

# Non-Linear Generation And Loads, Their Impact On Transmission Network Voltage Harmonics and Available Measurement Techniques.

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## 1. Introduction

Traditional thermal and hydro voltage generators produce a sinusoidal voltage at their terminals which can be represented by :-

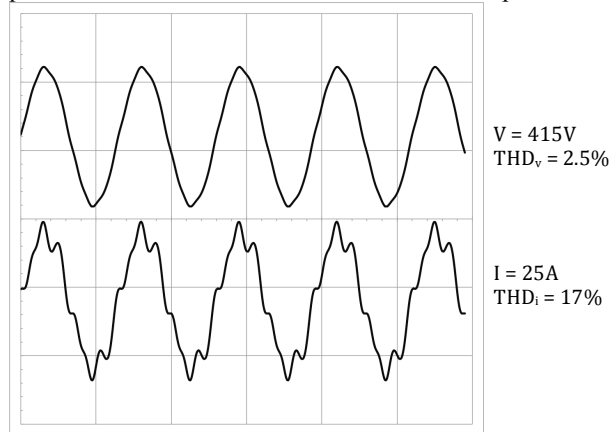
$$V(t) = V_o \sin(\omega t) \dots\dots\dots (1)$$

When connected to a electrical network comprising linear loads the generator provides a load current which can be represented by :-

$$I(t) = I_o \sin(\omega t + \phi) \dots\dots\dots (2)$$

where  $\phi$  is a function of the power factor at the connection point. Historically, in the absence of non-linear loads the design, protection and monitoring of power networks has been largely based on the measurement and analysis of these sinusoidal 50/60Hz quantities.

In the past 30 years the growing application of new technology to a wide variety of industrial and domestic equipment has resulted in a power system that now consists of a significant percentage of non-linear devices and so it is no longer safe to assume that the load currents can be represented by (2). Non linear loads result in distorted current waveforms that are periodic in nature but are not sinusoidal in shape.<sup>1</sup>

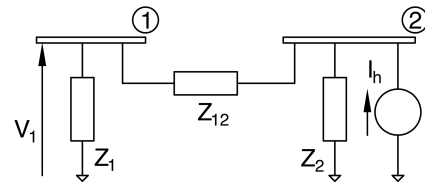


**Figure 1**

Fourier analysis [1] is used to characterise these distorted waveforms and simplifies the task of modelling and analysing their impact. The non-sinusoidal current is represented by a fundamental frequency together with one or more harmonic currents

<sup>1</sup> It is important to distinguish these periodic distorted current waveforms created by non-linear loads from the aperiodic highly distorted current waveforms associated with electric arc furnaces. The impact of these currents, which are not steady state, is often better characterized by measuring voltage dips and flicker.

whose magnitude and phase angle are such that when combined they exactly represent the original non-sinusoidal current. Lets us consider a simple network consisting of two connected nodes and one harmonic current source - Figure 2. The impedances  $Z_1$ ,  $Z_2$  and  $Z_{12}$  are a function of the network components and connected devices, are frequency dependent and may even have their own resonances.



**Figure 2**

$V_1$ , the impact of  $I_h$  at node 1 is given by the equation

$$V_1 = Z_{TR(2-1)} * I_h \dots\dots\dots (3a)$$

Where  $Z_{TR(2-1)}$  is the transfer impedance from node 2 to node one and is given by

$$Z_{TR(2-1)} = \frac{Z_2 Z_1}{Z_1 + Z_2 + Z_{12}} \dots\dots\dots (3b)$$

where  $Z_1$ ,  $Z_2$ , and  $Z_{12}$  are complex impedances whose values can change with frequency. This simple example serves to illustrate the complexity of harmonic modelling and analysis on a trivial circuit model. When a real world network is to be studied where there are hundreds of nodes to consider and complex impedances for every device and circuit then it is clear that specialist tools and skills are required to perform this work.

The situation is further compounded by the fact that in addition to the proliferation of non-linear loads, modern technology has also been applied to a new generation of power generation equipment and FACTS systems and these non-linear devices also contribute to the harmonic currents present on the electrical network. These non-linear devices include HVDC, SVC, Statcom, wind turbines, solar power generation equipment and series compensation schemes with thyristor controls.

