Project NETWORK EQUILIBRIUM
Voltage Limits Assessment Discussion Paper

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Contents

Purpose of the Discussion Paper

This discussion paper summarises the findings of the work undertaken as part of the Voltage Limits Assessment task, which forms the 2nd part of the Enhanced Voltage Assessment method, and the key learning gained from the responses of various stakeholders to a VLA questionnaire and the open discussion at a VLA workshop held during the initial phase of the Network Equilibrium project.

A brief overview of the present voltage limits in 11kV and 33kV distribution networks is provided and focus is given on the key considerations regarding the potential amendment of these limits and the opportunities for change.

Glossary

Abbreviation	Full Term
AVC	Automatic Voltage Controller
BS / BSI	British Standards / British Standards Institution
DCRP	Distribution Code Review Panel
DNO	Distribution Network Operator
EN	European Norm
ER	Engineering Recommendation
ESQCR	Electricity Safety, Quality and Continuity Regulations
EVA	Enhanced Voltage Assessment
GCRP	Grid Code Review Panel
HV	High Voltage
IEC	International Electrotechnical Commission
LCN	Low Carbon Networks
LV	Low Voltage
LVNT	LV Network Templates
LTDS	Long Term Development Statement
MV	Medium Voltage
OHL	Overhead Line
PCC	Point of Common Coupling
RMS	Root Mean Square
RVC	Rapid Voltage Change
VLA	Voltage Limits Assessment

1 Introduction

This discussion paper is one of the knowledge dissemination documents produced through the course of the Network Equilibrium project[1] and aims to capture the learning from the Voltage Limits Assessment (VLA) work performed.

The Network Equilibrium project is a Tier 2 Low Carbon Networks (LCN) project that was awarded funding by Ofgem in 2014. The focus of the project is to "*balance voltages and power flows across the distribution system*", ultimately aiming to "*integrate additional distributed generation within electricity networks more efficiently and deliver major benefits to distribution customers*". It is proposing an analytical study and three innovative methods to tackle the problem of the infrastructure reaching thermal and voltage limits associated with the proliferation of renewable energy systems and load growth.

VLA is the analytical study and includes a theoretical investigation into whether steady-state statutory voltage limits and voltage step change limits for the 11kV and 33kV networks could and should be amended. The investigation assesses the rationale for the existing limits, assesses if the validity of the original assumptions remains and also explores any potential barriers to future amendments to the limits, stemming either from Distribution Network Operators' (DNO) and customer equipment or any commercial, safety or customer reasons.

Based on the investigation, VLA creates a basis of recommendations regarding amendments to voltage limits (the statutory steady-state supply voltage limits and voltage step change limits) and proposes further actions that need to be taken as part of future evaluations.

It is recognised that parts of the UK network operate at 6.6kV instead of 11kV, but the two voltage levels relate closely in terms of planning and operation. Therefore, despite the VLA investigating the 11kV systems, the observations and conclusions could, in broad terms be associated with 6.6kV systems.

The examination of changes to statutory Low Voltage (LV) limits is not in the scope of Network Equilibrium. However, for completeness, the VLA reviewed the status of LV voltage tolerances and investigated the possible impact on LV of any changes implemented at Medium Voltages (MV) (11kV and 33kV).

The discussion paper first provides some background on the existing statutory steady-state limits and voltage step change limits applicable in the UK and then presents the main findings of the review of barriers and the impact of changing voltage limits in the following sections:

[1] WPD Innovation, *Network Equilibrium*, [www.westernpowerinnovation.co.uk/Projects/Network-Equilibrium.aspx]

Section 5:	Manufacturing standards and equipment specifications.
Section 6:	Investigation of the potential impact of changing the steady-state or step change limits at 11kV and 33kV from a technical perspective
Section 7:	Consideration of the commercial impact of changing voltage limits.
Section 8:	Findings from the VLA questionnaire
Section 9:	Findings from the VLA workshop
Section 10:	Overall conclusions of the VLA study
Section 11:	Recommendations for the way forward

2 Background

In the UK, the present statutory steady-state supply voltage limits in the UK are set in the Electricity Safety, Quality and Continuity Regulations (ESQCR) of 2002[2], while Engineering Recommendation (ER) P28[3] defines the limits for voltage step changes.

The European Norm (EN) 50160 recommends limits for the steady-state supply voltage variations and provides indicative values for Rapid Voltage Changes (RVC) of the supply voltage from the perspective of network performance. EN 50160 has been adopted by the UK through the British Standards Institution (BSI)[4].

Parts of the UK network operate at 6.6kV instead of 11kV, but the two voltage levels relate closely in terms of planning and operation. Therefore, despite the VLA only investigating 11kV systems, the observations and conclusions could, in broad terms, be associated with 6.6kV systems.

2.1 Steady-State Supply Voltage Limits

In the UK, the statutory limits related to steady-state operation of 11kV and 33kV networks are ±6% of the nominal voltage. However, assessment of compliance is not explicitly mentioned in the ESQCR.

For the same voltage levels, the respective limits suggested in EN 50160 are ±10% of the supply voltage. EN 50160 looks at the limits from a network performance perspective and adopts a probabilistic methodology for monitoring compliance. EN 50160 can be interpreted as representing a compromise between the three parties that exert an influence on the power quality of supply voltage, i.e. the network operator, the network

[2] Statutory Instruments, *The Electricity Safety, Quality and Continuity Regulations 2002*, No. 2665 (Crown, 2002)

[3] Energy Networks Association, *Engineering Recommendation P28 1989: Planning limits for voltage fluctuations caused by industrial, commercial and domestic equipment in the United Kingdom* (2003 Energy Networks Association)

[4] British Standards Institution, *BS EN 50160:2010 – Voltage characteristics of electricity supplied by public electricity networks* (BSI, 2011)

users and the manufacturer of equipment. As a consensus-driven standard, with equal representation from all countries, it reflects the lowest common agreed-upon values for power quality limits.

Table 1: Steady-state Supply voltage limits for 11kV and 33kV networks in the UK and EU

UK – ESQCR 2002 (statutory)	EU – EN 50160:2010
±6% of declared voltage (no time requirement defined)	±10% of U_C (declared supply voltage) 99% of 10-minute mean values over a week **PLUS** ±15% of U_C 100% of time

2.1.1 Rationale

The rationale behind the setting of the statutory limits in the UK is difficult to establish, but anecdotal evidence dating back to the 19th century point towards electrical machinery standards and voltage drop allowances for MV networks of the time.

As for European standards, the rationale appears to be based on establishing harmonisation and on the ability of existing systems to operate without significant change.

2.2 Voltage Step Change Limits

2.2.1 UK Limits

In the UK, voltage step changes are generally distinguished by event predictability and are classified into two types with different limits applying to each type. The first type is planned switching events or outages and the second is unplanned outages, such as faults.

Frequent and infrequent planned voltage fluctuations are defined in ER P28, with a maximum limit of ±3% applying to these voltage step changes at the Point of Common Coupling (PCC). ER P28 is a planning standard that provides design limits applicable to system users.

