Subgroup Report – Harmonics above 50th

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1 Existing standards/Literature

This section aims to review existing literature to find out if there are national or international standards mandating assessment on harmonics above 50th, and if they exist to which voltage levels they apply.

The ENA report [1], “Review of Engineering Recommendation G5/4-1 Stage 3 connections and higher order harmonics”, November 2012, by Andrew Bower doesn’t clearly conclude on the need or requirements for assessment of harmonics above 50th. The main conclusions are;

- At present (2012) there are no nationally or internally recognized limits for harmonic emissions above 50th order for HV and EHV systems. IEC 61000-2-12 only provides indicative limits for LV and MV networks (section 1.2).
- The current G5/4-1 uses Partial Weighted Harmonic Distortion (PWHD) for harmonics above 25th due to the difficulty in measuring accurately both the magnitude and the phase angle for these higher order harmonics (section 4.2). IEC 61000-3-12 uses the concept of PWHD and sets emission limits for LV equipment rated between 16A and 75A per phase.
- The IEC 61000-4-30 does not have provisions for harmonic orders beyond 50th. However, it provides an informative annex to cover measurements in the range 2kHz-150kHz which may be considered in the next revision of IEC 61000-4-30 (section 4.2.1).
- The results presented in ACE report 73 suggest that distribution network VTs and CTs begin to attenuate harmonics beyond 30th (section 4.2.3).
- Measurements may be made on equipment known to create higher order distortion at the device terminals and at locations further away in the network to assess to what extent the higher order harmonics actually propagate through the network (section 5.2.3). However, the report states that measuring devices may not have the informative requirements of 61000-4-7 to measure harmonics in the higher range (2kHz to 9kHz) implemented.
- There is a potential for developing evidence based (from a measurement campaign) compatibility limits based on the current network conditions for higher order harmonics. This campaign should if possible involve the wider DNOs in Europe via Eurelectric’s standardization Network Experts (sections 5.2.3 and 6.2.1)

Table 1 summarizes existing standards stating harmonic limits on emissions, on planning or on compatibility.

Table 1: Standards for design/planning limits

Standard	Region	Voltage range	Limits	Compatibility levels
ENA G5/4-1, ETR 122	UK	400V to 400kV	Planning limits up to 50th harmonic	Up to 50th harmonic
PD IEC TR 61000-3-6	UK/International	1kV and above	Planning limits up to 50th harmonic	Up to 50th harmonic
BS EN 61000-3-2	UK/International	220/380V, 230/400V and 240/415V	Current emission limits up to 40th harmonic	n/a
BS IEC 61000-3-4	UK/International	Up to 240V single phase, 600V three phase	Current emission limits up to 40th harmonic	n/a
BS EN 50160: 2010	UK/International	Up to 150kV	Individual **indicative** values up to 25th harmonic, THD value including frequencies up to 40th harmonic.	n/a
IEEE 519	USA/ International	120V to over 161kV	Up to the 50th harmonic (individual and THD)	n/a
IEC 61000-3-14	International	Up to 1kV	n/a	Compatibility limits up to 50th harmonic
BS EN 61000-2-12	UK/International	1kV to 35kV	n/a	Compatibility limits up to 50th harmonic

Table 2 summarizes existing standards for measurement equipment and measuring equipment installation.

Table 2: Standards for measuring equipment

Standard	Region	Harmonic Range	Comments
BS EN (IEC) 61000-4-7	International (IEC)	Up to 40th harmonic, 2kHz to 9kHz (annex as informative only)	The standard covers for harmonic measurements up to 40th and also provides an annex to cover harmonics from 2kHz to 9kHz.
BS EN (IEC) 61000-4-30	International (IEC)	2kHz to 150kHz	
CISPR 16-1-2	International (IEC)	9kHz to 100MHz	This standard covers the characteristics and performance of equipment for the measurement of radio disturbance voltages and currents from 9kHz to 100

Table 3: IEC 61000-3-6 planning and compatibility limits

Voltage level	Planning Level	Compatibility Level	Comments
LV: Un ≤ 1kV	No	Yes	Compatibility levels are same for LV & MV
MV: 1kV < Un ≤ 35kV	No	Yes	Compatibility levels are same for LV & MV MV has its own planning level
HV: 35kV<Un≤ 230kV	Yes	No	Planning levels are same for HV & EHV
EHV: Un > 230kV	Yes	No	Planning levels are same for HV & EHV

In IEC 61000-3-6, the above limits are defined up to 50th harmonic order.