The paper discusses some of the consequences of these non-linear devices being connected to electrical transmission and distribution networks.

## 2. Harmonics and why they are important

If the levels of harmonic currents and/or voltages become excessive then they can impact the utility or their connected customers in a number of ways including:-

- increased losses and overheating in transformers
- damage to capacitor banks
- mal-operation of protection or other control equipment
- pulsating torques in rotating plant
- exceeding harmonic limits as defined by IEEE 519, utility grid code or operating license.

In order to avoid the expense of remedial action that may be required to reduce high levels of voltage harmonics to be within specified limits it is important to:-

- monitor network background harmonic levels
- implement a network planning strategy that ensures that the harmonic impact of changes to the network or new network connections are assessed and managed.

It is usually sufficient to measure the voltage harmonics at key nodes on the network but it should be noted that harmonic levels can be significantly impacted by connected generation or network configuration and so field measurements, where possible, should be made over a period that covers all major network configurations. In many cases it may be more practical to install permanent harmonic measurement equipment at major nodes on the network.

It is generally accepted when making background harmonic measurements that harmonics up to the 50<sup>th</sup> order should be measured, however some utilities and standards bodies are now recommending that higher orders should also be considered. This is in part being driven by devices based on voltage source technology that are known to produce harmonics that are significantly above the 50<sup>th</sup> order.

| Class | Measurement | Conditions                                      | Maximum error                           |
|-------|-------------|---|---|
| I     | Voltage     | $U_m \geq 1\% U_{nom}$<br>$U_m < 1\% U_{nom}$   | $\pm 5\% U_m$<br>$\pm 0,05\% U_{nom}$   |
|       | Current     | $I_m \geq 3\% I_{nom}$<br>$I_m < 3\% I_{nom}$   | $\pm 5\% I_m$<br>$\pm 0,15\% I_{nom}$   |
|       | Power       | $P_m \geq 150\text{ W}$<br>$P_m < 150\text{ W}$ | $\pm 1\% P_{nom}$<br>$\pm 1,5\text{ W}$ |
| II    | Voltage     | $U_m \geq 3\% U_{nom}$<br>$U_m < 3\% U_{nom}$   | $\pm 5\% U_m$<br>$\pm 0,15\% U_{nom}$   |
|       | Current     | $I_m \geq 10\% I_{nom}$<br>$I_m < 10\% I_{nom}$ | $\pm 5\% I_m$<br>$\pm 0,5\% I_{nom}$    |

$I_{nom}$ : Nominal current range of the measurement instrument  
 $U_{nom}$ : Nominal voltage range of the measurement instrument  
 $U_m$  and  $I_m$ : Measured values

Table 1

IEC 61000-4-7 requires that harmonic measurements meet the accuracy requirements specified in Table 1. IEEE standard 519 recommends that voltage distortion should comply with the following table.

| Bus Voltage at PCC       | Individual Voltage Distortion (%) | Total Voltage Distortion THD (%) |
|--------------------------|-----------------------------------|----------------------------------|
| 69 kV and below          | 3.0                               | 5.0                              |
| 69.001 kV through 161 kV | 1.5                               | 2.5                              |
| 161.001 kV and above     | 1.0                               | 1.5                              |

NOTE — High-voltage systems can have up to 2.0% THD where the cause is an HVDC terminal that will attenuate by the time it is tapped for a user.