The Distribution Code of Great Britain[5] stipulates the same limit for the above cases, but also allows designs to be based upon a voltage step change of ±10% for unplanned events and for energisations of sites with multiple transformers, if they occur less frequently than once a year. The Distribution Code is a licence obligation with which the DNOs have to comply, so it takes precedence over ERs if there is conflict.

[5] Distribution Code Review Panel, *The Distribution Code and the Guide to the Distribution Code of Licensed Distribution Network Operators of Great Britain* (Issue 25, November 2014)

Voltage step change limits are currently undergoing review by the ER P28 Working Group (WG), which is leading a UK industry-wide consultation process, expected to conclude by the end of 2016.

Table 2: Voltage step change limits for 11kV and 33kV networks in the UK

UK – Distribution Code		UK – ER P28	
Maximum Number of Occurrences (n)	**Limits**	**Maximum Number of Occurrences (n)**	**Limits**
n > 1 per 10 minutes	<3% (see P28 flicker limit)	n > 1 per 10 minutes	<3% (see P28 flicker limit)
n > 1 per year AND not > 1 per 10 minutes	3%	n > 1 per several months AND not > 1 per 10 minutes	3%
n ≤ 1 per year	10%	n ≤ 1 per several months	DNO discretion

2.2.2 EU Limits

In Europe, EN 50160 defines voltage change events at the supply terminals including RVCs, flicker and supply voltage dips/swells. For an event to be characterised as an RVC, the supply voltage during the change should not drop below 90% or go higher than 110% of the reference voltage. If these thresholds are exceeded, the event is characterised as a voltage dip or swell respectively.

Voltage dips, swells and RVCs do not have explicit performance limits, but only indicative values given in Annex B of EN 50160. At MV, indicative values for RVCs range between 4% and 6%.

Table 3: Indicative values of RVC limits for 11kV and 33kV networks in the EU

EU – EN 50160:2010	
Maximum Number of Occurrences (n)	**Limits (Indicative)**
	$\Delta V/U_C$
Unspecified	≤4%
Some times per day	≤6%

2.2.3 Rationale

The limits in ER P28 are based on laboratory tests and field experience. Identifying and minimising the risks of customer disturbance from excessive flicker was the main rationale behind the setting of those limits.

Certain national standards adopted by European countries stipulate a maximum limit of 10% for voltage change events of limited duration. The literature survey shows that this limit does not jeopardise the immunity characteristics of equipment and industrial processes supplied by the public network.

3 Review of Equipment Limitations

3.1 Manufacturing Standards

The review of manufacturing standards was focussed on the voltage withstand characteristics and allowable voltage variations for a wide range of distribution equipment suitable for connection at 11kV and 33kV. This included switchgear, generators and motors, transformers and tap changers, other distribution system plant such as overhead equipment, lines and cables, network measurement and metering equipment.

The two types of rated voltages that are of particular interest for the purpose of the VLA study are defined typically as:

- The highest voltage for equipment U_m, or rated voltage U_r, for most equipment types
- The standard rated short-duration power frequency withstand voltage, or U_d, for most equipment types

U_m is defined as the highest value of phase-to-phase RMS voltage for which the equipment is designed in respect of its insulation as well as other characteristics. This voltage can be applied continuously to the equipment, under normal service conditions. U_d is defined as a sinusoidal voltage with frequency between 48Hz and 62Hz and duration of 60sec.

It is acknowledged that equipment manufactured before some of the standards referenced in subsequent sections may still be operating in today's networks. In all cases, standards as far back as readily available were reviewed.

3.1.1 Insulation co-ordination

British Standard BS EN 60071-1:2006+A1:2010 "*Insulation co-ordination Part 1: Definitions, principles and rules*" is the UK implementation of EN 60071-1:2006+A1:2010. It is identical to IEC 60071-1:2006, incorporating amendment 1 of 2010[6].

Part 1 of this standard applies to three-phase AC systems having a highest voltage for equipment above 1 kV. It specifies the procedure for the selection of the rated withstand voltages for the phase-to-earth, phase-to-phase and longitudinal insulation of the equipment and the installations of these systems. It also gives the lists of the standard withstand voltages from which the rated withstand voltages should be selected.

[6] British Standards Institution, *BS EN 60071-1:2006+A1:2010 – Insulation co-ordination - Part 1:Definitions, principles and rules* (BSI, 2010)

The standard states that the selected withstand voltages should be associated with the "highest voltage for equipment" (U_m). Under normal service conditions, specified by the relevant apparatus committee, this voltage can be applied continuously to the equipment. The association with the U_m voltage is for insulation co-ordination purposes only and does not relate to human safety of equipment during operation.

The values of standardised U_m are listed in Table 2 of the standard (see Figure 1 below). 12kV RMS rated voltage is specified for systems with nominal voltage of 11kV and 36kV RMS rated voltage for systems of 33kV nominal.

The standard short-duration power frequency voltage is defined as a sinusoidal voltage with frequency between 48Hz and 62Hz, and duration of 60sec. The values of standard rated short-duration power frequency withstand voltages are defined in clause 5.6 and in Table 2 of the standard (see Figure 1 below). The 28kV RMS withstand voltage is specified for equipment rated at 12kV and the 70kV RMS withstand voltage for equipment rated at 36kV.

Highest voltage for equipment (U_m) kV (r.m.s. value)	**Standard rated short-duration power-frequency withstand voltage** kV (r.m.s. value)	**Standard rated lightning impulse withstand voltage** kV (peak value)
3,6	10	20 40
7,2	20	40 60
12	28	60 75 95
17,5 [a]	38	75 95
24	50	95 125 145
36	70	145 170
52 [a]	95	250
72,5	140	325

Figure 1 Standard insulation levels in BS EN 60071-1:2006+A1:2010 (up to Um =72.5kV)

Previous versions, BS EN60071-1:1996 and BS 5622-1:1979, specified the same values.

3.1.2 Switchgear Plant

BS EN 62271-1:2008+A1:2011 "*High-voltage switchgear & controlgear – Part 1: Common specifications*"[7] applies to AC switchgear and controlgear designed for indoor and

[7] British Standards Institution, *BS EN 62271-1:2008+A1:2011 – High-voltage switchgear & controlgear – Part 1: Common specifications* (BSI, 2011)

outdoor installation and for operation at service frequencies up to and including 60Hz on systems having voltages above 1kV. This standard applies to all HV switchgear and controlgear except as otherwise specified in the relevant IEC standards for the particular type of switchgear and controlgear.

Clause 4.1 of the standard stipulates the definition of the rated voltage (U_r). It indicates the maximum value of the “highest system voltage” of networks for which the equipment may be used. Reference is also made to Clause 9 of IEC 60038.

Standard values of rated voltages within Series I are 3.6kV, 7.2kV, 12kV, 17.5kV, 24kV, 36kV, 52kV, 72.5kV etc.

