frac{G_{hMV}}{\sqrt{h}} \quad (9)$$

For a given value of α, if k_5, has been determined, other values (for h ≤10) can be found by proportion

$$k_h = k_5 \frac{G_{hMV}}{G_{5MV}} \sqrt{\frac{5}{h}} \quad (10)$$

At h = 11, α is chosen as 2, and k_{11} cannot be found from (10) – it needs to be determined from a detailed calculation, as for k_5. Once determined, other values (for h ≥ 11) can be found from

$$k_h = k_{11} \frac{G_{hMV}}{G_{11MV}} \sqrt{\frac{11}{h}} \quad (11)$$

4. EXAMPLE CALCULATION

4.1. System Data

We now consider the case of Figure 2 where the data in Table II applies. The aim is to determine the allocation constant k_h for the 5^{th} harmonic.

Table II - Data for first example

V_{US}	V_{MV}	S_t	x_t	h	α	L_{US5}	L_{MV5}	x/km
33kV	11kV	25MVA	15%	5	1.4	.031	0.051	0.35Ω/km
Load	**A**	**B**	**C**	**D**	**E**	**F**		
Type	Uniform	Uniform	Lumped	Lumped	Lumped	Lumped		
S-MVA	2.5	2.5	2.5	1.5	1.5	1.5		
Posn -km	0-10	0-5	15	10	20	30		

4.2. Outline of calculations

The full calculation is given in Appendix B. A base of 1MVA is chosen for per unit calculations. System harmonic impedances are found in Section B.1, including equivalent impedances for lumped equivalents to S_A and S_B. The highest harmonic voltage is seen to occur at the end of Feeder 3B. In Section B.3, for the Planning Levels given in Table II, G_{hMV}, the harmonic voltage available for local MV loads is found as 3.1%. With k_h = 1, MV loads would cause a voltage rise of 158% (Section B.4). The ratio of G_{hMV} to this voltage gives a value for k_h of 0.0197.

As an example of its use, for load S_C, E_{IhC} is determined from (3) as $0.0197 \times 2.5^{1/1.4}/\sqrt{0.247}$ or 0.0763 pu. Relative to its fundamental current of 2.5 pu, this is an allocated 5^{th} harmonic current of 3.1%.

4.3. MATLAB verification

An independent MATLAB calculation has been made to check the proposed methodology. The system has been represented with each loads replaced by the harmonic current in Section B.4 scaled up by k_h from Section B.5. Harmonic voltages were found as given in Table III. The largest voltage is found at the end of Feeder 3B (Node 7) and just equals G_{hMV} as determined in Section B.3 showing that the approach is sound.

Table III - V_h and fundamental loading for each node. Nodes at the end of feeders are shown in bold.

Node	1	2	3	4	5	6	7
ΣS×length	0	12.5	12.5	43.8	45	60	75
V_h	0.0097	0.0167	0.0159	0.0267	0.0231	0.028	0.0312

V_h has been plotted against fundamental loading in Figure 4 to check the method for finding the weakest feeder. It can be seen that there is close relationship between these two parameters so that loading is a good predictor of the weakest feeder.

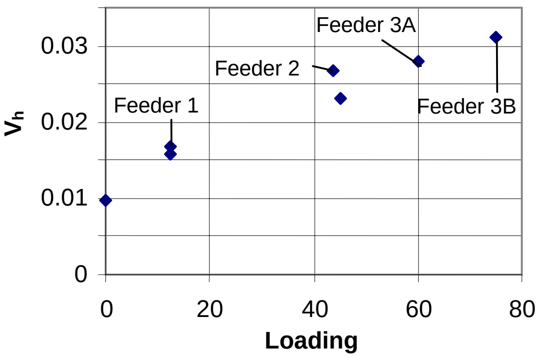

Figure 4 - Plot of V_h vs ΣS×length

4.4. Sensitivity

The sensitivity of k_h on system data has been determined from the MATLAB program. For system parameters, the sensitivity is 0.3%-per-% or less. The highest sensitivity is for load characteristics at D and F on the weakest feeder. This compares with about 2%-per-% sensitivity to parameters defined in the standards such as α and L_{MVh} . This demonstrates that the proposed method is robust.

5. CONCLUSIONS

An approach has been developed to implement the basic principles of harmonic standards for rural systems. This leads to the concept of a harmonic allocation constant for a particular local power system. Calculations can be simplified by (i) determining the voltage only at the end of one feeder which can be easily identified, (ii) making full calculations only at two harmonic frequencies. Uniformly distributed MV loads can be lumped into a single equivalent load. The calculations are sufficiently simple that they can be implemented by spreadsheet.

6. REFERENCES

[1] Euroelectric Report, February 2002 "PQ in European Electricity Supply Networks"

[2] AS/NZS 61000.3.2:1998, "Electromagnetic compatibility (EMC) Part 3.2: Limits-Limits for harmonic current emissions (equipment input current less than or equal to 16A per phase)"

[3] AS/NZS 61000.3.6-2001, "Limits – Assessment of emission limits for distorting loads in MV and HV power systems", Standards Australia 2001.