Table 2- Voltage Distortion Limits

## 3. Network Changes and Non-Linear devices

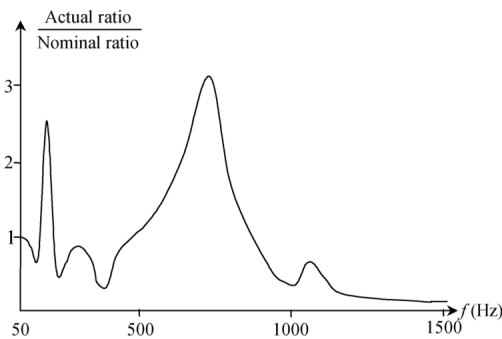
In Europe and the Americas environmental pressures and concern about global climate change are driving the closure of many old inefficient and polluting thermal power plants. These power plants were largely linear devices and so did not produce any significant levels of harmonics. In many instances, the UK being a good case in point, these changes are resulting in the introduction of a whole new generation of non-linear equipment onto the transmission network. The Trent valley in the centre of England was the location for more than 12 GW of coal fired power plants power plants that are gradually being phased out due to environmental and end of life issues. A significant percentage of this generation is being replaced by large off-shore wind farms, many of which are located off the west coast of Scotland. Due to congestion on the transmission network and the need to minimise transmission system losses significant changes are being implemented on the transmission network where HVDC connections and series compensation schemes are being added. These non-linear systems have the potential to cause harmonic problems on the transmission network if not correctly designed commissioned and monitored. There is also a large number of off-shore wind farms with a total capacity of more than 10 GW planned in the North Sea that will be directly connected to the transmission network and these systems too have the potential to increase the existing background level of harmonics. This could cause levels to rise above the statutory limits set in the in EA Engineering Recommendation G5/4 which is in turn referred to in the Grid Code as the compliance requirement.

Other countries have also found that replacement generation for old retired thermal power plants is often less conveniently located and this also necessitates addition of similar series compensation and HVDC systems. A recent market report states that the HVDC market will grow by 17% (CAGR) between now and 2020.

At distribution voltages the trend is also for a growing installed base of non-linear devices. These include small scale solar and wind generation schemes and the inexorable increase in variable frequency drives (e.g. in air conditioning and heat pump systems), low energy lighting and solid state electronic equipment. Electric vehicle charging points are a new and growing non-linear load on distribution. While much of the harmonic energy generated on the distribution network remains and is dissipated there, monitoring has shown that some of these harmonics make their way on to the transmission network and are present at network voltages as high as 500kV.

#### 4. Instrument Transformer Performance

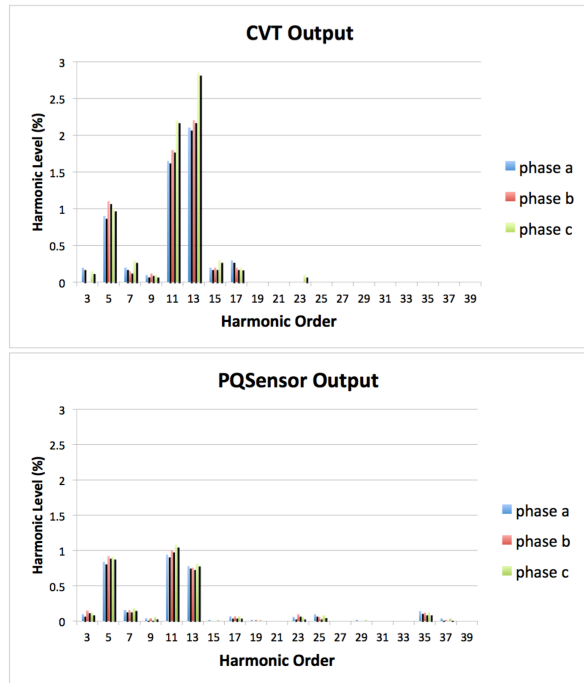
It is important to ensure that the instrument transformers used to make voltage harmonic measurements have the required accuracy. This can present significant difficulties since the most common instrument voltage transformers have major limitations when it comes to making accurate voltage harmonic measurements.



**Figure 3**

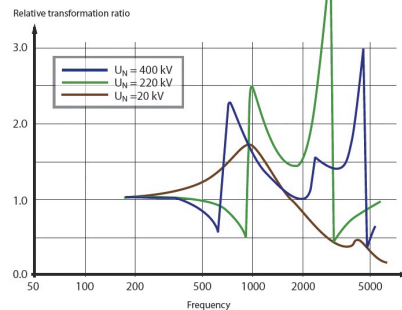
The majority of transmission substations are equipped with Capacitor Voltage Transformers (CVTs) and while they are available with class 0.5 and 0.2 accuracy this accuracy only relates to the fundamental frequency and does not apply to harmonic measurements. The inherent design of a CVT is based around a tuned circuit with its resonant frequency being equal to the nominal power system frequency. As a consequence, at frequencies significantly removed from nominal they produce large errors. A CVT frequency response graph published in IEEE Transactions On Power Delivery, Vol. 19, No. 3, July 2004 is shown in Figure 3 and clearly shows errors in excess of a factor of 3 in the frequency band of interest as defined by both IEC and IEEE. Figure 4 shows actual field measurements from a CVT compared with those taken at the same measurement point using an instrument transformer with suitable bandwidth. These results clearly show that in some cases the CVT will exaggerate the levels