So, typically for equipment operating on 11kV and 33kV networks, rated voltages of 12kV and 36kV are selected. This represents a rating for equipment that is higher by approximately 9% than the nominal system voltage.

Clause 4.2 is concerned with the selection of rated insulation levels, i.e. the rated withstand voltage values for lightning impulse voltage (U_p), switching impulse voltage (U_s) (when applicable), and power frequency voltage (U_d). An extract from Table 1a of the standard, where the above values are presented, is given in Figure 2 below with focus on the power frequency voltage levels.

As seen, for the rated voltages of 12kV and 36kV, short-duration power frequency withstand voltages of 28kV and 70kV are stipulated respectively as “common values”. These refer to application of voltage over a period of 1 minute. The common values refer to voltages which are phase-to-earth, between phases and across the open switching device.

Rated voltage U_r kV (r.m.s. value)	Rated short-duration power-frequency withstand voltage U_d kV (r.m.s. value)	
	Common value	Across the isolating distance
(1)	(2)	(3)
3,6	10	12
7,2	20	23
12	28	32
17,5	38	45
24	50	60
36	70	80
52	95	110
72,5	140	160

Figure 2: Rated insulation levels for rated voltages of range I, series I in BS EN 62271-1 (up to Um = 72.5kV)

Previous standards, such as BS EN 62271-2008, BS EN 60694:1997 and BS 6581:1985, specified the same voltages. Before these, BS 162:1961 titled "*Specification for electric power switchgear and associated apparatus*" specified that for 11kV rated switchgear assemblies a power frequency voltage of 27kV for 1 minute should be applied during a test at the manufacturer's premises, whereas for 33kV rated switchgear assemblies a power frequency test voltage of 76kV should be applied for 1 minute.

3.1.3 Rotating Electrical Machines

BS EN 60034-1:2010 stipulates requirements for the rating and performance of rotating electrical machines, including generators and motors[8]. With respect to rated voltages and for ratings higher than 1kV, AC machines are classified into various bands of preferred ratings in this standard, ranging between 1kV and 15kV.

Electrical operating conditions are detailed in Clause 7 of the standard and the form and symmetry of supply voltages and currents are defined for AC motors, AC generators, synchronous machines and DC motors supplied from static power converters.

Section 7.3 of the standard is concerned with voltage variations during operation of both AC and DC machines. For AC machines rated for use on a power supply of fixed frequency supplied from an AC generator (whether locally or via a supply network), combinations of

[8] British Standards Institution, *BS EN 60034-1:2010 – Rotating electrical machines Part 1: Rating and performance* (BSI, 2010)

voltage variation and frequency variation are classified as being either zone A or zone B, in accordance with Figure 3 below. The plot on the left applies to generators and synchronous condensers, while the one on the right applies to motors.

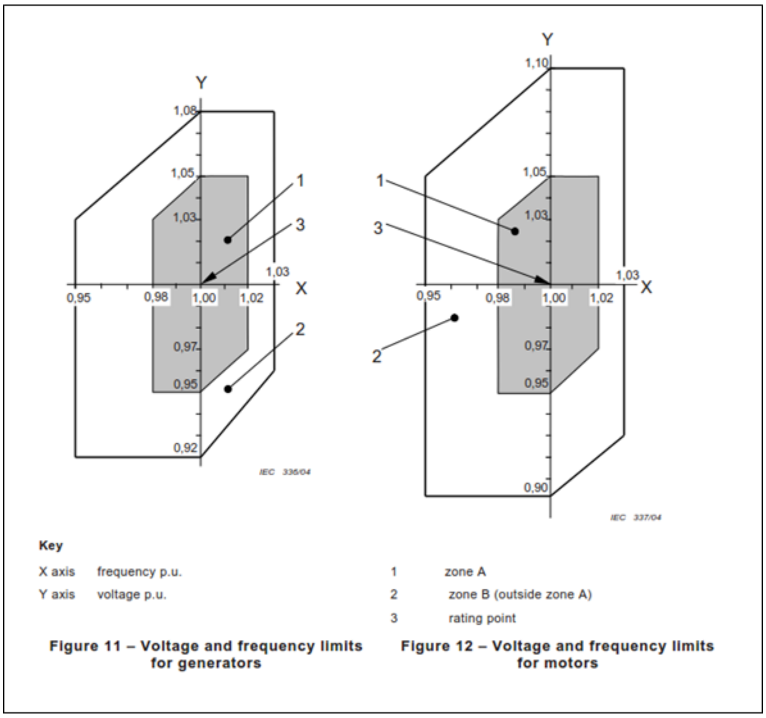

Figure 3: Voltage and frequency limits for generators and motors in BS EN 60034-1

A machine needs to be capable of performing its primary function continuously within zone A, but need not comply fully with its performance at rated voltage and frequency (rating points in Figure 3), and may exhibit some deviations. Temperature rise may be higher than at rated voltage and frequency. It shall also be capable of performing its primary function within zone B, but may exhibit greater deviations from its performance at rated voltage and frequency than in zone A. Temperature rise will most likely be higher than those in zone A. Extended operation at the perimeter of zone B is not recommended.

Therefore, it can be observed that for generators operating at nominal frequency, the voltage variations for operation within zone A are between 0.95pu and 1.05pu (i.e. ±5%). This range is extended to 0.92pu – 1.08pu (i.e. a voltage tolerance of ±8%) for operation within zone B, but it is not recommended to operate a generator at the extreme limits of this voltage range. The lower voltage limit is more onerous for operation at higher frequencies, while the same applies for the higher voltage limit at low-frequency operation.

The operating range for motors is exactly the same as for generators when it comes to operation within zone A, but the allowable voltage tolerance for zone B operation is wider (0.90pu – 1.10pu, i.e. a ±10% tolerance).

The standard does not make reference to any operation of generators and motors outside of the limits of zone B, therefore these limits could be interpreted as absolute in terms of system voltage variations.

Connections of rotating machines to the 11kV or 33kV network could be through a transformer or static converter, as is the case for wind farm generators or motors operating at lower voltages. In such cases, LV voltage limits are applicable rather than 11kV or 33kV limits

The 2010 version of BS EN 60034 was derived by CENELEC from IEC 60034 1:2010 and supersedes BS EN 60034 1:2004, which was withdrawn in 2013. The same requirements regarding voltage and frequency variations, as detailed above, were also stipulated in that standard, as well as in the 1998 and 1995 versions.

3.1.4 Transformers

BS EN 60076-3:2013[9] details the standard test voltages for power transformers according to the phase-to-phase "highest voltage for equipment applicable to a transformer winding" (U_m). The U_m is selected as the value equal to or nearest above the value of the rated voltage of the windings. For example, for a 33/11kV transformer the U_m values of the two windings would be 36kV and 12kV respectively.

The standard does not explicitly define U_m in terms of duration of application or operating conditions, but it might be fair to assume that it follows the definition in BS EN 60071-1.