[4] V.J. Gosbell, S. Perera, V. Smith, D. Robinson and G. Sanders, "Power Quality – Recommendations for the application of AS/NZS 61000.3.6 and AS/NZS 61000.3.7", Standards Australia, HB 264-2003, August 2003, ISBN 0 7337 5439 2

[5] V.J. Gosbell and D Robinson, "Allocating harmonic emission to MV customers in long feeder systems", AUPEC03, Sept-Oct, 2003, Christchurch

[6] V.J. Gosbell, D.A. Robinson and B.S.P. Perera and A. Baitch, "The application of IEC 61000-3-6 to MV systems in Australia", ERA Conference, Thame, Feb 2001, pp 7.1.1-7.1.10

LIST OF MAIN SYMBOLS

Symbol	Meaning
E_{Ihi}	Harmonic current emission allocation to load "i"
G_{hMV}	Harmonic voltage available to local MV loads
h	Harmonic order
I_{hi}	Harmonic current from load "i"
k_h	Allocation constant
L_{MVh}	Local MV Planning Level
L_{USh}	Upstream Planning Level
R	Ratio of fault levels at supply and downstream ends of feeder
SBase	Base MVA
S_{eq}	Equivalent lumped max demand for uniformly distributed load
S_i	Load "i" maximum demand
V_{hMV}	Voltage at end of feeder due to MV loads
x_{av}	Average impedance at pcc for uniformly distributed load
x_{eq}	Equivalent lumped impedance at pcc for uniformly distributed load
x_{ih}	Harmonic impedance at pcc of load "i"
α	Summation exponent

APPENDIX A - UNIFORMLY DISTRIBUTED MV LOADS

This theory used in this section is based on results from [5]. Suppose we have a feeder with the following features:

- Total distributed load S
- Load distributed between points having fundamental reactance x_s at supply end and x_d at downstream end
- Harmonic order h with Summation Law coefficient α
- Load allocated harmonic current following the principle of equal harmonic VA to equal loads

A specific installation S_i is allocated a current I_{hi} based on the harmonic VA principle and following (3). The harmonic current drawn by this load can be closely approximated by [5].

$$I_h \sim k_h S^{(1/\alpha)} R^{-0.3}/\sqrt{(hx_s)} \quad (A.1)$$

The harmonic voltage caused by this load is highest at the far end and can be approximated by

$$V_h \sim k_h \sqrt{(hx_s)} S^{(1/\alpha)} R^{0.33} \quad (A.2)$$

We now find an equivalent lumped load S_{eq} and position x_{eq} (given in terms of fundamental short-circuit reactance) to give the same results. We thus need to solve the following simultaneous equations

$$k_h S_{eq}^{(1/\alpha)}/\sqrt{(hx_{eq})} = k_h S^{(1/\alpha)} R^{-0.3}/\sqrt{(hx_s)} \quad (A.3)$$

$$k_h \sqrt{(hx_{eq})} S_{eq}^{(1/\alpha)} = k_h \sqrt{(hx_s)} S^{(1/\alpha)} R^{0.33} \quad (A.4)$$

Multiplying (A.3) by (A.4) $S_{eq}^{2/\alpha} = S^{2/\alpha} R^{0.03}$

giving $$S_{eq} = SR^{0.03\alpha/2} \quad (A.5)$$

Dividing (A.4) by (A.3) $1/x_{eq} = 1/(R^{0.63} x_s)$

Giving $$x_{eq} = R^{0.63} x_s \quad (A.6)$$

There are approximations in this derivation and it was checked and further improved by means of a spreadsheet study. A model was set up where the uniformly distributed load was assumed to be accurately represented by a 10-stage discrete model. Values of harmonic current and voltage were determined for combinations of R = 6, 10, 28 and α = 1, 1.4, 2. Based on the above theory, the lumped model was assumed to be of the form

$$S_{eq} = SR^{x1.\alpha} \quad (A.7)$$

$$x_{eq} = x_s R^{x2} \quad (A.8)$$

Values were found for the parameters x1, x2 to minimise the maximum of the percentage errors between the "accurate" and the lumped equivalent model. The following modified equations gives a worst-case error of less than 11% and an average error of 5% over the studied range of R and α.

$$S_{eq} = SR^{0.044\alpha} \quad (A.9)$$

$$x_{eq} = x_s R^{0.64} \quad (A.10)$$

The original equations (A.7, A.8) gave a worst-case error of 21% and an average error of 7%.

APPENDIX B - NUMERICAL EXAMPLE

These calculations have been set out so that they can easily adapted to a spreadsheet. Choose a base S_{Base} = 1 MVA. This choice leads to each value of S in per unit being identical to the MVA value as given in Table II.