of some harmonic frequencies, attenuate others and for higher order harmonics not report them at all.



**Figure 4**

The suitability of inductive or wound VTs for harmonic measurements can best be assessed by reviewing published frequency characteristics of these devices.



**Figure 5**

The chart in Figure 5 shows wound transformer frequency response data published by CIGRE working group 36. It is clear that above the 7th harmonic order these devices can introduce significant errors although the actual performance is very much a function of the burden on the transformer output.

The PQSensor™ is a transducer that can be fitted to a CVT and provides an additional output signal that accurately reflects the harmonic spectrum of the primary voltage. It does not in any way affect the operation of the CVT and its output signal is compatible with all major power quality meters and monitors. The PQSensor™ does not attempt to

compensate for the errors introduced by the CVT but instead measures known quantities within the CVT and accurately derives a signal that represents the primary voltage applied to the CVT. This device in most cases provides the most cost effective solution for making accurate harmonic voltage measurements on transmission networks.

### 5. Harmonic Case Study

The importance of managing the background levels of voltage harmonics can be illustrated by considering the following case study. The owner and operator of a 132kV generation and transmission network had a requirement to add a large pumping station to their network that would require the addition of four 25MW pumps controlled by variable frequency drives. The installation was also to include a 200MW open cycle gas turbine generator to be installed in the vicinity of the pumping station. Some initial LV harmonics measurements were made at a few locations adjacent to the installation site and there was no indication of any significant levels of background harmonics. This was reported to the designers of the installation and so their design was based on the basis that it would be connected to a IEEE ‘harmonic’ compliant 132kV network. Each of the variable frequency drives was equipped with harmonic filters to ensure that excessive levels of harmonics were not injected back on to the connected 132kV network.

Just prior to commissioning of the pumping station it became clear that from time to time the level of voltage harmonics on the 132kV network could significantly exceed the IEEE limits. It was not known at the time but it later transpired that there was a network resonance on the 132kV system that was close to the 5<sup>th</sup> harmonic frequency. Changes in the network configuration could move the resonant frequency point and when this coincided with the 5<sup>th</sup> harmonic then the level of 5<sup>th</sup> harmonic voltage could increase by as much as a factor of 5. As commissioning of the pumping station began it transpired that the desired network configuration for operating the equipment was also the configuration that placed the network resonance on the frequency of the 5<sup>th</sup> harmonic. Some network switching was carried out as part of the investigation into the network resonance and some of the results can be seen in Figure 6 below. The results illustrate how switching one feeder without disconnecting any load caused the level of voltage harmonics to drop very significantly due to impact on the resonant frequency.

Attempts to commission the new pumping station were thwarted by the fact that the harmonics on the 132kV network were being absorbed by the harmonic filters supplied with the variable frequency drives and this

would very quickly push them into an overload position where they would trip, making it difficult to operate the system.

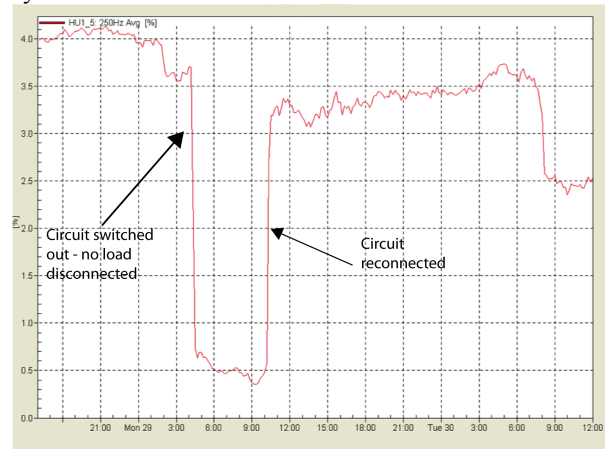


Figure 6

An interim solution was found by running all four drives concurrently and this resulted in the impact of the 132kV network voltage harmonics being shared between all four harmonic filters which marginally kept them below an overload condition.