For transformers with $U_m \leq 72.5$kV, the Applied Voltage (AV) test is one of the routine tests that verifies the alternating voltage withstand capability of line and neutral windings. It is applied for 60 seconds on each separate winding in turn and can be considered as the counterpart of the power frequency test specified in the latest BS EN 60071-1. Typical AV test voltages for 11kV and 33kV windings are 28kV (or 34kV) and 70kV respectively.

In its previous issues in 1970 and 1959 similar power frequency test voltages were specified. The 1959 and 1970 versions specified other power frequency withstand voltages for transformers that were not designed to undergo an impulse voltage test, such as dry type transformers; the power frequency test voltage was 25kV and not 28kV as for the other types.

[9] BS EN 60076-3:2013, *Power transformers. Insulation levels, dielectric tests and external clearances in air* (BSI, December 2013)

3.1.5 Tap Changers

Standard BS EN 60214-1:2014[10] specifies the requirements for on-load and off-circuit tap changers. U_m is defined as the highest phase-to-phase voltage in a three-phase system for which the tap changer is designed with respect to its insulation. As with power transformers, the duration of the application of such a voltage and the operating conditions under which this might occur are not explicitly defined. The U_m values of tap changers are the same as the ones in the power transformers standard, i.e. 12kV for 11kV nominal and 36kV for 33kV nominal voltage.

Test voltages in BS EN 60214-1:2014 are based on the transformer standard BS EN 60076-3:2013 and are the highest given test voltages per U_m. Therefore, the AV test voltage is 34kV for 11kV tap changers and 70kV for 33kV tap changers for duration of 60sec. These values apply to both on-load and off-circuit tap changers.

3.1.6 Overhead Equipment

3.1.6.1 Overhead Lines (OHL)

Standard BS EN 50341-1:2012 specifies the general requirements for transmission and distribution OHL of 1kV AC or higher. For GB and Northern Ireland, it is supplemented by BS EN 50341-2-9:2015, which details the pertinent National Normative Aspects (NNA). It uses the term “highest voltage for equipment” (U_m) for the insulation levels of insulators and other equipment connected to OHL. In juxtaposition with IEC 60038:2009 it can be derived that for nominal system voltages (U_n) of 11kV and 33kV, the U_m values are 12kV and 36kV respectively.

Overhead line insulators are tested for their power frequency withstand voltage levels under wet conditions. Different standards apply to the different insulator types and materials, for example BS EN 60383-1:1998 for ceramic and glass insulator units and BS EN 61109:2008 for composite suspension and tension insulators.

3.1.6.2 Surge Arresters

BS EN 60099-4:2014 details the requirements and testing conditions for metal-oxide, gapless surge arresters that are applied to systems with U_s above 1kV. Other parts of BS EN 60099 cover other types of surge arresters. BS EN 60099-5:2013 provides information and guidance on the selection and applications of surge arresters.

Surge arresters’ characteristic voltages are defined in a relatively unique manner and are not to be directly compared with similar definitions of other types of equipment. Their rated voltage (U_r) is one of the fundamental parameters and it is the maximum voltage that the surge arrester can withstand for 10sec. The continuous operating voltage (U_c) is

[10] BS EN 60214-1:2014, Tap-changers. Performance requirements and test methods, (BSI, September 2014)

defined as the voltage that can be continuously applied between the surge arrester terminals. Typical values are not provided.

The above voltages are associated with the surge arrester's internal parts and are used during operating duty tests that determine the capability to recover after the injection of thermal energy or thermal charge. Insulation withstand tests are separate and determine the withstand capability of the external insulation of the arrester housing.

3.1.7 Cables

IEC 60183[11] gives guidance on the selection of AC high-voltage cables and cable systems with extruded insulation, to be used on three-phase alternating systems, operating at voltages exceeding 1kV (in this standard the term "high voltage" is used to cover any cables above 1kV).

The voltages pertaining to the cable and its accessories are defined as follows:

- U_0 = the rated RMS power frequency voltage between each conductor and screen or sheath for which cables and accessories are designed
- U = the rated RMS power frequency voltage between any two conductors for which cables and accessories are designed
- U_m = the maximum RMS power frequency voltage between any two conductors for which cables and accessories are designed. It is the highest voltage that can be sustained under normal operating conditions at any time and point in a system.

Based on the above, cables are designated by U_0 / U (U_m), for example 19/33 (36)kV, in order to provide guidance on the compatibility with switchgear and transformers. The critical value of voltage for the selection and applicability of a particular cable type for operation within a specified system (under normal operating conditions) is U_m. Clause 4.3 stipulates that this voltage should be chosen to be equal to or greater than the highest voltage of the three-phase system.

Figure 4 below shows the relationship between U_0/U and U_m. It can be seen that the U_m voltage levels up to 72.5kV are identical to the ones stipulated in BS EN 60071 (Figure 1).

[11] International Electrotechnical Commission, *IEC 183:1984+A1:1990 – Guide to the selection of high-voltage cables* (CEI 1990)

Rated voltage of cables and accessories (U_0/U kV)	Highest voltage for equipment (U_m kV)
1.8/3 and 3/3; 1.9/3.3 and 3.3/3.3	3.6
3.6/6 and 6/6; 3.8/6.6 and 6.6/6.6	7.2
6/10 and 8.7/10; 6.35/11 and 8.7/11	12
8.7/15	17.5
12/20; 12.7/22	24
18/30; 19/33	36
26/45; 27/47	52
38/66; 40/69	72.5
63.5/110; 66/115	123
76/132; 80/138	145
87/150; 93/161	170
127/220; 133/230	245
159/275; 166/287	300
190/330; 200/345	362
220/380; 230/400	420
290/500	525
405/700; 430/750	765

Figure 4: U0, U and (Um) values in IEC 60183:1984+A1:1990

IEC 60502 2:2005 relates to power cables with extruded insulation and their accessories for rated voltages from 6kV (Um = 7.2kV) up to 30kV (Um = 36kV).

Table 1 of that standard associates the recommended rated voltages of cables (U_0) with the highest system voltages (U_m) as per Figure 4 above for three categories of systems operated with different earth fault clearing times. For the most common categories A and B, a rated voltage U_0 equal to 6kV is recommended for a U_m of 12kV and a U_0 of 18kV is recommended for a U_m of 36kV. IEC 60502 2:2005 also specifies a 5 minute routine test at ambient temperature at a voltage of 3.5Uo for single core cables and 3.5Uo x 1.73 for three core cables. The same rated voltages, routine tests and test voltages are specified in IEC 60502 2:1997+A1:1998.

BS 6622:2007, which considers armoured cables with thermosetting insulation, specifies that for cables rated 6.35/11 (12)kV and 19/33 (36)kV the routine voltage tests on complete lengths of cables should be carried out for 15 minutes at voltages of 25.5kV and 76kV respectively between the conductors and the earthed metallic screens. The same test voltages for the same duration were defined in BS 6622:1999. Different voltages and time requirements were specified in the preceding version BS 6622:1991. The test voltage had to be applied for only 5 minutes and it was 15kV single phase for 6.35kV rated cables and 45kV single phase for 19kV rated cables. It appears that these were not changed from the previous version BS 6622:1985.