B.1 System impedances

Find the relevant fundamental and harmonic reactances for h = 5.

$$x_s = x_t = 0.15\times(\text{New base/Old base})$$
$$= 0.15\times1/25 = 0.0060 \text{ pu}$$
$$x_{sh} = hx_s = 0.0300 \text{ pu}$$

At 11kV, $Z_{Base} = V^2/S_{Base} = 11^2/1 = 121\Omega$

Determine harmonic reactances corresponding to each lumped load connection point. For uniform loads, determine the quantity x_{dh}, the harmonic reactance to the downstream end of the distributed load. At A:

$$x_{Adh} = x_{sh} + len_A\times hx/Z_{Base}$$

$$= 0.0300 + 10\times5\times0.35/121 = 0.1746 \text{ pu}$$

Similarly, x_{Bdh} = 0.1023 pu, x_{Ch} = 0.2469 pu, x_{Dh} = 0.1746 pu, x_{Eh} = 0.3193 pu, x_{Fh} = 0.4639 pu

Determine equivalent MVA and point of connection for the distributed loads A and B.

$$S_{Aeq} = S_A R_A^{0.044\alpha} = 2.5\times5.82^{0.062} = 2.79 \text{ pu}$$
$$S_{Beq} = S_B R_B^{0.044\alpha} = 2.5\times3.41^{0.062} = 2.70 \text{ pu}$$
$$x_{Aeqh} = x_{sh} R_A^{0.64} = 0.030\times5.82^{0.64} = 0.0926 \text{ pu}$$
$$x_{Beqh} = x_{sh} R_B^{0.64} = 0.030\times3.41^{0.64} = 0.0658 \text{ pu}$$

B.2 Weakest feeder

Since in this case line lengths are proportional to impedances, we use them in the loading calculation for simplicity.

1: $S_A\times len_{Aav} = 2.5\times10/2 = 12.5$

2: $S_B\times len_{Bav} + S_C\times len_C = 2.5\times5/2 + 2.5\times15 = 43.8$

3A: $S_D\times len_D + S_E\times len_E + S_F\times len_D$
$= 1.5\times10 + 1.5\times20 + 1.5\times10 = 60$

3B: $S_D\times len_D + S_E\times len_D + S_F\times len_F$
$= 1.5\times10 + 1.5\times10 + 1.5\times30 = 75$

Feeder 3B is the weakest as it has the largest S×length product.

B.3 Harmonic voltage available to MV loads

Determine the voltage available for MV loads.

$$G_{hMV} = \sqrt[\alpha]{L_{MVh}{}^{\alpha} - L_{USh}{}^{\alpha}} = \sqrt[1.4]{0.051^{1.4} - 0.031^{1.4}} = 0.0312 \text{ pu}$$

B.4 Harmonic voltage at end of weakest feeder

Determine the voltage at the end of the weakest feeder 3B with k_h provisionally put to "1", using the symbol ' as a reminder. We need to determine the harmonic currents injected by each load from (5).

$$\text{Feeder A: } I_{Ah}' = \frac{S_A{}^{1/\alpha}}{\sqrt{hx_{Aeq}}} = \frac{2.79^{1/1.4}}{\sqrt{0.0926}} = 6.83 \text{ pu}$$

Similarly, I_{Bh}' = 7.92 pu, I_{Ch}' = 3.87 pu, I_{Dh}' = 3.20 pu, I_{Eh}' = 2.36 pu, I_{Fh}' = 1.96 pu.

We also need to determine the appropriate impedance for each load to give the impact of its harmonic current on the harmonic voltage at the end of weakest feeder 3B. These are x_{sh}, x_{sh}, x_{sh}, x_{Dh}, x_{Dh} and x_{Fh} for loads A-F respectively. Hence the harmonic voltage at the end of Feeder 3B is made up of the following components which will need to be combined by the Summation Law:

A: $V_{Ah}' = I_{Ah}'x_{sh} = 6.83\times0.0300 = 0.21$ pu

Similarly, V_{Bh}' = 0.24 pu, V_{Ch}' = 0.12 pu, V_{Dh}' = 0.56 pu, V_{Eh}' = 0.41 pu, V_{Fh}' = 0.91 pu.

Combining these voltages

$$V_h' = \sqrt[\alpha]{V_{Ah}{}^{\alpha} + V_{Bh}{}^{\alpha} + V_{Ch}{}^{\alpha} + V_{Dh}{}^{\alpha} + V_{Eh}{}^{\alpha} + V_{Fh}{}^{\alpha}}$$

$$= \sqrt[1.4]{0.21^{1.4} + 0.24^{1.4} + 0.12^{1.4} + 0.56^{1.4} + 0.41^{1.4} + 0.91^{1.4}} = 1.58$$

B.5 Allocation constant

k_h is determined as the ratio of G_{hMV} from B.3 and V_h' from B.4

$$k_h = 0.0312/1.58 = 0.0197$$

As a quick check, we can compute the relative harmonic current for a couple of the loads, for example B (the closest to the supply) and F (the furthest).

For B: $I_{Bh} = k_h I_{Bh}' = 0.0197\times6.83 = 0.16$ pu
Relative to I_{B1}, $I_{Bh} = 0.16/S_B = 0.16/2.5 = 6.2\%$

For F: $I_{Fh} = k_h I_{Fh}' = 0.0197\times1.96 = 0.039$ pu
Relative to I_{F1}, $I_{Fh} = 0.039/S_F = 0.039/1.5 = 2.6\%$.

These values are in the range of typical MV 5th harmonic current allocations and decrease for loads further away from the supply as would be expected from a harmonic VA allocation policy.