As of today there is no standard establishing limits for emissions or planning levels in the frequency range 2kHz to 150kHz [2].

2 Product Survey of equipments emitting above 50th harmonic

This section provides emission spectrum either calculated or measured from AFE converters, WTG converters, SVCs and HVDCs.

2.1 AFE (IGBT) Inverters

Figure 1 to Figure 3 show emission spectrums (calculated) for different ratings of AFE inverters from a major supplier. The LV distortions are calculated at 400V with the PWM filter. The software calculates harmonics up to the 49th and for all inverter ratings harmonic emissions above 37th are either 0 or <0.1%. Typical industrial applications for AFE inverters are in conveyors, extruders, pumps and fans.

Figure 1: Emission spectrum (calculated) for an AFE inverter (1250kVA)

Figure 2: Emission spectrum (calculated) for an AFE inverter (630kVA)

Figure 3: Emission spectrum (calculated) for an AFE inverter (3150kVA)

2.2 Domestic Measurements

Figure 4 shows harmonic distortions measured at a suburban house for harmonics up to 2.5kHz. For the same period, Figure 5 shows the harmonics recorded above 2.1kHz. The distortions measured above 2.1kHz (42nd harmonic) are < 0.02%.

The following devices were in use during the measurements provided in Figure 4 and Figure 5.

Item	ON (Time)	OFF (Time)
Laptop Charger	19:08	-
LED Driver (cabinet lights)	19:11	-
Washing Machine Direct Drive Inverter	19:19	20:49
Dishwasher	19:12	-
TV	19:11	-
Microwave	19:24	19:25

Figure 4: Measurement at a domestic house (harmonics below 2.5 kHz)

Figure 5: LV measurement at a rural domestic house (harmonics below 2.1 kHz)

Figure 6 shows harmonic distortions measured at an office for harmonics up to 5kHz. The distortions measured above 2.5 kHz (50th harmonic) are <0.05%.

Figure 6: LV Measurements in an office

Figure 7 shows harmonic distortions measured at a domestic house for harmonics up to 5 kHz. The distortions measured above 2.5 kHz (50th harmonic) are <0.02%.

Figure 7: LV Measurements in a domestic house

2.3 Harmonic Emissions (WTG converters, PV inverters, HVDC converters)

2.3.1 WTG Converters

The graphs below show harmonic voltage emission spectrum from a 6MW WTG converter. Note that the vertical axis scaling is adjusted to show low order harmonics and for this reason 46th (6%) and 48th (12%) harmonics are clamped at 2.5%.

Figure 8: Harmonic voltage emissions from WTGs in the range 4MW to 6MW (before PWM filter)

2.3.2 PV inverters

Table 4 to Table 8 shows banded higher order current emissions (calculated) for different PV inverter ratings. These indicate very small current emissions above 50th harmonic. The emissions are measured with PWM filter that come with the inverter modules.