3.1.8 Network Measuring Equipment

The IEC 61869 series of standards specifies the requirements for the operation of various types of instrument transformers, including Current Transformers (CTs), Voltage Transformers (VTs), Capacitor Voltage Transformers (CVTs) and combined transformers. Electronic VTs and CTs are specified in IEC 60044 Parts 7 and 8 respectively.

According to BS EN 61869-1:2009, the rated primary insulation level for instrument transformers shall be based on the "highest voltage for equipment" (U_m) value, which under normal environmental conditions should be at least equal to the "highest system voltage" (U_s). For instrument transformers rated at U_m = 12kV, the rated power frequency withstand voltage is 28kV, while for those rated at U_m = 36kV, the rated power frequency withstand voltage is 70kV. The duration of the test for the power frequency withstand voltage of the primary terminals is 1 minute and it is considered a routine test.

3.1.9 Control and Metering Equipment

BS EN 62052 Part 11 specifies the general requirements, tests and test conditions for AC electricity metering equipment[12]. The standard is identical to IEC 62052-11:2003.

Standard reference voltages for meters range between 120V and 480V for direct connection and between 57.7V and 230V for connections through voltage transformers.

Clause 7.1 defines the electrical requirements regarding the influence of supply voltage. A specified operating range of $0.9U_n – 1.1U_n$ is stated (where U_n is the reference voltage), which is defined as the range of voltage which forms a part of the rated operating conditions. The extended operating voltage range is set as $0.8U_n – 1.15U_n$ and describes extreme conditions that an operating meter can withstand without damage and without degradation of its metrological characteristics when it is subsequently operated under its rated operating conditions. For this range, relaxed accuracy requirements may be specified.

3.2 Equipment Specifications

A large number of equipment specifications and operational manuals was provided by WPD and reviewed with respect to their voltage withstand characteristics. The specifications covered a range of age profiles and, in various cases, made references to historical manufacturing British Standards, which have now been superseded.

Particular focus was given on the rated voltage for equipment (or the highest continuous voltage that the equipment can withstand) and the short duration power frequency voltage, i.e. the RMS voltage which the equipment can withstand for 1 minute or longer.

It was found that the equipment that was examined was in accordance with the UK manufacturing standards that were applicable at the time, which by and large have not changed significantly. For some of the equipment, ANSI standards were referenced that provided higher values of rated voltages or power frequency withstand voltages for 11kV and 33kV equipment.

Despite the fact that the majority of equipment fall into similar ranges of rated voltage and voltage withstand levels, it is recommended that the dedicated standards for the

[12] British Standards Institution, *BS EN 62052-11:2003 – Electricity metering equipment (AC) – General requirements, tests and test conditions – Part 11: Metering equipment* (BSI 2003)

different types of equipment are consulted, since discrepancies in definitions and test conditions might be encountered (e.g. with surge arresters).

4 Investigating the Impact of Changing Limits

Investigations of the impact of a potential amendment to the current statutory steady-state limits (ESQCR 2002) and the voltage step change limits were carried out.

In particular, a system study was undertaken to understand the potential extent of network (33kV and 11kV) that would be operating outside the current statutory limits, if the limits were to be changed in the future. Also, a preliminary exercise was undertaken that considered data collected during WPD's Low Voltage Network Templates (LVNT) project as an example and that examined the length of time that LV feeder end voltages might lie outside LV statutory limits, if the limits at 11kV or 33kV were amended.

Lastly, other aspects of impact were considered through literature review.

4.1 System Study – Impact on Locations

The study considered the 33kV and 11kV networks below the Bridgwater and Street BSPs in WPD's South West licence area. The models consisted of an equivalent infeed from 132kV, the 33kV network below the two BSPs, the 33/11kV primary transformers and the downstream 11kV networks.

4.1.1 Method

In order to understand the effects of widened steady-state voltage limits on the 33kV and 11kV network, two demand and generation cases were examined:

- A low voltage case, with loads at their maximum demand values, and all generation offline
- A high voltage case, with loads at assumed minimum demand values, and all generation online and at full output

The main assumptions included:

- Thermal limits of network components were not considered
- Scaling of load and generation was applied uniformly across the model
- The assumed minimum demand was 36.5% of maximum load
- For the loads, both real and reactive power demand were scaled equally
- For the generators, only the real power output was scaled

4.1.2 33kV Results

33kV nodes corresponded to transformer or substation connections points.

Figure 5 shows a cumulative frequency plot of 33kV node voltages when the system loading (low voltage case) or generation (high voltage case) within the upstream model is increased until the worst case voltages hit the widened steady-state voltage limits. Both the high and low voltage cases are shown.

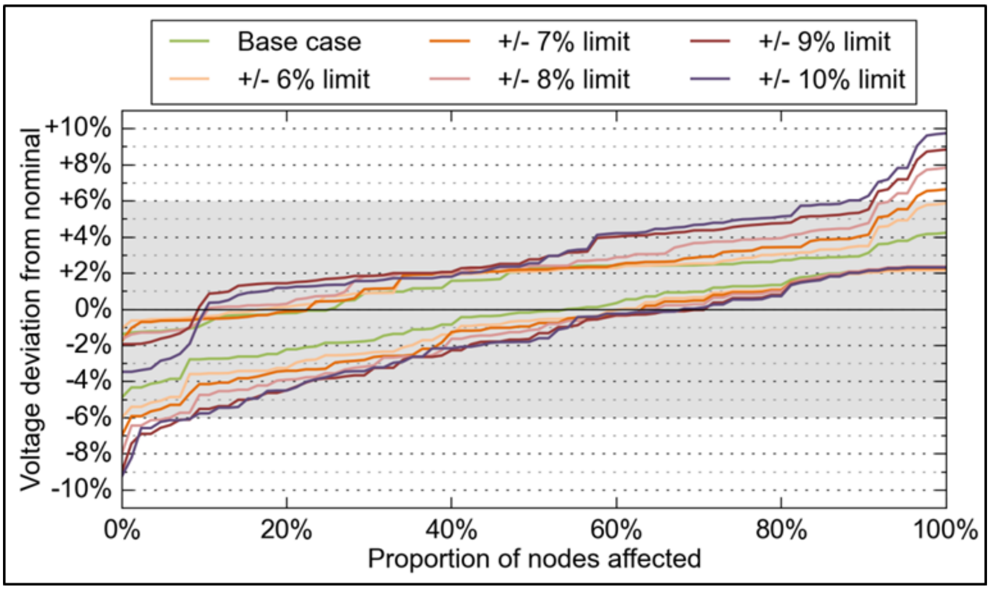

Figure 5: Cumulative frequency plots of steady state voltages for the high and low voltage cases when widened voltage limits are applied at 33kV (results from upstream model)

Figure 6 shows the proportion of 33kV nodes that would fall outside the current statutory steady-state voltage limits if widened voltage limits were applied. No 33kV node was found to experience both over- and under-voltages.

