Harmonic Measurements On Transmission Networks

Background

For many years the measurement of power system harmonics was restricted to LV networks with a few notable exceptions when it was deemed necessary to make measurements at higher voltage levels. The primary reason for this being that the non-linear loads that were the cause of these harmonics were, with a few exceptions, connected to the low voltage network and the magnitude of the resulting harmonics were seldom large enough to have any significant impact at higher network voltages.

In recent years the introduction of a wide variety of large non-linear loads directly connected at distribution and transmission voltages has permanently changed the harmonic profile of the world's transmission networks. This has created a whole new set of problems for those responsible for the planning and operation of transmission networks.

Transmission Network Harmonics

HVDC links, large wind farms, FACTS systems, VFDs, SVC systems and other voltage source converter technologies are just some of the sources of these new transmission network harmonics. The harmonics generated by these non-linear systems range from the third harmonic upwards and it is generally accepted that when monitoring transmission networks, as a minimum, harmonics up to the fortieth rank should be considered and in most cases this should be extended to the fiftieth. The relevant IEC and IEEE standards provide guidelines for the permissible levels of harmonics at transmission voltages and these levels are often used (sometimes with minor modifications) to define the harmonic limits contained in transmission Grid Codes or Operating Licenses around the world. It is a requirement that transmission network owners plan and operate their network to ensure that harmonic levels stay within these limits.

Harmonic Order	HV (>35 kV) IEC Planning Level (%)
5	2.0
7	2.0
11	1.5
13	1.5
17	1.2
19	1.1
23	0.9
25	0.8
29	0.7
31	0.7
35	0.6
37	0.6
41	0.5
43	0.5
47	0.4
49	0.4

IEC Harmonic Planning Levels

Table 1

Required Measurement Accuracy

It is clear from Table 1 that for higher orders the permissible harmonic levels are low and a high degree of measurement accuracy will be required to ensure that compliance with these limits can be reliably monitored.

The accuracy with which these measurements must be made is also defined in the IEC standard which states that the error shall be less that 5% of the measured harmonic level for harmonics greater than 1% and be less than 0.05% of nominal voltage for harmonic less than 1%. To meet this accuracy requires that the instrument transformer providing the voltage signal used for the harmonic measurements also meets or exceeds these accuracy requirements for all harmonics up to the 50th rank.

Grid Connections and Harmonic Data

As an illustration of the importance of understanding the harmonic profile of a transmission network consider the situation where a grid operator has to write a specification for the connection of a large off-shore wind farm to its 220 kV network. Large wind farms and their associated interface equipment - often including SVC systems - are known to be significant sources of harmonics and may require harmonic filters to ensure compliance with the specified harmonic limits. Upon commissioning of the wind farm not only must the resulting harmonic levels at the connection point meet the requirements of the grid code but ideally they should also leave sufficient harmonic 'headroom' so that it will be possible to make additional connections in the future without exceeding the harmonic limits at that time. The new connection specification obviously cannot be prepared without a detailed knowledge of the existing transmission network harmonic profile which in turn will require accurate measurements of harmonic levels to be made.

Harmonic Surveys

Aside from the non-linear loads that generate the harmonic currents the level of harmonic voltage on the network is a function of the type and size of loads on the network and as a result will vary significantly due to the time of day, the day of the week and even the season. As a result, spot or short term measurements will often not give an accurate picture of the harmonic levels on the network. Furthermore, all transmission networks, to a greater or lesser extent, suffer from network resonances that also impact harmonic levels. That is to say that the impact of harmonic currents generated by non-linear loads is a function not only of the magnitude of the harmonic currents but also the network impedances at the given harmonic frequencies. These network impedances can change significantly as a result of the network configuration, the connected generating plant, capacitor bank and reactor status etc which in turn impact the voltage harmonic levels. As a result it is often necessary to make measurements over an extended period to gain a comprehensive picture of the network harmonic profile as ideally all combinations of loads and network configuration should be considered. In many cases permanent measurement is the best solution.

Voltage Signal Requirements

In order to measure the harmonic levels on a transmission network a suitable instrument transformer or equivalent device is required in the substation to provide a low voltage signal that can be used by the harmonic measurement device. It is important to note that this instrument transformer must have the bandwidth and accuracy to ensure that these signals can be measured to the accuracy specified in the IEC or IEEE standards - i.e. it must be able to measure all harmonics up to the 50^{th} with an error of less than 5%. The most common instrument transformers installed in transmission substations are Capacitor Voltage Transformers (CVTs) and Inductive or Wound Voltage Transformers (IVTs). The performance of these devices for making harmonic measurements will be discussed in detail later in this document suffice to say at this stage that it is generally accepted in the industry that both of these types of instrument transformer have significant limitations in harmonic measurement applications.