Table 4: Emission spectrum above 42nd harmonic - 250kW PV inverter

P [% of P_N]	10	20	30	40	50	60	70	80	90	100
f [kHz]	I_H [% of I_N]	I_H [% of I_N]	I_H [% of I_N]	I_H [% of I_N]	I_H [% of I_N]	I_H [% of I_N]	I_H [% of I_N]	I_H [% of I_N]	I_H [% of I_N]	I_H [% of I_N]
2.1	0.03	0.03	0.03	0.02	0.03	0.02	0.02	0.03	0.03	0.03
2.3	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
2.5	0.02	0.02	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.02
2.7	0.03	0.03	0.03	0.03	0.03	0.02	0.02	0.03	0.03	0.03
2.9	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
3.1	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
3.3	0.01	0.02	0.01	0.01	0.01	0.01	0.01	0.02	0.02	0.01
3.5	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
3.7	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
3.9	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
4.1	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
4.3	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
4.5	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
4.7	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
4.9	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
5.1	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
5.3	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
5.5	0	0.01	0	0.01	0.01	0.01	0.01	0.01	0.01	0
5.7	0	0	0	0.01	0.01	0.01	0.01	0.01	0.01	0
5.9	0	0	0	0.01	0.01	0.01	0.01	0.01	0.01	0
6.1	0	0	0	0.01	0.01	0.01	0.01	0.01	0.01	0
6.3	0	0	0	0.01	0.01	0.01	0.01	0.01	0.01	0
6.5	0	0	0	0.01	0.01	0.01	0.01	0.01	0.01	0
6.7	0	0	0	0.01	0.01	0.01	0.01	0.01	0.01	0
6.9	0	0	0	0.01	0.01	0.01	0.01	0.01	0.01	0
7.1	0	0	0	0.01	0.01	0.01	0.01	0.01	0.01	0
7.3	0	0	0	0.01	0.01	0.01	0.01	0.01	0.01	0
7.5	0	0	0	0	0.01	0.01	0.01	0.01	0.01	0
7.7	0	0	0	0	0.01	0.01	0.01	0.01	0.01	0
7.9	0	0	0	0	0.01	0.01	0.01	0.01	0.01	0
8.1	0	0	0	0	0.01	0.01	0.01	0.01	0.01	0
8.3	0	0	0	0	0	0	0	0.01	0.01	0
8.5	0	0	0	0	0	0	0	0.01	0.01	0
8.7	0	0	0	0	0	0	0	0.01	0.01	0
8.9	0.03	0.03	0.03	0.02	0.03	0.02	0.02	0.03	0.03	0.03

Table 5: Emission spectrum above 42nd harmonic - 500kW PV inverter

P [% of P_N]	10	20	30	40	50	60	70	80	90	100
f [kHz]	I_H [% of I_N]	I_H [% of I_N]	I_H [% of I_N]	I_H [% of I_N]	I_H [% of I_N]	I_H [% of I_N]	I_H [% of I_N]	I_H [% of I_N]	I_H [% of I_N]	I_H [% of I_N]
2.1	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04
2.3	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03
2.5	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
2.7	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04
2.9	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.04	0.04
3.1	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03
3.3	0.02	0.02	0.02	0.02	0.02	0.02	0.03	0.03	0.03	0.03
3.5	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.03	0.03
3.7	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
3.9	0.01	0.01	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
4.1	0.01	0.01	0.01	0.01	0.02	0.02	0.02	0.02	0.02	0.02
4.3	0.01	0.01	0.01	0.01	0.01	0.02	0.02	0.02	0.02	0.02
4.5	0.01	0.01	0.01	0.01	0.01	0.01	0.02	0.02	0.02	0.02
4.7	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.02	0.02
4.9	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.02	0.02
5.1	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.02	0.02
5.3	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.02	0.02
5.5	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.02	0.02
5.7	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.02	0.02
5.9	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.02	0.02
6.1	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.02	0.02
6.3	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.02	0.02
6.5	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.02	0.02
6.7	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.02	0.02
6.9	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.02	0.02
7.1	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.02	0.02
7.3	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.02	0.02
7.5	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.02	0.02
7.7	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.02	0.02
7.9	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.02	0.02
8.1	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.02	0.02
8.3	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.02	0.02
8.5	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.02	0.02
8.7	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
8.9	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04