This interim solution was only partially successful since in the event of one of the units tripping due to a process fault then other three units would often also trip in a cascade fashion due to the increased impact of the 132kV network harmonics.

The long term solution was to commission a proper harmonic study of the 132kV network and the design and installation of a 132kV harmonic filter.

### 6. Harmonic studies for a new non-linear connection – a UK perspective and case study

When supplying to the UK electrical transmission grid all equipment suppliers, manufacturers and system designers must follow Grid Codes, which are in turn based on international standards, such as IEC, or national specifications in the form of British Standards or UK Engineering Council Recommendations. The harmonic standard adopted in the Grid Code is Engineering Recommendation (ER) G5/4. The equivalent IEC standard is IEC 61000-3-6. ER G5/4 sets the permissible harmonic voltage levels from low voltage busbars up to transmission voltages. It is a requirement of the UK regulator, Ofgem, that all Distribution Network Operators (DNOs), generation companies and the grid operator comply with the limits specified in the standard, which extend to the 50<sup>th</sup> harmonic. This ER is being reviewed at present and will extend the compliance requirements to the 100<sup>th</sup> harmonic.

In this case study we will consider the process followed in the UK when considering an application for a new HVDC connection to the 400kV transmission network with regard to the impact on network harmonic voltages.

The procedure follows the guidelines in G5/4 and consists of three main steps:

- a) To model the network as accurately as is practically possible at and around the connection point.
- b) To measure the existing background harmonic levels at and around the connection point.
- c) Using the existing background harmonic levels in the network and the margin available between these levels and the G5/4 planning levels as a basis to determine the permissible levels of incremental harmonic distortion from the new HVDC converter.

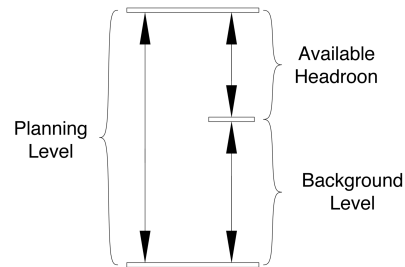
For system modeling a dedicated harmonic analysis software suite is used. In the UK the complete 275 and 400 kV networks owned by the transmission utility are programmed into their harmonic modeling software, and include an equivalent linear model for the loads at voltages of 132 kV and below. Network load representation has an extremely important effect on the overall modeling process. Distortion caused by harmonic current injection at the point of connection will be amplified or attenuated through network resonances or damping when reflected to other nodes in the system. Therefore, when setting the harmonic emission limits for a new connection, it is essential that the scope of the study includes the assessment of ER G5/4 limits at all nodes around the connection point to ensure that there are no violations.

A good indication of the area of the network that should be included in the project scope can be obtained by using the network model to analyze the harmonic voltage gains from the point of connection (PoC) to adjacent substations. Where a high gain is detected this indicates that the substation should be considered in the scope of the assessment.

The measurement of the existing background harmonic levels is important because it determines the harmonic headroom available for new connections. The harmonic headroom is the difference between the existing background level of harmonics and the harmonic limit specified in the G5/4 grid code – Figure 7.

Measurements on the network and system simulations have shown that harmonic distortion at the PoC can be transferred through the network as a result of harmonic voltage gains to other nodes and because of the possibility of harmonic resonances some of these gains

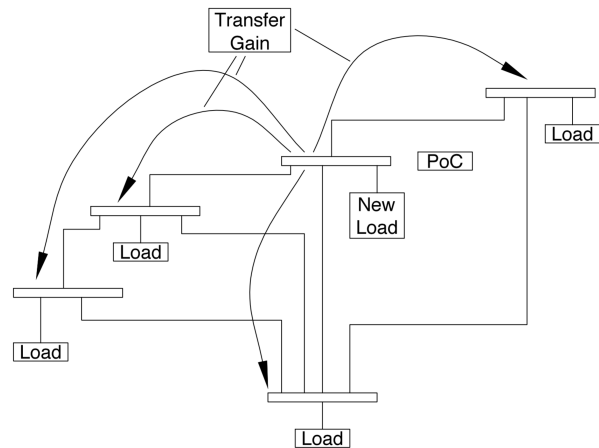
may be significantly higher than unity. Furthermore, the headroom available at different nodes very much depends on the existing background which may not be the same at all nodes.