Resistor Capacitor Dividers

When required to make high accuracy harmonic or transient measurements many utilities often resort to the use of a Resistor Capacitor Divider (RCD). RCDs consist of a voltage divider made from a network of resistors and capacitors and when correctly installed, calibrated and matched to the measuring device will provide accurate measurements up to frequencies close to the megahertz range. While the accuracy of harmonic measurements made using an RCD is widely accepted they are most often used for short term measurements and special investigations. RCDs are not widely installed due to their cost and the fact that they are not ideally suited for use with protection relays. Also, they can suffer from calibration difficulties and stability issues.

The PQSensor™

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™ achieves this result by measuring the currents flowing the capacitor divider and Electromagnetic Unit primary circuits within the CVT. It then uses this data together with the known values of C1 and C2 in the CVT to produce an output signal that accurately reflects the CVT primary input voltage. The accuracy of the PQSensor™ exceeds the requirements for harmonic measurements as defined in the IEC and IEEE specifications.

PQSensor™ Accuracy

While the accuracy of the PQSensor™ can easily be demonstrated by applying Kirchoff's law and some basic mathematics its accuracy has also been validated using data from field measurements. In a recent installation a PQSensor™ and a calibrated

Figure 1 PQSensor™ v RCD

RCD were installed in parallel on a 138 kV busbar and harmonic measurements were made from both devices using identical harmonic monitors. Data was recorded for a 36 hour period. Figure 1 shows the correlation of the results from both signal sources (the PQSensor™ and the RCD) and it is clear that the worst case errors between the two measurements is significantly smaller than the accuracy limits defined in the IEEE standard confirming that the PQSensor™ is a viable solution for accurate harmonic measurements in transmission substations. By way of further evidence Figure 2 shows the results of a factory test where a PQSensor™ was injected with an input signal containing 0.1% of 5th, 9th, 19th ... 99th harmonics. It is clear that the PQSensor™ output faithfully tracks the input and that any error is a fraction of the limits specified by IEC.

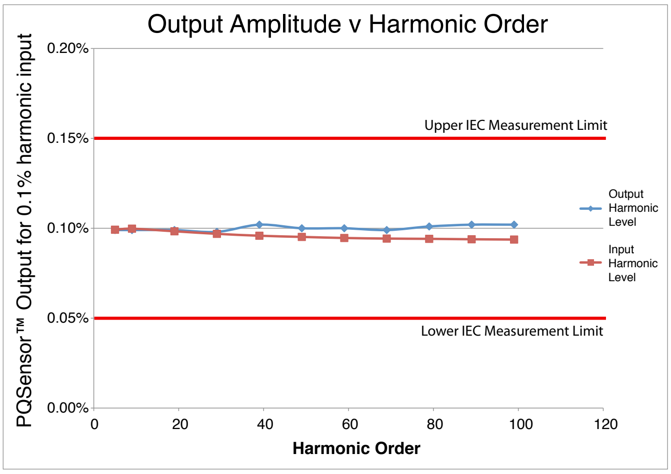

Figure 2 PQSensor™ Accuracy

CVT Performance

The majority of transmission substations are equipped with Capacitor Voltage Transformers (CVTs) and they are used to provide the voltage signals used by SCADA systems and protection relays.