Table 6: Emission spectrum above 42nd harmonic - 1000kW PV inverter

P_n [%]	0	10	20	30	40	50	60	70	80	90	100	110*	120*
f [kHz]	I_h [%]	I_h [%]	I_h [%]	I_h [%]	I_h [%]	I_h [%]	I_h [%]	I_h [%]	I_h [%]	I_h [%]	I_h [%]	I_h [%]	I_h [%]
2.1	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.05	0.05	0.05	0.05	0.05	0.05
2.3	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04
2.5	0.03	0.03	0.03	0.03	0.03	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
2.7	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05
2.9	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04
3.1	0.04	0.03	0.04	0.04	0.04	0.03	0.04	0.04	0.04	0.04	0.04	0.04	0.04
3.3	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03
3.5	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03
3.7	0.02	0.02	0.02	0.02	0.02	0.02	0.03	0.03	0.03	0.03	0.03	0.03	0.03
3.9	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.03	0.03	0.03	0.03	0.03	0.03
4.1	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.03	0.03	0.02	0.02
4.3	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
4.5	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
4.7	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
4.9	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
5.1	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
5.3	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
5.5	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
5.7	0.02	0.02	0.01	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
5.9	0.02	0.02	0.01	0.01	0.01	0.01	0.02	0.02	0.02	0.02	0.02	0.02	0.02
6.1	0.02	0.01	0.01	0.01	0.01	0.01	0.02	0.02	0.02	0.02	0.02	0.02	0.02
6.3	0.01	0.01	0.01	0.01	0.01	0.01	0.02	0.02	0.02	0.02	0.02	0.02	0.02
6.5	0.01	0.01	0.01	0.01	0.01	0.01	0.02	0.02	0.02	0.02	0.02	0.02	0.02
6.7	0.01	0.01	0.01	0.01	0.01	0.01	0.02	0.02	0.02	0.02	0.02	0.02	0.02
6.9	0.01	0.01	0.01	0.01	0.01	0.01	0.02	0.02	0.02	0.02	0.02	0.02	0.02
7.1	0.01	0.01	0.01	0.01	0.01	0.01	0.02	0.02	0.02	0.02	0.02	0.02	0.02
7.3	0.01	0.01	0.01	0.01	0.01	0.01	0.02	0.02	0.02	0.02	0.02	0.02	0.02
7.5	0.01	0.01	0.01	0.01	0.01	0.01	0.02	0.02	0.02	0.02	0.02	0.02	0.02
7.7	0.01	0.01	0.01	0.01	0.01	0.01	0.02	0.02	0.02	0.02	0.02	0.02	0.02
7.9	0.01	0.01	0.01	0.01	0.01	0.01	0.02	0.02	0.02	0.02	0.02	0.02	0.02
8.1	0.01	0.01	0.01	0.01	0.01	0.01	0.02	0.02	0.02	0.02	0.02	0.02	0.02
8.3	0.01	0.01	0.01	0.01	0.01	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
8.5	0.01	0.01	0.01	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
8.7	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
8.9	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02

2.3.3 SVCs

Figure 9 shows emission spectrum (calculated) from a true multilevel VSC based SVC converter. The converter rating is 125MVAr connected at 33kV. The SVC is without any dedicated filters connected.

Figure 9: Emissions (calculated) from a true multilevel VSC SVC (33kV connected/125MVAr)

Figure 10 shows the calculated current emissions directly from the TCR branch of a 135MVAr SVC/20kV. Usually the SVC will have a filter connected to the same busbar as the TCR. The current distortions are below 0.097% from 37th harmonics onwards.

Figure 10: Emissions (calculated) in the Thyristor Controlled Reactor (TCR) branch

2.3.4 HVDC converter (Multi level converter)

Figure 11 shows the harmonic voltage emission spectrum from a true multilevel (>300) VSC HVDC converter (400kV connected, 1000MW). The emission spectrum (calculated) shows a faint six pulse signature. The calculated voltage emissions above 50th harmonic are << 0.04%.

Figure 11: Emissions from a true multilevel VSC HVDC converter (400kV connected/1000MW)

The figures Figure 12 to Figure 15 below show current emissions from four VSC type HVDC suppliers.

Figure 12: Emissions spectrum from supplier A

Figure 13: Emissions spectrum from supplier B

Figure 14: Emissions spectrum from supplier C

Figure 15: Emissions spectrum from supplier D. Note that supplier D has no emissions above 25th harmonic.

3 Models and Measurements

Power system software packages are widely used for harmonic modelling and analysis. The outcome of such analysis is dictated by the accuracy of the models used to represent network elements. Similarly measurements rely on the accuracy of the transducers and monitors that collect them. This section highlights on models for some network elements, available transducers and monitors for harmonic measurements, and analysis of some historical data.

3.1 Electrical plant modelling

3.1.1 Transformer stray capacitance

Figure 16 shows part of a 33kV and 11kV distribution network. Frequency scans have been done looking at 33kV node (pink rectangle) and 11kV node (green rectangle).

Figure 16: Model of an actual distribution network

Figure 17 shows the frequency scans carried out in Power Factory without transformer stray capacitances for 132kV/33kV transformers and 33kV/11kV distribution transformers. The overhead lines and cables have been modelled using distributed parameters.

Figure 17: Frequency Sweep without Transformer Capacitance

In order to improve the high frequency effects of transformer model, stray capacitances are considered. These capacitances are equivalent capacitances of the transformer model provided in the Power Factory software package. Users have the possibility to enable them or disable them in the software.

