INTRODUCTION TO HARMONIC ASSESSMENT IN POWER SYSTEMS

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1. INTRODUCTION

The free energy market rules have forced grid operators to adopt flexible new customer connection policies while at the same time maintain a high level of security, reliability and quality of the system operation.

In the UK, as a result of deregulation and European green energy directives in recent years many wind farm projects and HVDC connections to overseas transmission systems have been either commissioned or are in the advanced planning stage. The use of HVDC technology for these overseas connections together with an increasing number of wind farm installations has raised concerns over power quality issues on the transmission system.

The first HVDC link between the UK transmission grid and France was commissioned in 1983 with a capacity of 2000 MW. The transmission network in Northern Ireland was connected to the main UK network in 2000 with a 500 MW DC link. In recent years, the feasibility and detailed design works have been on going for another DC link between the UK 400 kV grid and the 380 kV system in the Netherlands. The project which is known as the BritNed link will be capable of bidirectional power transfer, have a rating of 1300 MW and will be commissioned in 2010. There are also other HVDC links being considered to Belgium, France and the Republic of Ireland. The latter has passed the tendering stages and the first two are firm connection agreements.

Further, because of difficulties in obtaining planning permission to construct transmission lines between Scotland and England plans are in place to transfer energy from new wind farms in the north of Scotland to the south through undersea HVDC cable transmission networks. Some of these projects will use voltage source converter stations instead of classic current source technology which although offering some advantages also introduces some challenges especially in area of power quality. This is primarily due to the fact that harmonic emissions from voltage source converter stations extend beyond 50^{th} harmonic.

The growth of wind power globally represents a huge investment by the energy industries in the hundreds of billions of US $. In 2007, a total of $148 billion was invested globally, which saw a 60% growth from 2006. Of this growth, a third of it was in wind energy. Environmental concerns over global warming, economic concerns over shortage of fossil fuels and the rising costs of oil and gas and political concerns over dependency on importing oil and gas have all contributed to accelerated growth of the wind energy sector. In 2007, the total operational wind capacity in Europe amounted to 55GW. In the U.K., the government's published Energy white paper in May of 2007 has set a target of 60% carbon reduction by 2050 with real progress to be achieved by 2020. The National Grid Company's published Seven Year Statement shows a significant growth in sanctioned wind generation connections in Scotland as well as England and Wales.

In England and Wales, the generating capacity of new wind farms has grown rapidly to where a number of wind farms in the range of 300 - 1000 MW are currently under construction. These present a challenge to the transmission grid operators in terms of the size of the connection and the time scales in which they are required. Consultation between government and industry experts has identified areas that will yield the highest levels of wind energy and these will be hotspots for future wind farms sites. Accommodating all of the connections anticipated in these areas identified to be rich in wind energy resource presents a technical challenge not only from a Security and Quality of Supply Standard (SQSS) point of view but also when considering the Voltage Waveform Quality as stipulated in the UK Grid Code (GC).

The UK Grid Code requires connections which are likely harmonic sources to be assessed according to Engineering Recommendation G5/4, which results in limits being specified under intact-network and outage conditions. The connection of wind farms, HVDC converter stations and other polluting sources/loads in the same area (electrically close) has a cumulated effect on voltage distortions. This is due to the harmonic emissions seen on the network together with the harmonic transfer impedance between nodes on the network. This means that levels of harmonics can increase at multiple nodes on the network for a single given source of harmonic emissions. As a consequence, the available harmonic distortion allowance for each new connection decreases as the number of connections increases. Therefore, it is vital that assessment of each connection is performed as accurately as possible to ensure that harmonic problems are avoided at remote network nodes.

In most countries in Europe as well as the UK, it is the policy to include power quality compliance criteria in the connection contract to which the customer is required to comply. Voltage harmonic emission limits are set for the point of connection, which specify the allowed contribution from each connection to the overall harmonic distortion. These requirements together with the details of the network impedance at the point of connection are used in the design of any harmonic mitigation required.

In the following sections the procedure adopted in the UK for system harmonic assessment, the determination of the harmonic emission limits and the connection design specification is described.

2. HARMONIC VOLTAGE ASSESSMENT REQUIREMENTS IN THE UK

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 accompanying document Engineering Technical Report (ETR) 122 provides a guide for applying 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 extra high voltage (EHV) substations, including 400 kV. It is a requirement of the UK regulator, Office of gas and electricity markets (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^{th} harmonic.

It is worth mentioning here that the main difference between ER G5/4 and 61000-3-6 is in the allocation of the available harmonic headroom to new connections.

There are two sets of harmonic levels in the standards namely planning levels and compatibility levels. The planning level is used in the design stage whereas the compatibility levels are the limits to which the harmonic levels must conform at all times. The document together with ETR 122 outlines the procedure for the assessment of the effect of a new connection.

For any connection application submitted to the utility commercial department, a number of reviews and studies are carried out to ensure compliance with all related Grid Codes. The results of these studies are added as an annex to the connection contract. Appropriate monitoring is also included in the final agreement to ensure that the contract is not violated.