**Figure 7**

For these reasons and to ensure compliance with the grid code the scope is expanded to include additional nodes in the connection assessment.

The example in Figure 8 illustrates the transfer of harmonics in a network and indicates why transfer gains to nodes not directly connected to the PoC often need to be considered.



**Figure 8**

The following steps are considered when planning the required background harmonic voltage measurements:

- I. The model is used to identify nodes that have a high harmonic gain wrt the PoC. Measurements will be required at these points
- II. When substations with a high transfer gain from the PoC requiring measurements have been identified then it is important to check whether suitable voltage transducers are available in the substations, without which a meaningful measurement is not possible. Note that accurate measurement of the existing background is an essential part of the assessment which directly affects the determination of the harmonic headroom and therefore the allowance that is granted for new connections. Inductive (wound)

voltage transformers (IVT) have limited bandwidth. Inquiries with major suppliers have indicated these devices may be suitable only up to the 10<sup>th</sup> harmonic for EHV systems. CIGRE and IEC have published test results for IVTs that confirms their limitations. As already discussed, due to their design and construction, CVTs do not have suitable frequency response and very high errors at low as well as high order harmonics are the norm. Specialist transducers including the PQSensor™ or RCDs (Resistor / Capacitor dividers) will provide the required accuracy and are the preferred solution.

- III. It is important to record the network topology (whether intact or with circuit outages) during the measurement period.
- IV. According to most recognized standards including IEC 61000-4-7, IEC 61000-4-30, EN 50160 and ER G5/4, the measurement period should be at least one week. Although desirable it is not required by any standard at present that the measurements at all substations be carried out simultaneously.
- V. According to standards the 95 percentile of the data over the measurement period should be deduced and used in the analysis. This is the level that 95% of the measurements are below. The measurement window for most connections is 10 minutes average according to Class A in IEC 61000-4-30 and IEC 61000-4-7. The only exception in the UK is traction loads where the measurement interval is 1 minute.

The effect of harmonic injection at one node on all adjacent nodes can be determined by using the harmonic voltage gain between the injection node and other busbars. A voltage gain of less than unity indicates voltage attenuation and gains of higher than unity leads to magnification. Equation (4) shows the voltage gain  $G_h$  :

$$G_h = \frac{V_{rh}}{V_{ih}} \dots\dots\dots (4)$$

Where subscript h denotes harmonic order,  $V_{rh}$  is the remote node voltage and  $V_{ih}$  is the voltage at the point of connection and is given by (2) below:

$$V_{ih} = Z_{sh} * I_{ih} \dots\dots\dots (5)$$

$Z_{sh}$  and  $I_{ih}$  are respectively the self impedance at the point of connection seen by the non-linear load and the current injected by it.

$V_{ih}$  and  $V_{rh}$  are also known as incremental voltages due to the current injection which are in turn added to the background harmonic voltages when the new non-linear load is connected.

Using the injected current at the PoC the voltages at the remote nodes are calculated by using transfer impedance seen from the PoC node as given below:

$$V_{rh} = Z_{th} * I_{ih} \dots\dots\dots (6)$$

$V_{rh}$  is defined as the voltage produced at the remote node due to current injected at the PoC. The transfer impedance,  $Z_{th}$ , is the off diagonal elements of the bus impedance matrix for the network. Note that assuming a balanced three phase network, the transfer impedance from the PoC to any remote node is equal to the transfer impedance from that node to the PoC.

Substituting (6) and (5) into (4) yields:

$$G_h = \frac{Z_{th}}{Z_{sh}} \dots\dots\dots (7)$$

Therefore, the ratio of the transfer impedance from the PoC to any node to the self impedance at the PoC is the harmonic gain to that node.