Figure 18 shows the frequency scans with transformer stray capacitances enabled in the model. There is a significant difference in the impedance between the two modelling approaches.

Figure 18: Frequency Sweep with Transformer Capacitance

The table below shows typical stray capacitances for different transformer ratings [3]

MVA Rating	C_{hg} (nF)	C_{hl} (nF)	C_{lg} (nF)
1	1.2 – 14	1.2 – 17	3.1 – 16
2	1.4 – 14	1 – 18	3 – 16
5	1.2 – 14	1.1 – 20	5.5 – 17
10	4 – 7	4 – 11	8 – 18
25	2.8 – 4.2	2.5 – 18	5.2 – 20
50	4 – 6.8	3.4 – 11	3 – 24
75	3.5 – 7	5.5 – 13	2.8 – 30
100	3.3 - 7	5 - 13	4 – 40

3.1.2 Transformer resistance

Figure 19 shows different approaches used to represent resistance of a transformer. The results are for a 400/132kV, 200MVA transformer. At higher frequencies above 50th the difference in resistance is very significant. Since the reactance becomes dominant at high frequency, the magnitude of the impedance shown in Figure 20 is less impacted by the differences in resistance at high frequency.

Figure 19: Frequency dependent resistance – Cigre Model A and B

Figure 20: Frequency dependent impedance – Cigre Model A and B

3.1.3 Transformer actual scans

Figure 21 shows measured impedance versus frequency of a 200MVA, 400kV/132kV transformer. The impedance is measured from the 400kV side to the neutral point. There are multiple resonance points indicating the effect of stray capacitances.

Figure 21: Actual frequency scan of a 400kV/132kV auto transformer (phase A to neutral)

3.1.4 Cable modelling

There are various approaches to model the frequency dependency of cable resistance and reactance. They are listed below;

- CIGRE model, 1996
- IEC 60287 model
- CIGRE (WG B1.30 report 531) model, 2013

Figure 22 shows comparison of frequency dependent resistance calculated for an onshore 220kV cable using the above three modelling approaches. The graph labelling is “IEC cable resistance”- IEC 60287 model, “SINCAL cable resistance” -CIGRE model, 1996 and “Cable resistance –Bessel function” -CIGRE model 2013.

Figure 23 and Figure 24 show the inductance and impedance comparisons respectively.

Figure 22: 1600sqmm (220kV land cable) resistance vs frequency with different cable models

Figure 23: 1600sqmm (220kV land cable) inductance vs frequency with different cable models

Figure 24: 1600sqmm (220kV land cable) reactance vs frequency with different cable models

Different modeling approaches provide different resistance and reactance which can have a significant impedance difference in case of long AC cables.

It is noted suppliers provide frequency dependent information for cables using any of the above methods. These parameters are also affected by cable construction and cable laying arrangement.

3.1.5 Source representation

When using voltage or current distortions provided by supplier for harmonic assessment, sometimes the Thevenin or Norton impedances are not provided along with the distortions. Where such information is lacking this information should be obtained and represented in the harmonic model.

3.2 Measurements (monitors, transducers, site records)

3.2.1 Monitors

There are a number monitors available on the market for recording harmonic data. The following shows a comparison of these monitors

Table 7: Comparison of harmonic measuring equipment

PQ Monitor	Length of recording	Resolution of data capture	Harmonics range covered	Phase angle measurement	Sampling Rate
Metrum - PQ140	128MB	±0.05%	Up to 50th	No	2MHz
Draenetz - HDPQ	7 day survey gathers 10-12Mbytes of data, so with 4 Gigabytes of storage this will last for approx 6 years	±0.05%	Volt to 127th Current to 63rd	Yes and can display this in the Dranview Software	The HDPQ samples at 512 sample per second hence 35microseconds between the sample points, BUT it also runs a fast sampler of 1megasamples per cycle between these point – hence can capture a transient with a rise time of 1microsecond.
Eberle - PQ200	4GB	±0.05%	Up to 50th and then bands 2kHz to 9kHz according to IEC61000-4-7	Yes	2MHz
Outram - PM7000	128MB + USB Memory Stick	0.1Vac	Volt to 100th, current to 100th both = 50 each	No	1228.8kHz
INO 7650	Server req.	0.10%	Up to 63rd	No	51.2kHz
Fluke - 1738 PQ Monitor	128MB	±(0.02% +0.01%)	Up to 50th	No	10.24kHz

