PRACTICAL ISSUES WITH TRANSMISSION SYSTEM HARMONIC ALLOCATION USING IEC/TR 61000.3.6, EDITION 2, 2008

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ABSTRACT

Despite the existence of relatively detailed harmonic standards, regulatory rules, and guidelines, to date there is still no satisfactory harmonic allocation strategy for major loads in HV/EHV transmission systems. Application of existing strategies often results in the network harmonic absorption capability being underutilised, and for some system scenarios the planning levels may be exceeded. The application of these existing harmonic allocation strategies may also result in additional costs to the network owner or customers due to the lack of optimisation techniques or incomplete analysis.

In this paper harmonic allocation for a reduced HV/EHV transmission system in Australia are undertaken utilising IEC/TR 61000-3-6, Edition 2, 2008 strategies. Network models based on a simplified purely inductive network and then a more detailed network model including line capacitances, etc. are developed. It is shown that the application of the IEC/TR 61000-3-6 allocation methodology using the purely inductive network model approach will omit key issues associated with transmission networks. Application of harmonic allocation using more realistic network modelling will provide much improvement, however results suggest that harmonic voltages at all buses cannot be guaranteed to be below the planning levels for some network scenarios.

Application of IEC/TR 61000-3-6 is a complex multistage exercise which requires, besides application of the recommendations, constant reconsideration of network models, network capabilities, and reality checks of the results. Complex large loads and network augmentation are illustrated as two key areas requiring further consideration by transmission utilities.

1. INTRODUCTION

Excessive harmonic voltage levels can result in additional losses, overheating and malfunctioning of power system equipment and connected loads [1]. Distorting loads such as power electronic control equipment are being integrated into power systems at a rapid rate due to their increasingly affordable costs, flexible applications, higher efficiency and improved control [2, 3]. This trend has presented major challenges for utilities to coordinate and control harmonic emission levels within their networks.

HV/EHV Transmission systems inherently consist of highly meshed networks coupled with large loads and long transmissions lines. Network configurations and load characteristics typically differ significantly from MV and LV systems. General application of the current IEC technical report 61000-3-6 [4] for major loads in transmission systems tends to result in either the network absorption capability being underutilised or the planning levels being exceeded [5]. Underutilisation of network harmonic absorption capability will incur additional costs to customers to lower their harmonic emissions. On the other hand, exceeding planning levels will require utilities to install additional harmonic filters to mitigate excessive harmonics in the network.

The IEC guidelines fundamentally assume that the network configuration is static and the values of the α exponents used in the second summation law are optimised for 95% and 99% non-exceeding probabilities, diversity of loads and magnitude and phase angle variations of harmonic voltages in the MV and LV distribution systems.

This paper demonstrates that application of the guidelines of the present IEC technical report [4] will not always be practical for complex loads in a realistic transmission network and recommends further optimisation of the allocation process used in conjunction with the second summation law to allocate harmonic emissions to major loads in transmission systems.

2. COMPLEXITIES OF TRANSMISSION SYSTEMS

It is essential to identify the complex nature of transmission systems. Unlike MV/LV distribution or industrial systems, HV/EHV transmission systems tend to undergo network augmentation continuously throughout its lifespan [6], and some states within Australia are currently seeing significant expansion of the HV/EHV network due to large infrastructure requirements for the resource industry.

The following features are inherent in transmission systems, but uncommon for distribution and industrial systems:

- Highly meshed system in which harmonic impedances heavily depend on network configurations, such that minor changes of a network configuration can cause significant resonances at some buses [7].
- Large and complex loads employing sophisticated power electronic based control systems with broad and dynamic range of harmonic current angles, e.g. Static VAr Compensators (SVCs), motor drives, and HVDC, etc.
- Long transmission lines and large non-detuned

capacitor banks often lead to greater likelihood of harmonic resonances at the remote buses.

- Increased likelihood of harmonic propagation and penetration in the transmission system.