Power quality studies are an essential part of the investigation into the effect of a new load on the system. This is more so for loads such as new traction, HVDC and wind farms connections, which are classified as the most polluting loads in the UK. Capacitor banks, because of their potential effects on background harmonic levels, and SVC installations also fall into this category. The criteria to which the new connection must comply are the outcomes from these studies.

3. THE ASSESSMENT

In this article a connection application for a HVDC installation is considered. For other types of connections the procedure is similar with some slight differences in the area of assessment of the effect of the connection on the network background (existing) harmonic voltages. This is due to the fact that at the time of the assessment by the utility of the impact of a converter station the filter parameters are not known and therefore it is not possible to study their effect. The change in the network background harmonic voltage is dealt with by the filter supplier to ensure that all harmonics comply with the harmonic specification issued by the utility. In the case of an offshore wind farm application for example, the connection's passive network parameters (including those of the high voltage cable) are known and in most cases will have significant impact (amplification or attenuation) on the background harmonics which in turn affect the harmonic allowance and therefore should be included in the assessment.

The objective of the harmonic study is to determine the harmonic emission limits for the HVDC converter station such that compliance with ER G5/4 is assured for all harmonics from the 2^{nd} to the 50^{th} and beyond if required.

The procedure follows the guidelines in the G5/4 and ETR 122 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, the margin available between these levels and the G5/4 planning levels gives a basis to determine the permissible levels of incremental harmonic distortion from the new HVDC converter.

3.1. SYSTEM MODELLING

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. The model includes transmission lines and cables at 275 and 400 kV, all generation and reactive power control equipment such as shunt reactors and capacitors, including the damper network components for any mechanically switched capacitors and static VAr compensators (SVC). The model also includes the 132 kV busbars that are fed directly by super grid transformers (SGT) from 275 and 400 kV nodes. There are three distinct network models; for maximum, intermediate and minimum network loadings. The loading criteria changes the generation connections, capacitor banks, shunt reactors and demand. These networks are respectively designated 100%, 60% and 36% demand models, with 100% demand being equivalent to about 45 GVA, which is the network winter total demand. It is interesting to mention here that until a decade ago the minimum demand rating was about 30% of the winter loading occurring in summer, but with increasing use of air conditioning loads in summer the minimum demand has increased to 36% in recent years.

The grid operator in the UK has developed an equivalent linear model for the loads at voltages of 132 kV and below. The standard distribution voltage levels in the UK are 66 kV, 33 kV, 11 kV and 6.6 kV with some 3.3 kV in different parts of the country. The nominal low voltage (LV) is 415 V. The load model is based on the MW demand at a node, from which are extracted typical transformer reactances, cable capacitances and induction motor effects. These models are based on the typical distribution network parameters and load in the UK. Describing the load model in great detail is out of the scope of this article and therefore avoided here. It is sufficient to mention here that the network harmonic model built into the suite includes the load equivalent at 132 kV by default. The load representation has an extremely important effect on the overall modeling process. Distortion caused by the 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. This requirement also applies to supply points at 132 kV and below in the DNO network despite the fact that they are not owned by the grid operator.

When carrying out a harmonic study it is up to the experience and engineering judgment of the project personnel to decide on the area of the network that should be included in the project scope. A good indication 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. Once the area to be included in the study has been identified then the load models at the 132 kV nodes within the area are removed and actual distribution network data is added. This new data includes all lines/cables, step down transformers and loads at lower voltages. The DNO provides this distribution network data.

It is common practice for the grid operator to ignore the 415 V network and instead use the equivalent load at 11 kV. Due to their complexity it is recommended that in the load equivalent model the lowest voltage level is not considered when setting the emission limits for the connection point. For example, if the lowest voltage level were 11 kV with the load equivalent connected at that level, then all nodes up to the 33 kV would be considered when setting the emission limits.

Harmonic load models have been defined by both CIGRE [4 & 5] and IEEE [6].

3.2. MEASUREMENT OF EXISTING HARMONIC LEVELS IN THE NETWORK

The measurement of the existing background harmonic levels is important because it determines the headroom available for any new connections.

In general there are two main approaches to determining the effect of a new polluting connection. One is to assume that the only node affected by the new connection is the Point of Connection (PoC) and therefore no other nodes surrounding the PoC need be considered. This in itself implies that the harmonic distortion created by the new connection at the PoC does not propagate in the network and it is only local. This in turn means that if the harmonic levels at the PoC comply with the standard then all other nodes in the network will also be compliant. This inherently assumes that all harmonic gains from the PoC to other nodes are less than unity and there is enough harmonic headroom at other nodes to accommodate the new connection.

Experience has shown that the above will not always be true for all harmonics. The harmonic distortion at the PoC does get 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.

As a result a second more exhaustive approach is now more commonly adopted. To ensure compliance with ER G5/4 and IEC 61000-3-6, the scope is expanded to include additional nodes in the connection assessment. The example in Fig 1 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. Fig 2 shows in simple terms the relationship between the background harmonic levels, planning level and headroom. The extraction of the headroom from the planning level and background harmonic voltages is not always linear arithmetic and depends on the adopted standard.