Pqube	Server req.	±0.05%	Up to 63rd	No	12.8kHz
Elspec - g4430	16GB or server	not stated	Up to 511th	No	51.2kHz
Unipower UP-2210			IEC 61000-4-30, Class A		
NGET own monitor	4GB (compact Portable) 16GB (Rack-Mount Permanent)	±0.05% U_{nom} ±0.15% I_{nom} (as per IEC 61000-4-7)	Up to 100th	Yes	25kHz

3.2.2 Transducers

ACE report 73 provides limitation on frequency response of existing VTs and CTs as provided in Table 8 [1].

Table 8: Indicative frequency response for existing VTs and CTs

Voltage Range	Device	Capability
≤66kV	Electromagnetic VTs	Up to 1500Hz (30th harmonic)
≥132kV	Capacitor Voltage transformers	Unsuitable tuned at 50Hz
≥132kV	Capacitor Voltage Divider	Suitable provided load impedance >10 times 50Hz impedance of bottom arm
<132KV	Wound ring core CT	1500Hz (30th harmonic)
275kV and 400kV	Large ring core Ct	Up to 10kHz (200th harmonic)

Work carried out at the University of Manchester on WVTs and CVTs also showed limitation of these types of VTs to measure high frequencies accurately [4]. The work concluded that 400kV WVT frequency response is limited to 500Hz (10th harmonic) and that of a 275kV CVT is limited to 200Hz (4th harmonic). The work also concluded that the connected burden has less impact on the frequency response of the WVT where as the burden significantly impacted on the frequency response of the CVT as shown in Figure 25 and Figure 26.

Figure 25: 400kV WVT frequency response under rated voltage with different burdens [4]

Figure 26: 275kV CVT frequency response under rated voltage with different burdens [4]

Figure 27 and Figure 28 show the frequency response of current and voltage transformers at present technology according to IEC 61869-103 [5]. The standard states (section 6.1) at present little experience is available very far from what would be needed in order to perform totally reliable power quality measurements. It further states the inductive instrument transformers up to now have been designed to have linear behaviour in the range of primary signal at rated frequency and outside these ranges their behaviour is not standardised.

Figure 27: Voltage transformer technology frequency range according to present experience [5]

Figure 28: Current transformer technology frequency range according to present experience [5]

A PQ CVT is a capacitive VT that uses two current sensing CTs. The CTs are connected in the neutral end of the main branch and the secondary branch. NGET TS 3.02.05 specifies the requirements for a CVT intended for power quality monitoring.

The PQ CVT offers a wider bandwidth than wound VTs and conventional CVTs. PQ CVTs are used at UK transmission systems for power quality measurements up to the 100th harmonic.

3.2.3 Recorded Measurements

3.2.3.1 Distribution Network

Figure 29 shows site records of harmonic measurements taken at a 33kV node in the network given in section 3.1.1 (pink box). The vertical axis shows the phase to ground voltage in percentages. The measurements indicate distortions exceeding 0.1% up to 11th harmonic. At harmonics above 50th the recoded distortion is < 0.045%.

Figure 29: 33kV node measurements

Figure 30 shows site records of harmonic measurements taken at an 11kV node in the network given in section 3.1.1 (green box). The vertical axis shows the phase to phase voltage in percentages. The measurements indicate distortions exceeding 0.1% up to 11th harmonic. At harmonics above 50th, no distortions were recorded.

Figure 30: 11kV node measurements

3.2.3.2 Distribution network - Historical trends

Historical harmonic data taken at four 33kV nodes of Western Power Distribution network have been analysed to see the trend in harmonics above 2.1 kHz (42nd harmonic). The data is banded into 0.2 kHz. All the voltages provided are phase to phase voltages. This area of the network has a large number of PV farms but they do not have dedicated system filters other than the filters supplied with the PV modules.

The Table 9 shows the PVs connected to Pyworthy and North Tawton area.