3. OVERVIEW OF IEC/TR 61000-3-6, EDITION 2, 2008 HARMONIC ALLOCATION METHODOLOGY

The IEC/TR 61000-3-6, Ed. 2 2008 technical report [4] was commissioned to introduce improved allocation methods supplementing the existing methodologies described in the previous version, which was adopted as a full standard by the Australian National Regulatory Authorities [8]. The aim was to achieve fair and equitable share of harmonic allocation for all loads. The harmonic emission rights should be proportional to the maximum "agreed power" (S_i) of the distorting loads. The underlining principle of the IEC allocation methodology is the second summation law (exponent α varying with the harmonic order h, refer Table I) which attempts to incorporate the diversity of loads, allowing frequency domain studies to predict cumulative probability levels of time varying harmonics with phase diversity. Accordingly, if the individual voltage sources have 95th percentile voltage values of magnitude V_{hi}, the 95th percentile of their combined voltage can be determined as

$$V_h = \sqrt[\alpha]{\sum_{i=1}^{n} V_{hi}^{\alpha}} \qquad (1)$$

Table I - Summation law exponent α variation with h

Harmonic Order	α
$h < 5$	1
$5 \le h \le 10$	1.4
$h > 10$	2

The IEC allocation methodology comprises three stages, (i) simplified evaluation, (ii) emission limits relative to system characteristics and (iii) acceptance of higher emissions. Allocations using stage (ii) will be the most applicable in the allocation planning process, and consists of three steps:

- Step 1: At each harmonic order h, calculate the influence coefficients $K_{h,j-i}$ which is the harmonic voltage of order h caused at node i when 1 p.u. harmonic voltage of order h is applied at node j with all harmonic currents at other nodes being set to zero. In other words, if we inject harmonic current E_{Ihj} at node j until voltage at node j reaches 1 p.u (V_{hj} = 1 = $Z_{h(j,j)}$ x E_{Ihj}, hence E_{Ihj} = 1 / $Z_{h(j,j)}$) and harmonic currents at other nodes are set to zero, the influence coefficient $K_{h,j-i}$ is the voltage measured at node i (V_{hj-i} = $Z_{h(i,j)}$ x E_{Ihj}) due to the harmonic current E_{Ihj} injected at node j. Therefore, at each harmonic order h, the influence coefficients can be simply defined by

$$K_{hj-i} = V_{hj-i} = \frac{Z_{h(i,j)}}{Z_{h(j,j)}} \qquad (2)$$

V_{hj-i}: Voltage measured or calculated at node i when 1 p.u. voltage is applied at node j.

$Z_{h(i,j)}$: Impedance between node i and j, e.g transmission line impedance.

$Z_{h(i,j)}$: Impedance at node j where harmonic current is injected.

- Step 2: Use influence coefficient $K_{h,j-i}$ to calculate the permissible harmonic voltage limit at its point of common coupling (PCC).
- Step 3: Calculate the harmonic current limits based on the permissible harmonic voltage from Step 2 and network harmonic impedance $Z_{ii}(h)$.

The global contribution of harmonic emission at bus m is defined by (3).

$$G_{hm} \le \sqrt[\alpha]{\frac{S_{tm}}{\left(K_{h1-m}^{\alpha} \times S_{t1}\right) + \left(K_{h2-m}^{\alpha} \times S_{t2}\right) + .. + \left(K_{hn-m}^{\alpha} \times S_{tn}\right)}} \times L_{hHV} \quad (3)$$

For a system with n buses, there are n conditions required to be satisfied for each busbar, e.g. for bus busbar $B1$:

Condition 1:

$$G_{hB1} \le \sqrt[\alpha]{\frac{S_{t1}}{(S_{t1}) + \left(K_{h2-1}^{\alpha} \times S_{t2}\right) + ... + \left(K_{hn-1}^{\alpha} \times S_{tn}\right)}} \times L_{hHV} \quad (3.1)$$

Condition 2:

$$G_{hB1} \le \sqrt[\alpha]{\frac{S_{t1}}{\left(K_{h1-2}^{\alpha} \times S_{t1}\right) + (S_{t2}) + ... + \left(K_{hn-2}^{\alpha} \times S_{tn}\right)}} \times L_{hHV} \quad (3.2)$$

Condition n:

$$G_{hB1} \le \sqrt[\alpha]{\frac{S_{t1}}{\left(K_{h1-n}^{\alpha} \times S_{t1}\right) + \left(K_{h2-n}^{\alpha} \times S_{t2}\right) + ... + (S_{tn})}} \times L_{hHV} \quad (3.n)$$