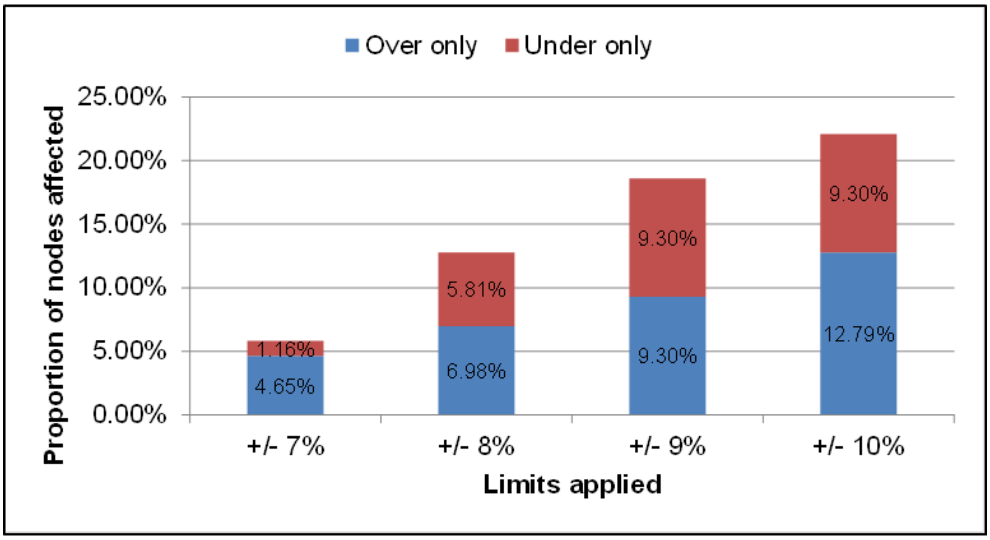

Figure 6: Proportion of 33kV nodes outside the current statutory limits

The fully exploited ±7% widened limits led 5.81% of the total nodes to go above the existing +6% upper statutory limit (4.65%) or below the -6% lower statutory limit (1.16%).

The effect on 132/33kV and 33/11kV transformer tap operation was assessed. With network operating at the -10% limit, no transformers hit the limits of their tap changers. At the +10% limit a single 33/11kV primary transformer (Burnham) hit the limit of its tap operation and could not control voltage to within the AVC bandwidth.

4.1.3 11kV Results

11kV nodes corresponded to points where 11kV/LV transformers were connected.

Figure 7 is a cumulative frequency plot of 11kV node voltages. It is clear to see that the maximum voltages are only affected for the feeders containing generation (the nodes on the top right).

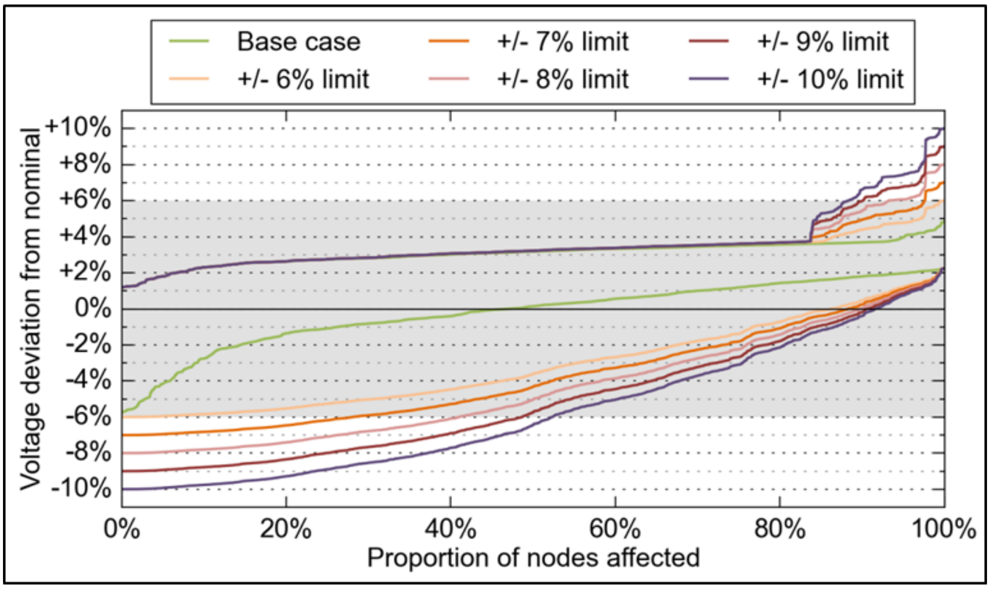

Figure 7: Cumulative frequency plots of steady state voltages for the high and low voltage cases when widened voltage limits are applied at 11kV (results from downstream model)

Figure 8 shows the proportion of 11kV nodes that would fall outside the current statutory steady-state voltage limits if widened voltage limits were applied and then fully exploited within each feeder.

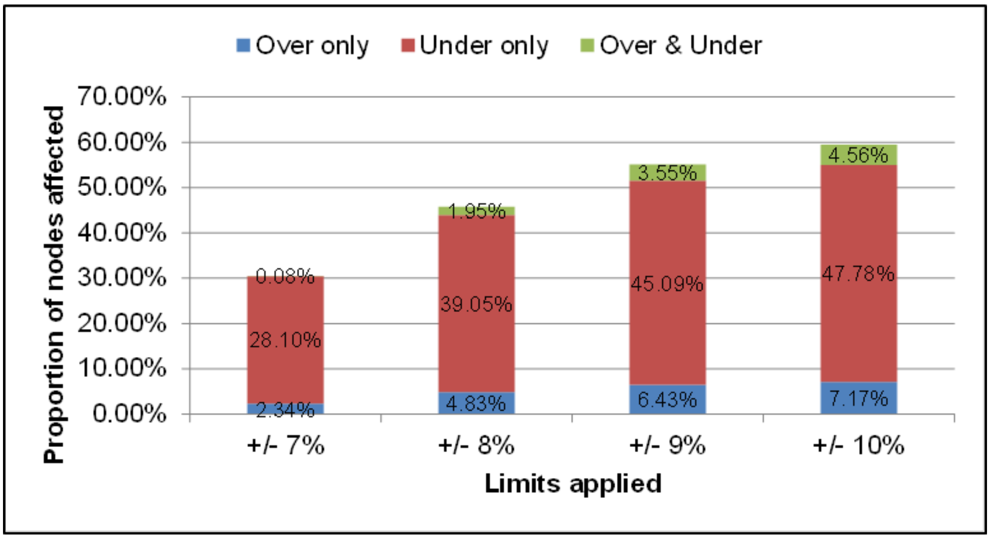

Figure 8: Proportion of 11V nodes outside the current statutory limits

For example, with limits widened to ±7% and after achieving their full exploitation on each 11kV feeder, 30.51% of the total studied 11kV nodes went outside the existing limits (28.10% went above the +6% limit, 2.34% went below the -6% limit, while another 0.08% exceeded both ±6% limits).