Table 9: PVs connected to Pyworthy and North Tawton area

Generator type	Year	Capacity (MW)	Aggregated generation (MW)
PV	2012	5.0	5.0
PV	2013	3.5	8.5
PV	2014	3.2	
PV	2014	3.3	
PV	2014	18.0	
PV	2014	10.0	
PV	2014	5.0	48
PV	2015	5.0	
PV	2015	5.0	
PV	2015	7.0	
PV	2015	7.0	72

Figure 31 shows the harmonic distortions at North Tawton in 2014, 2015 and 2016. The data shows increased harmonic distortions around 3.1kHz and 3.3kHz in 2014 and 2015 mainly due to PVs connected to the area. It is not clear why this was not observed in 2016 data. The magnitude of the voltage distortions above 3.3 kHz (66th harmonic) is < 10V (0.03%) in the analysed data.

Figure 31: 33kV historical data recorded at North Tawton

Figure 32 (a), (b) and (c) show the average daily profiles for North Tawton in May 2014, Nov 2015 and Nov 2016.

(a) NT May 2014 profile

(b) NT Nov 2015 profile

(c) NT Nov 2016 profile

Figure 32: North Tawton May 2014 (a), Nov 2015 (b) and Nov 2016 (c) daily profiles

Figure 33 shows the data at Pyworthy in 2014, 2015 and 2016. Similar to North Tawton, increased harmonic distortions are seen at 3.1kHz and 3.3kHz in 2014 due to PVs connected to the area. The difference in distortions at 3.1kHz and 3.3kHz in 2014 data compared to 2015 and 2016 could be due to difference in irradiance levels.

Figure 33: 33kV historical data recorded at Pyworthy

Figure 34 (a), (b) and (c) show the average daily profiles for Payworthy in May 2014, Nov 2015 and Nov 2016.

(a) PY May 2014 profile

(b) PY Nov 2015 profile

(c) PY Nov 2016 profile

Figure 34: Pyworthy May 2014 (a), Nov 2015 (b) and Nov 2016 (c) daily profiles

Figure 35 shows the data at St. Tudy for 2016. The data shows distortions at 3.1kHz and 3.3kHz of 42V (0.13%) and 61V (0.19%) respectively. The magnitudes of harmonic distortions above 66th are < 0.03%.

Figure 35: 33kV historical data recorded at St. Tudy

Figure 36 shows the average daily profile for ST Tudy in Nov 2016.

Figure 36: St Tudy 2016 daily profile

Figure 37 shows the data at Weston for 2013 and 2017. The data shows distortions at 2.7kHz (54th harmonic) of 0.15% in 2017 recorded data.

Figure 37: 33kV historical data recorded at Weston BSP

Figure 38 (a) and (b) show the average daily profile for Weston in Sep 2013 and Jan 2017.

(a) WE Sep 2013profile

(b) WE Jan 2017 profile

Figure 38: Weston Sep 2013 (a) and Jan 2017 (b) daily profiles

Figure 39 shows the distortions measured at the PV farm at 33kV level directly. The distortion measured at 2.5kHz is 0.12% and is < 0.09% for harmonics above 2.7kHz.

Figure 39: 33kV data recorded at PV farm connected Weston BSP

Figure 40 shows the average daily profile for the PV farm in Jan 2017.

Figure 40: PV farm April 2017 profile

3.2.3.3 Transmission Network

Figure 41 shows 400kV harmonic measurements from a 400MW wind farm. The reading is 20 days 95% values. The WTGs connected to the site have an emission spectrum shown in Figure 8. The measured distortions above 50th harmonic are << 0.1%. In addition to the WTG PWM filters, the site had its dedicated system filters at 132kV.

Figure 41: 400kV connected wind farm site records

Figure 42 shows harmonic measurements taken from a 12 pulse LCC type HVDC converter. The site has dedicated high pass filters. However, at the connection point distortions above 0.1% can be seen on some of the characteristics harmonics.

Figure 42: LCC type HVDC harmonic measurements

Figure 43: 95-Percentile over three and half months at Substation A- 400 kV, in south east Measurement through PQ-CVT (No HVDC connection in the close proximity)

Figure 44: 95-Percentile over four months at Substation B, 275 kV, in north Measurement through PQ-CVT (No HVDC connection in the close proximity)

Figure 45:95-Percentile over nine days at Substation C, 400 kV, in south west Measurement through PQ-CVT (No HVDC connection in the close proximity)

4 Practical cases on high order harmonic disturbances

4.1 In UK

There is a reported case of an onshore wind farm installation causing equipment malfunction due to 62nd harmonic voltage distortion. Following an investigation by the distribution network owner, filters were installed at the turbine which solved the problem.