The lowest value of all n cases of G_{hB1} will be selected to calculate the individual emission limits at bus $B1$ or bus m (i.e. G_{hm}= G_{hB1}). Individual emission limit of load S_i connected to node (substation) m is

$$E_{Uhi} = G_{hm} \sqrt[\alpha]{\frac{S_i}{S_{tm}}} \qquad (4)$$

Harmonic current allocation to a distorting load can be defined using

$$E_{Ihi} = \frac{E_{Uhi}}{Z_{hi}} \qquad (5)$$

S_i: Agreed Power of the load S_i

S_{tm}: Total supply capacity at node m.

E_{Uhi}: Emission limit of load S_i connected at bus m.

G_{hm}: Maximum global contribution to the h^{th} harmonic voltage of all distorting loads that can be connected at bus m.

Z_{hi}: Harmonic impedance of the system at bus m for installation S_i – use scalar quantity only ($|Z_{hi}|$).

Harmonic performance can be evaluated based on the total harmonic voltage calculated at each bus, e.g. bus i, according to (6) below.

$$V_{hi} = \sqrt[\alpha]{\sum_{j=1}^{n} \left(\left|Z_{h(i,j)}\right| \times E_{Ihj}\right)^{\alpha}} \qquad (6)$$

The IEC method also recognises that in meshed HV/EHV systems the distortion caused by the installations at node i may have more impact on the voltage distortion at node j, than at node i. There are cases for which the influence coefficients ($K_{h,j-i}$) can be quite high where series resonance exists between nodes i and j. Treatment for series resonance, but not parallel resonance, is also included in the technical report [4] as described below in order to lower harmonic emission limits at node i, rather than unduly limiting emissions at node j.

Wherever the influence coefficient $K_{h,j-i}$ is greater than unity, a reduction factor of F_{zj} must also be applied to that influence coefficient to reduce the impact of resonances to an acceptable level. The corrected influence coefficient is defined by

$$K^{\alpha}_{hn-m\_Corrected} = \left(K_{hn-m} \times F_{zj}\right)^{\alpha} \quad (7)$$

$$F_{zj} = \frac{Z_{hj}}{h \times Z_{1j}} \quad (8)$$

Z_{hj}: harmonic impedance at node j for harmonic order h,
Z_{1j}: impedance at node j at fundamental frequency.

Derivation of this correction factor F_{zj} is based on the assumption that the system is purely inductive, i.e. harmonic impedance increases linearly with harmonic order h. If the reduction factor F_{zj} still exceeds unity, this would be due to a parallel resonance and a different approach, which has not been considered in [4], might be needed.

The harmonic current emission limit at busbar j is calculated by

$$E_{Ihj} = \frac{E_{Uhj}}{h * Z_{1j}} \quad (9)$$

4. NETWORK MODELLING

Network modelling is an important foundation for all harmonic studies. For ease of calculation, a complex network is often reduced and simplified before being modelled. A case study was undertaken using a simplified transmission network as shown in Figure 1. This network was modelled separately using two different methods.

- *Method 1* - Purely inductive network model: All resistive and capacitive elements are ignored. Harmonic impedances are linearly proportional to harmonic frequencies. Phase angles of harmonic impedances are constant over the entire spectrum of harmonic frequencies, magnitudes of harmonic impedances increase linearly with harmonic frequencies. The influence coefficients are also constant over the harmonic frequency spectrum.
- *Method 2* - Realistic network model: All network elements are modelled according to CIGRE Working Group CC02 document [9]. Both magnitudes and phase angles of network harmonic impedances vary non-linearly with harmonic frequencies. Therefore, the characteristics of harmonic voltages over the frequency spectrum are specific and unique for each network configuration due to the complex relationship between network configuration and characteristics of harmonic impedances. Changes in transmission network configuration, e.g. re-route of an existing line or installation of an additional line, can lead to significant changes in harmonic impedances and subsequently harmonic emissions and performance. Harmonic influence coefficients from (2) are heavily dependent on the bus harmonic impedances, which vary according to specific network scenario.