4.1.4 Effect on Voltage Step Change

Fundamentally, voltage step change is determined by the currents flowing through the network before a contingency event, and the difference in impedance that a contingency will cause.

The results of the steady-state voltage limits study have shown that significant increases in load and generation would be required to exploit the widened steady-state limits. Therefore, network reinforcement would be required in order to provide enough thermal capacity to allow for additional load and generation. This would lower impedances and thus decrease voltage step changes. Therefore, it is difficult to assess where applying widened steady-state limits would result in voltage steps greater than the existing limits and whether increased voltage step change limits would be required.

If the exploitation of widened steady-state voltage limits in particular areas were to lead to voltage step change outside the current limits, this could be mitigated through the use of solutions such as an SVC to reduce the reactive power flow through the transformers and associated voltage step change.

4.2 Low Voltage Network Templates – Impact on Time

LVNT[13] was an LCN Fund Tier 2 project that mainly looked to accurately identify different cluster types of load and voltage profiles, referred to as "templates", at a particular substation negating the need for extensive LV monitoring or reliance on historic assumptions.

For the purposes of VLA, a few monitored points at the end of LV feeders were examined. These points were associated mainly with domestic consumers, with some businesses also included, and captured single-phase voltage measurements at or electrically very close to the supply terminals for a period of at least one year (10-minute averages). For 17 Monitored supplied in 2013, the most common recorded voltages lay between +5% and +8% of the nominal 230V.

Emulating potential future growth, the observed voltages were extrapolated to investigate the percentage of time within each voltage band, should the voltage be lower than the statutory -6% limit for 0.5% of the time only. The distribution of reduced voltages is shown in Figure 9

[13] WPD Innovation, *Network Templates* [http://www.westernpowerinnovation.co.uk/Projects/Network-Templates.aspx]

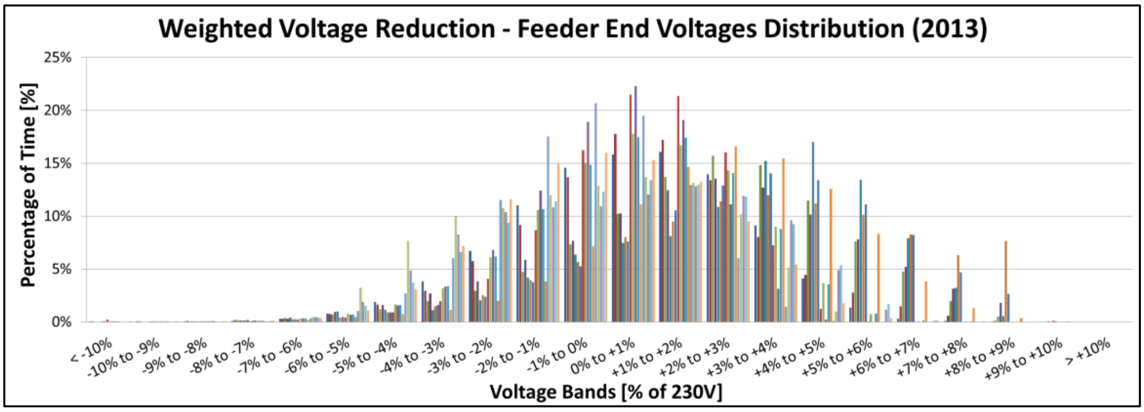

Figure 9: Distribution of reduced feeder end voltages

The distribution for each individual end point shows voltages between -5% and -6% for between approximately 3% and 0.5% of the year. If future 11kV voltage limits were decreased by 1% and the load profile of future additional loads was similar to the existing one, then it is speculated that the percentage of time that the future system operated beyond -6% would be up to approximately 3% of the year.

This indicates that only a small proportion of the time would the LV feeder end voltages be impacted by a potential lowering of the 11kV statutory limit.

4.3 Other considerations to changing limits

4.3.1 G59 Protection Settings

The scope for a potential amendment of step change limits ought to be examined in association with steady-state limits and their present and proposed values. A voltage step change may occur with an initial voltage level which is not the nominal system voltage and, in extreme cases, may be the upper or lower statutory limit of the steady-state voltage.

As per the Distribution Code section 4.2.3.3, voltage step changes of ±10% are acceptable for design purposes in the cases of unplanned outages, such as faults and for energisation of sites with multiple transformers, on the condition that these do not become more frequent than once per year[14].

On that basis, a -10% step when operating at 0.94pu results in a voltage equal to 0.9 x 0.94pu = 0.846pu, i.e. a voltage 15.4% lower than nominal. A +10% step when operating at 1.06pu would give 1.1 x 1.06pu = 1.166pu, which is 16.6% higher than nominal voltage.

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[14] Distribution Code Review Panel, *The Distribution Code and the Guide to the Distribution Code of Licensed Distribution Network Operators of Great Britain* (Issue 26, September 2015)

The above are of particular importance to generation protection requirements. ER G59 sets the following under-voltage and over-voltage protection settings for generating plant connected at HV (clause 10.5)[15]:

- Under-voltage Stage 1 protection should have a setting of -13% and a time delay of 2.5sec
- Over-voltage Stage 2 protection at HV should have a setting of +13% with a time delay of 0.5sec

So, based on these settings, G59 protection would operate if the under-voltage of 15.4% was sustained for 2.5sec and if the over-voltage of 16.6% was sustained for 0.5sec.

This would imply that, if the statutory limits were widened, there would be need to review these G59 settings, so a smaller under-voltage or over-voltage limit may be needed to avoid G59 protection operation. Moreover, this would create scope for review of permitted step change limits, with consideration of a potential reduction.

4.3.2 LV Impact – Lighting

The design limits for voltage step change in ER P28 (3%) were based on laboratory tests and field experience regarding the visual annoyance of consumers to excessive flicker (P_{st}, short-term flicker severity) and are applicable to system users; they are not network design limits or network performance criteria. ER P28 was issued at a time when tungsten filament lamps were in widespread use, hence the design of the IEC flickermeter (IEC 61000-4-15:2010), which is still used for flicker assessment, was based on a 60W tungsten filament lamp as this was regarded to be the most sensitive lighting source at the time.

It has been demonstrated by the CIGRE C4.108 working group[16] that a selection of typical modern lamps are less sensitive to sinusoidal voltage fluctuations than a 60W tungsten filament lamp.

However, a study by the University of the Basque Country[17] demonstrated that not always modern lamps are less sensitive to flicker. For certain ranges of modulation frequencies, modern lamps are more sensitive to either sinusoidal or rectangular voltage fluctuations. Under real, more complex fluctuations, a more unpredictable behaviour was observed, which does not always correlate with behaviour under simpler fluctuations, thus further complicating the analysis.