The harmonic voltage gain for each frequency from the PoC to other nodes can be determined from the frequency scan of the bus impedance matrix.

In order to determine the harmonic allowance at the PoC all other nodes with high harmonic voltage gains around the PoC should be considered. The measurements at the remote nodes will be used to determine the headroom at each remote node. There are different approaches considered to calculate the headroom but the method used in the UK is presented here.

Due to the fact that synchronized measurements at all nodes are not a requirement because of practicality and cost, measurement of the voltage magnitude only is required. In order to consider the diversity of harmonic voltages the following basic rules have been recommended in ETR 122:

I. For the harmonic with the highest level amongst all harmonics measured at a given node the headroom is calculated by linear subtraction of the measured background from the planning level:

$$V_{HR-h} = V_{PL-h} - V_{bg-h} |_{highest\ bgd\ level} \quad (8)$$

This gives a worst cases scenario to ensure the planning level of the highest harmonic is not exceeded.

II. For other harmonics measured the available headroom is calculated using root sum of squares (RSS) rule as shown below:

$$V_{HR-h} = \sqrt{V_{PL-h}^2 - V_{bg-h}^2} \dots\dots\dots (9)$$

Where  $V_{HR-h}$  is the calculated headroom,  $V_{PL-h}$  is the planning level for each harmonic and  $V_{bg-h}$  is the background harmonic measured. The RSS rule assumes a diversity equivalent to 90°.

Note that depending on the standard for harmonic limits used, the planning level for different harmonics may be different.

Now that the headroom for each harmonic of each node considered in the assessment has been determined then these should be reflected back to the PoC node because that is the point where the specification applies and connection agreement is enforced.

In order to relate each headroom back to the PoC the following equation is used:-

$$V_{HR-h}^{PoC-j} = V_{HR-h}^j / G_h^{PoC-j} \dots\dots\dots(10)$$

Where:

$V_{HR-h}^{PoC-j}$  is the headroom related to node j reflected back to PoC.

$V_{HR-h}^j$  is the headroom at node j calculated by using (8) and (9) above.

$G_h^{PoC-j}$  is the gain from PoC to node j.

Notes:

- a)The gain from PoC to node j is not the same as the gain from node j to PoC.
- b)The self and transfer impedances of the bus impedance matrix and therefore the harmonic voltage gains change with outages in the network. Therefore outages should be considered.
- c)The method outlined above only determines the incremental voltage produced by the polluting loads and does not consider the effect of the new connection at the PoC on the modification of the background harmonic level. Furthermore, the method allocates all the available headroom to the new connection at the PoC.

Once all the headroom levels are reflected back to the PoC including one determined for the PoC by the background measurement at the PoC itself, then the minimum of all the headrooms would be the limit for the new connection. Following the above procedure ensures that the pollution at the PoC will not cause a violation of planning level not only at the PoC but also at all other nodes considered in the assessment.

There are other methods that can be used but this approach addresses the main objective which is to ensure compliance at all substations in the network when a new polluting load is to be connected to the system.

### 8. Conclusions

The impact of non-linear devices on electrical networks is increasing and the importance of harmonic assessment in this context was presented. It was shown that system modelling, background harmonic voltage measurements and an algorithm to determine harmonic

limits for new connections form the essential basis of such an assessment. Up to date network topology with appropriate harmonic models for electrical components is a necessity. The background harmonic voltage measurement is a very important part of the assessment as it directly affects the headroom available for new connections.

### 9. Biography

John Merron graduated in engineering from Queens University Belfast in 1978 and after several year working in small engineering companies started his own company with two partners. The company was acquired by the Hathaway Corporation of Denver Colorado in 1991 where John continued in the position of Engineering Director in their Belfast facility. He was responsible for the development of several families of fault recording and condition monitoring products for transmission substation applications. Hathaway was acquired by Qualitrol in 2002 and John continued in several senior management positions until 2009 when he resigned and started his own company - BVM Systems.

John Merron is currently the Managing Director of BVM Systems Limited who provide innovative harmonic and transient measurement solutions.