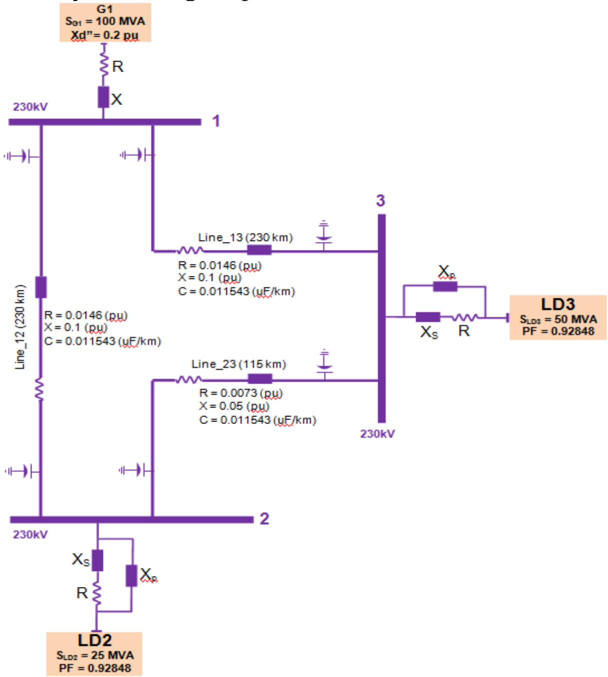

Figure 1 – A Simplified Transmission Network Model

The influence coefficients calculated using the *Method 1* approach for the network in Figure 1 were constant, as expected. In contrast, influence coefficients calculated from *Method 2* varied non-linearly with harmonic frequencies and indicate harmonic resonances at various frequencies. Results of both cases are shown in Table II.

Table II – Variation of Influence Coefficients

	h	***Influence Coefficients***					
		K_{h2-1}	K_{h3-1}	K_{h1-2}	K_{h3-2}	K_{h1-3}	K_{h2-3}
Method 1 - Purely Inductive Network	All	0.74	0.72	0.76	0.8	0.78	0.86
Method 2 - Realistic Network	5th	1.90	1.97	2.51	1.78	2.46	1.68
	7th	7.97	7.66	4.28	4.99	4.16	5.04
	17th	1.95	2.10	2.24	2.96	2.19	2.70

Influence coefficients greater than unity indicate existence of resonance. Significant harmonic resonances due to series or parallel resonances only appear in the realistic network model. Therefore, major harmonic issues may not be identified in harmonic studies for transmission systems if purely inductive network models are used. It is recommended that only realistic network modelling similar to the approach described in [9] should be used for harmonic studies in transmission systems.

5. PHASE ANGLES OF HARMONIC CURRENT SOURCES

Another study was performed on the network of Figure 1 using *Method 2* to identify the potential issues associated with different phase angles of harmonic currents. Maximum harmonic current emissions allocated to all loads are injected into the network and phase angle of one of the current sources, e.g. load LD3 - E_{Ih3}, is varied from -90° to +90°. All other sources inject their maximum emission at 0° phase angles (relative to fundamental). Harmonic voltages at all buses were calculated using $[V_{hi}] = [Z_{h(i,j)}][E_{Ihi}]$ and plotted against the phase angles. It was found that over a certain range of phase angles, bus harmonic voltages exceed planning levels.

Application of the IEC methods in realistic transmission networks may not guarantee all harmonic voltage magnitudes to be below planning levels if a major complex load in the system, e.g. Static VAr Compensator (SVCs), injects harmonic currents predominantly (e.g 75% of its operating time) at a phase angle that will cause bus voltages to exceed planning levels. This situation is further explored and discussed in Section 6 below.

6. PRACTICAL ISSUES OF IEC/TR 61000-3-6 ED.2:2008

The guidelines of IEC technical report [4] was used to allocate harmonic emission rights to all major loads (bus 2 and bus 3 loads) in the simplified transmission system shown in Figure 1. Maximum harmonic current emissions E_{Ih2}, E_{Ih3} allocated to loads at bus 2 and bus 3 respectively were used to calculate the total harmonic voltages at all buses using the IEC second summation law and power law (values of exponent α). Equation (6) can be expanded as shown below.