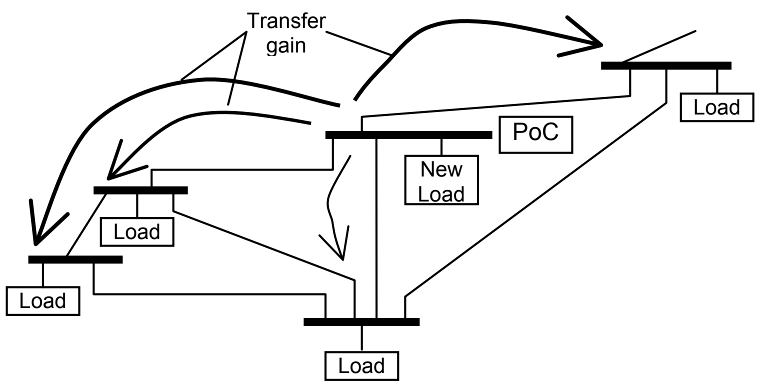

Fig 1- Harmonic Gain from a Node to Others

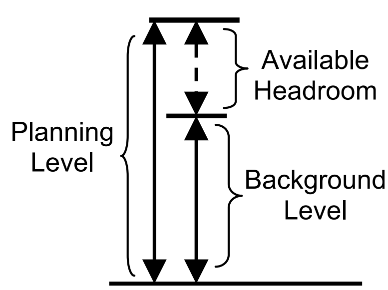

Fig 2- Relationship between Planning, Background and Headroom Levels

The following steps are considered when setting up a background harmonic voltage measurement campaign:

I. Once the model has been created and the lower voltage circuits and loads around the PoC have been included in the model a few preliminary runs are performed to identify high harmonic voltage gains between the PoC and other nodes. Calculation of harmonic gains will be covered in the next section.

II. When substations with a high transfer gain from the PoC 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 suitable only up to the 10th harmonic for EHV systems. CIGRE and IEC have published test results for IVTs that confirms their limitations. 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.

III. It is important to record the network topology (whether intact or with outage) 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.

3.3. HARMONIC VOLTAGE GAIN AND TRANSFER IMPEDANCE

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 (1) shows the voltage gain G_h :

$$G_h = \frac{V_{rh}}{V_{ih}} \qquad (1)$$

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:

$$V_{ih} = Z_{sh} I_{ih} \qquad (2)$$

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:

$$V_{rh} = Z_{th} I_{ih} \qquad (3)$$

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 (3) and (2) into (1) yields:

$$G_h = \frac{Z_{th}}{Z_{sh}} \qquad (4)$$

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.

3.4. DETERMINATION OF HARMONIC ALLOWANCE AT THE POC

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:

$$V_{HR\text{-}h} = V_{PL\text{-}h} - V_{bg\text{-}h}\Big|_{\text{highest background level}} \qquad (5)$$

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:

$$V_{HR\text{-}h} = \sqrt{V_{PL\text{-}h}^2 - V_{bg\text{-}h}^2} \qquad (6)$$

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

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:

$$V_{HR\text{-}h}^{PoC\text{-}j} = \frac{V_{HR\text{-}h}^{j}}{G_h^{PoC\text{-}j}} \qquad (7)$$

Where:

$V_{HR\text{-}h}^{PoC\text{-}j}$: Headroom related to node j reflected back to PoC.

$V^{j}_{HR\text{-}h}$: Headroom at node j calculated by using (5) and (6) above.

$G^{PoC\text{-}j}_{h}$: 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 connect to the system.

4. CONCLUSIONS

The importance of harmonic assessment in today's electrical networks with a growing number of polluting loads was discussed.

It was shown that system modeling, background harmonic voltage measurement 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 should be used. The background harmonic voltage measurement is a very important part of the assessment as it directly affects the headroom available to the connection. Note that very small harmonic headroom leads to low limits that in turn affect the harmonic mitigation requirements for new connections that can be costly in terms of equipment design, rating and space requirement.

5. GLOSSARY

[1] "Planning levels for harmonic voltage distortion and the connection of non-linear equipment to transmission systems and distribution networks in the United Kingdom", Engineering Recommendation G5/4.

[2] "Guide to the application of engineering recommendation G5/4 in the assessment of harmonic voltage distortion and connection of non-linear equipment to the electricity supply system in the UK", Engineering Technical Report 122.

[3] "Assessment of emission limits for distorting loads in MV and HV power systems", IEC 61000-3-6

[4] "Connection of harmonic producing installations in ac high voltage networks with particular reference to HVDC; guide for limiting harmonic voltage effects", WG 14.03/CC02, Electra No 149, August 1993.

[5] "Guide for assessing the network harmonic impedance", CIGRE WG CC02, Electra No. 167, August 1996.

[6] "Tutorial on Harmonics Modeling and Simulation", IEEE PES publication, IEEE Task Force on Modelling and Simulation, IEEE Catalog Number 98TP125-0, Chapter 3.