4.2 International

A long term measurement campaign was carried (2012/2013) out in [5] at 25 sites measuring voltage distortions up to 40kHz. The paper states that high frequency distortions appeared to be a localised phenomenon that doesn't propagate far. No customer complaints have been known on the measurement networks associated with PV installations. The paper also stated that the EMC filter has a major influence on the resulting source behaviour of the inverter. The paper concluded by stating that grids with PV have elevated voltage distortions between 16kHz and 20kHz (PWM frequency being around 17kHz) during day time reaching up to 1V (0.43%). At night the levels are commonly as low as in grids without PV.

The paper also reports a practical case of LV equipment failure; noise from television, coffee maker failure, hair dryer control and periodic malfunction of a milling machine. The reported failures are within 200m of the each other. The source of the disturbance was identified as the mill itself. The mill used an inverter technology which was causing 8kHz distortions. The investigation showed that the mill was commissioned without an EMC filter. As a first mitigation, the factory feeder was moved to a different part of the grid. This solved the issues for all except for the malfunction of the milling machine itself. As a final solution, manufacturer specific filter was installed to stop malfunction of the milling machine.

4.3 Practicality of measurements on existing networks

The table below shows an indication on number of WVTs that may need to be replaced for a particular DNO area if the distribution networks were to monitor harmonics above 50th.

	No. of Sites Area 1	VT Count Approx		
		1	2	4
Count of Primary	325	325	650	
Count of BSP	44	44		176

	No. of Sites Area 2	VT Count Approx		
		1	2	4
Count of Primary	181	181	362	
Count of BSP	57	57		228

4.4 Contractual position

It is important that if recommendations are made to enforce harmonics above 50th harmonics then these should be indicative only. An example of a wording that could be used for harmonics above 50th are;

“The harmonic limits outlined in this document are indicative only. The limit values are based on “present art” and are subject to revision in the light of when future knowledge changes the state of “present art”

4.5 Applicable voltage levels

At present time there is some evidence of high order harmonics on the LV networks to a very low level. Some measurements have shown high frequency distortions far from harmonic sources. In relation to HV and EHV measurements there is evidence of high order harmonics which are also at a very low level. Therefore, when applying harmonics above 50th, it is difficult to exclude a specific voltage level.

5 Summary of conclusions

Based on the contents of the work presented, the following summary is made;

- Devices with much wider frequency spectrums are being connected to the network in increasing numbers. These devices have emissions in the frequency range well above 2.5 kHz.

- The accuracy of models used to represent the harmonic behavior of network elements is important. Various models available in the literature result in different outcomes of the harmonic assessment. The accuracy of these models becomes more important when considering harmonics above 50th as the differences becomes large at high frequency.

- The standards and literature suggests that present day technology on wound VTs and CTs have limited frequency response behavior. Depending on the voltage level, wound VTs have limited capability. Replacement of DNO VTs would have a significant cost and burden but this may be without a quantified need.

- There are a number of monitors available in the market capable of recording harmonics above 50th. However, this has to be looked at in the context of the transducer that feeds into the monitoring system.

- There is some evidence of high order harmonics on the LV networks but to a very low level at the present time. It is not clear whether these levels of high frequency harmonic penetration will increase proportionally with increased installations and if the emissions would propagate further from the source of the emissions in every case. Some measurements have shown high frequency distortions far from harmonic sources. In relation to HV and EHV measurements there is evidence of high order harmonics which are also at a very low level. However, when assessing the daily profile the high order harmonics magnitude correlates strongly with a PV generation profile.

- In order to manage future emissions on high frequency harmonics from installations, it may be relevant to consider a time frame for high frequency limits to be considered as indicative only. Sufficient time should be given to network operators to make changes to harmonic monitoring system. The cost of such changes versus the benefits it has to offer to the wider networks should be considered and justified.

- If limits on frequency above 50th harmonics are to be proposed either as recommendations or as indicative only, then the contractual position should be carefully considered. These come down to the accuracy of the models and transducers used to quantify whether compliance has been achieved or not.

References

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