$$V_{h1} = \sqrt[\alpha]{\left(\left|Z_{h(1,1)}\right| \times E_{Ih1}\right)^{\alpha} + \left(\left|Z_{h(1,2)}\right| \times E_{Ih2}\right)^{\alpha} + \left(\left|Z_{h(1,3)}\right| \times E_{Ih3}\right)^{\alpha}}$$

$$V_{h2} = \sqrt[\alpha]{\left(\left|Z_{h(2,1)}\right| \times E_{Ih1}\right)^{\alpha} + \left(\left|Z_{h(2,2)}\right| \times E_{Ih2}\right)^{\alpha} + \left(\left|Z_{h(2,3)}\right| \times E_{Ih3}\right)^{\alpha}}$$

$$V_{h3} = \sqrt[\alpha]{\left(\left|Z_{h(3,1)}\right| \times E_{Ih1}\right)^{\alpha} + \left(\left|Z_{h(3,2)}\right| \times E_{Ih2}\right)^{\alpha} + \left(\left|Z_{h(3,3)}\right| \times E_{Ih3}\right)^{\alpha}}$$

The results, which were calculated using the summation law employing the α exponents as per IEC/ TR technical report [4], show that all bus harmonic voltages are at or below the planning levels. However, due to the resonance conditions which exist at some harmonic orders, e.g. 5th, 7th and 17th harmonic orders, harmonic allocations for loads at bus 2 and bus 3 have to be reduced by 2% to 3% to avoid planning levels being exceeded.

The maximum harmonic emissions of bus 2 load (E_{Ih2}) and bus 3 load (E_{Ih3}) were injected into the system. Phase angle of bus 3 harmonic current source (E_{Ih3}) was varied from -90° to +90°, phase angle of bus 2 harmonic current source (E_{Ih2}) is set at 0°. Total harmonic voltages at all buses are calculated using (10) below.

$$\begin{bmatrix} V_{h1} \\ V_{h2} \\ V_{h3} \end{bmatrix} = \begin{bmatrix} Z_{h(1,1)} & Z_{h(1,2)} & Z_{h(1,3)} \\ Z_{h(2,1)} & Z_{h(2,2)} & Z_{h(2,3)} \\ Z_{h(3,1)} & Z_{h(3,2)} & Z_{h(3,3)} \end{bmatrix} \begin{bmatrix} E_{Ih1} \\ E_{Ih2} \\ E_{Ih3} \end{bmatrix} \quad (10)$$

The results indicate that bus harmonic voltages exceed the planning levels for phase angles between 40° to -90°, as shown in Figure 2. The results would have been unpredictable for a realistic transmission system with multiple large complex loads injecting maximum harmonic emissions simultaneously at unknown or undefined phase angles. In this simple case study, assuming that harmonic load at bus 3 is an SVC, which injects maximum harmonic emission (E_{Ih3}) at -55° phase angle into a simplified network that has background harmonic levels equivalent to the maximum harmonic emission (E_{Ih2}) of bus 2 load at 0° phase angle as shown in Figure 2. This scenario will result in all three bus voltages exceeding planning levels by 30-50% at some harmonic orders.

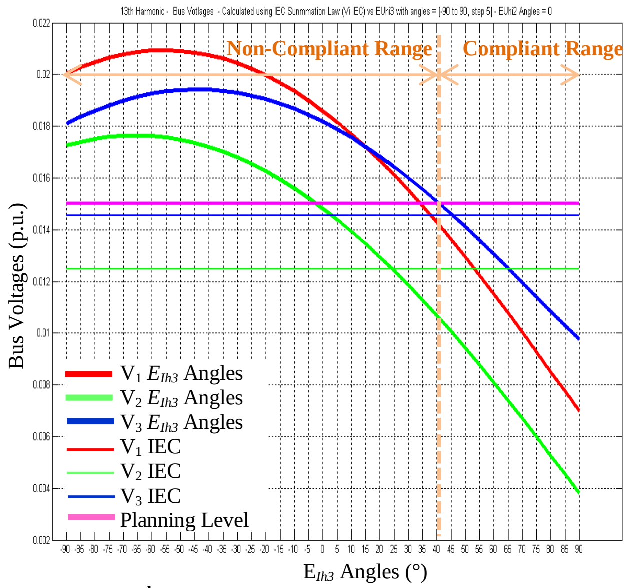

Figure 2 – 13th Harmonic Bus Voltages – IEC Summation Law and Alpha Constants vs E_{Ih3} Current Injection with phase angle variation

7. CRITICAL ANALYSIS OF 61000-3-6 ED.2:2008 HARMONIC ALLOCATION METHODOLOGY

The IEC second summation law and the power law make use of the influence coefficient K_{hj-i} and the exponent α constants. The influence coefficients essentially describe the characteristics of a network scenario through the expression of harmonic impedances as per (2).