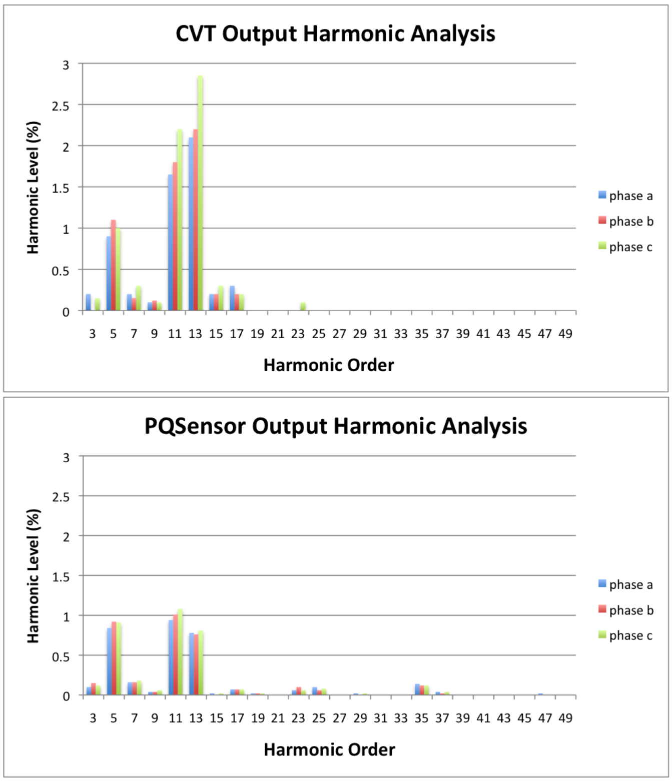

Figure 3

While CVTs 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 results in Figure 3 contrast the results from a PQSensor™ and a 132 kV CVT in a substation with a broad spectrum of harmonic voltages. In this case it is clear that the CVT overstates the values of the lower order harmonics - up to the 17th - but then does not detect the higher order harmonics that are clearly present and reported by the PQSensor™ .

Inductive or Wound Transformer Performance

The suitability of inductive or wound VTs for harmonic measurements can best be assessed by reviewing published frequency characteristics of these devices. The chart in Figure 4 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 graph in Figure 5 compares the error in data from a wound VT with a reference PQSensor™ where both devices were simultaneously monitoring voltage on the same busbar. For lower

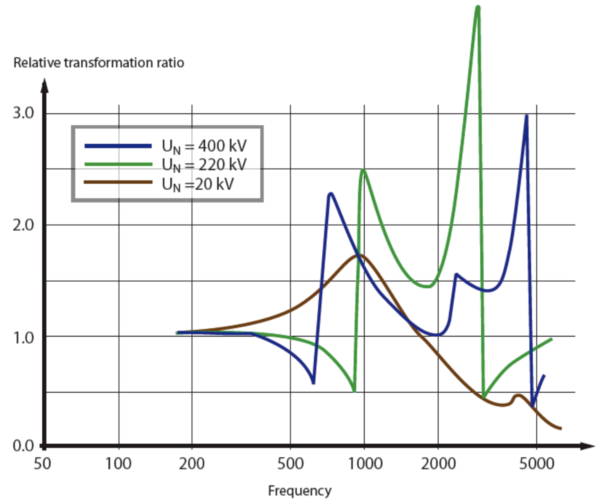

Figure 4 Wound VT Frequency Response - CIGRE WG 36

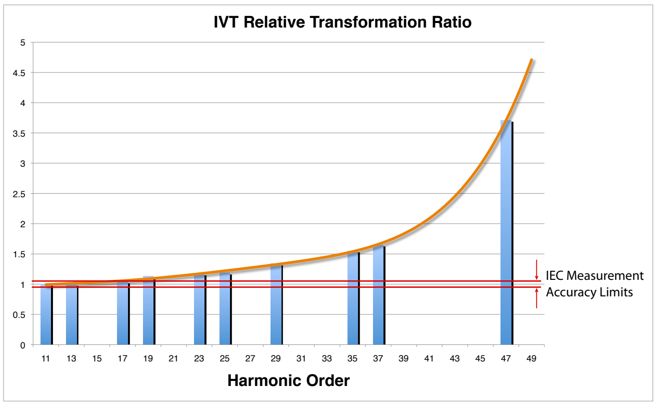

Figure 5 Wound VT performance v Reference PQSensor™

order harmonics the error is small but around the 17th harmonic the error exceeds the IEC limit and for higher harmonics the errors significantly exceed 100%. It is important to note that these results reflect the performance of the voltage transformer for one given burden only and the performance may change significantly of different values of output burden. The IEC error limits have also been shown on the graph for reference. It is clear from both the published frequency response curves and the measured voltage transformer performance results that the use of wound VTs for harmonic measurement has severe limitations.

Summary

The magnitude and propagation of voltage harmonics on a transmission network is not only a function of the non linear loads and the harmonic currents that they generate. It is also affected by network topology and resonances, connected generation and the loads supplied by the network.

To ensure compliance with Grid Code or IEC planning levels for network harmonics accurate monitoring up to the 50th harmonic is required - particularly on networks with HVDC, SVC and large wind farm connections.

Medium to long term measurement periods are often necessary to fully understand the harmonic profile of a network as all likely combinations of network configurations and loads should be considered. Permanent measurement of harmonics at selected nodes can often be the best solution.

When considering voltage sources for harmonic measurements it is clear that CVTs are totally unsuitable in all cirumstances. Inductive or wound voltage transformers are also subject to unacceptable errors above the 13th harmonic.

Voltage signal sources such as the PQSensor™ or a Resistor Capacitor Divider (RCD) should be considered when making HV or EHV harmonic measurements as the more traditional voltage sources do not meet the accuracy requirements as defined by IEC and most transmission utility grid codes.