Resonance condition exists between node *j* and *i* when $Z_{h(i,j)} > Z_{h(i,i)}$ (i.e. $K_{hj-i} > 1$), because 1 p.u. voltage applied at node *j* will produce more than 1 p.u. voltage at node *i*. For the purely inductive system, harmonic impedances increase linearly with harmonic order *h*, i.e. $Z_h = h \times Z_1$ - Where Z_1 is the impedance at fundamental frequency. Conversely, the influence coefficients calculated for any realistic network will vary nonlinearly with harmonic frequencies, i.e. $Z_h = F(h) \times Z_1$ - Where $F(h)$ is a complex non-linear function and dependent on the network model and the network configuration. Harmonic studies for transmission systems using purely inductive network model may lead to inconclusive findings. The methodology used to derive the correction factors for the influence coefficients in harmonic resonance conditions (i.e. $K_{hj-i} > 1$) in the IEC technical report [4] assumes that the system is purely inductive. Therefore, application of the influence coefficient correction factors is not always effective for a realistic transmission network.

The values of α exponent for the 95th percentiles were determined for various magnitudes of uniformly random amplitude and phase. The results of a case study in Section 6 imply that application of the IEC second summation law and the α exponents in its current forms may not be effective for a realistic transmission system with large complex loads injecting harmonics at undefined, or unknown, phase angles. There are potential opportunities to further improve the effectiveness of the IEC methodology: One option is to optimise the values of α exponents for transmission systems with large complex loads, alternatively, large complex harmonic loads in transmission system should be assigned with specific injection phase angle/s that will not cause planning levels to be exceeded at any bus in the system.

Application of technical report IEC/TR 61000-3-6, Edition 2:2008 is not effective for complex major loads in a realistic transmission network with long transmission lines and non-detuned capacitors, which are the major sources of resonance [10]. The following challenges are still to be further investigated and overcome:

- Overconservative allocation of harmonic emissions to major loads. The total network harmonic absorption capability is underutilised unnecessarily.
- Application of the α exponents as described in the IEC technical report has not been optimised for large complex harmonic loads, e.g. SVCs injecting harmonic currents at undefined phase angles in a realistic transmission system.
- Network augmentation changes network harmonic impedances and therefore also affects harmonic emissions and harmonic performance.
- Unless specified by the utility, major complex harmonic loads in transmission system do not normally have defined harmonic current phase angles. As a result, harmonic voltages measured from the real system can be worse than the voltages calculated using the existing second summation law and values of α exponents in the IEC technical report [4].

8. CONCLUSION

Application of the IEC/TR 61000-3-6 Edition 2:2008 for major loads in realistic transmission network scenarios is difficult because of its unrealistic assumptions, complex calculations and ineffective methodologies. Allocation of harmonic emissions to large complex loads in HV/EHV transmission network are likely to often result in conservative allocation or planning levels being exceeded. Application of the IEC summation law and the power law may appear to be sufficient in theoretical calculations of simplified network model, it is still far from being practical and satisfactory for large complex loads in a realistic transmission system. The allocation methodology of the IEC technical report [4] does not accommodate future network augmentation and large complex loads injecting full harmonic allocation at undefined phase angles. Furthermore, the method used to correct the influence establish coefficients under resonance conditions seems to be ineffective and may lead to inadvertent reduction of harmonic emission rights unnecessarily, hence increasing the capital cost to network participants.

It is recommended that further studies be conducted to optimise the values of α exponents that are more suitable for harmonic allocation to major complex harmonic loads with undefined phase angles in transmission system. Alternatively, further studies should be undertaken to examine the effectiveness and practicality of assigning harmonic current phase angle/s for some major complex loads in transmission system.

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