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[15] Energy Networks Association, *Engineering Recommendation G59: Recommendations for the Connection of Generating Plant to the Distribution Systems of Licensed Distribution Network Operators* (Energy Networks Association, Issue 3, September 2013)

[16] CIGRE/CIRED Working Group C4.108, *Review of Flicker Objectives for LV, MV, and HV Systems* (CIGRE, February 2011)

[17] I. Azcarate, J.J. Gutierrez, A. Lazkano, P. Saiz, K. Redondo, L.A. Leturiondo, *Experimental study of the response of efficient lighting technologies to complex voltage fluctuations*, University of the Basque Country UPV/EHU, (Elsevier, 2014)

Frank Deter (Miele) in a presentation[18] recommends the preservation of the IEC 61000-3-3 flicker curve and the CIGRE working group cautioned the readers of its report about the limited selection of modern lamps and also about the limited number of tests carried out, therefore recommending additional, wider testing before generalising conclusions.

So, despite the evolution of lighting technology, the existing flicker curve based on the 60W incandescent lamp is still relevant, in combination with the principle that any new lamp should not be more sensitive to flicker than this reference lamp. Careful consideration and extensive research are necessary prior to any possible amendment of the IEC 61000-3-3 flicker curve, the IEC flickermeter or even the ER P28 step voltage change limits.

4.3.3 Voltage Unbalance

Voltage unbalances, which can be a consequence of single-phase loads at the LV, larger single-phase loads at higher voltages, dissimilar impedances between the phases particularly with overhead lines or some fault conditions, can cause overheating to three-phase electrical machines or the injection of increased levels of harmonics by rectifiers or inverters.

ER P29 specifies a 2% limit for any 1-minute period for proposed new loads that might give rise to voltage unbalance at the PCC. Also, where a balance is used and for no more than 5 minutes every half an hour, the caused unbalance at the PCC may exceed 1.3% for 33kV systems and 1% for higher systems up to 132kV. ER P29 provides planning limits for new loads, not general network limits.

BS EN 50160:2010 recommends that voltage unbalance at supply terminals should stay within 0% and 2% for 95% of the 10-minute averages over one week.

Regulating system voltages based on only two of the phases might lead to the third phase breaching the statutory limits, even if voltage supply is compliant in terms of voltage unbalance, because the unmonitored voltage may be worst case. Due care should be given to the monitoring of supply voltages by the network operators so that compliance with voltage unbalance recommendations does not mislead to a voltage supply outside the statutory limits.

[18] F. Deter of Miele & Cie. KG, *Flicker and new lamps: How to keep electromagnetic compatibility after incandescent lamps have been phased out?*

5 Assessment of Commercial Impact of Changing Limits

5.1 Demand and Energy Consumption

A potential widening of voltage limits would mean that lower voltages could be allowed at the consumers' terminals. This could have a decreasing effect on energy consumption depending on the characteristics of the consumer's load, according to examined applications of Conservation Voltage Reduction (CVR). There would be no change in the energy consumed by fixed power loads or some fixed impedance loads, such as heating controlled by a thermostat, as they would consume the same. On the contrary, other types of fixed impedance loads, such as lighting, could consume less energy.

Demand levels may decrease as a consequence of reduced voltages. Indicatively and by conservative estimates, an average reduction in steady state voltage in the region of 1-2% could be expected to create a demand reduction of at least 1%.

Conversely, high voltages could increase a consumer's energy consumption depending on the characteristics of their load. Voltages near the upper extreme of the allowable range would occur only on generation feeders and consequently would have an effect on a limited number of nodes across the network, therefore would not be expected to increase energy consumption significantly.

5.2 Equipment Replacement

A direct commercial impact from the modification of voltage limits might arise from the need to replace equipment. Equipment may need to be replaced if the modified voltage limits were outside of their identified capability to withstand higher voltages, or operate within extended ranges of voltage (either higher or lower).

Based on the review of equipment standards and specifications it is anticipated that any proposed new voltage limits would be within equipment capabilities, provided that the new range of voltage variation would not be greater than ±10% and that operation in the extreme ends of that range would only be allowed for short periods of time, in the order of minutes, based on the examined equipment specification and demonstrated by power frequency withstand test magnitudes and durations

Therefore, it is not envisaged that significant replacements of equipment would need to take place in 11kV and 33kV networks.

5.3 HV Voltage Regulation

With regard to the voltage regulating operation of primary transformers within the examined area, as shown by the modelling study, even at the extreme ends of applied voltage of ±10% only one transformer out of the 15 primary substations hit the limit of its tap operation. Considering the fact that the modelling scenario examined represented an extremely onerous condition whereby generation output was increased by a scaling factor in the order of 400%, it is estimated that no issues would be expected to arise with regulating voltages on the HV network, due to the widened voltage limits.

5.4 LV Voltage Regulation

It can be deduced that the maximum variation of the HV voltage that typical distribution transformers can manage whilst LV system voltages remain within statutory limits is as follows:

- Maximum LV limit = +10%
- Minimum LV limit = -6%
- Maximum LV voltage variation defined by LV limits = 10 - (-6%) = 16%

This variation can be broken down into various parts including the voltage drop along the LV circuit and the distribution transformer. Typical assumptions correspond to a combined maximum voltage drop across the LV network of -8%. This leaves 8% (16 - 8%) for the voltage variation on the HV side of the distribution transformers.

The granularity of the taps available on the existing fixed tapped distribution 11kV/LV transformers should be taken into consideration. The tap steps are 2.5% so there is the possibility that a tap may not be entirely appropriate for the apparent system voltages. The maximum bandwidth that the tap step might be out from the most optimum setting is 1.25%, so this leaves approximately 6.75% (i.e. 8% - 1.25%) for the voltage variation of the HV system.

The appropriate tap position of the 11kV/LV transformer depends upon how the average 11kV nodal voltage sits against the +10% / -6% LV limits, along with the inherent voltage gain of the distribution transformer (typically 11kV/433V). If this average varies throughout the year, then the fixed tap position may be changed seasonally, if this is supported by a cost benefit analysis.

So, there is need for alternative ways for regulating voltage if the daily voltage at a particular 11kV node varies by more than 6.75%. The alternative may be an on-load tap changer (OLTC), a voltage regulator or, ultimately, the replacement of the entire distribution transformer.

The worst case HV voltage variation occurs at the remotest nodes and comprises variation due to the granularity of control at the upstream transformer and variation due to power flow through the 11kV circuit.

On an HV feeder with no generation, the minimum voltage is -6% and maximum voltage is approximately +0.75% (or +0.0075pu) higher than the AVC setting of the primary transformer, which represents half of its bandwidth. If the AVC set point is set at 1.03pu (as was the case for the transformers examined in the modelling study), the total voltage variation of 6.75% (or 0.0675pu) results in a minimum voltage of the HV feeder of 0.97pu (or -3%) (i.e. 1.03pu + 0.0075pu – 0.0675pu = 0.97pu), which allows the system to maintain LV voltages.

Assuming that no generation is present on the HV feeders (i.e. assuming the low voltage scenarios of the modelling study only), we can see in Figure 7 that for the existing voltage limits of ±6% and loading on feeders scaled up in order to fully exploit the -6%, 57% of the nodes along the feeder will reach 0.97pu or lower, thus requiring voltage regulation that could not be provided by existing LV voltage control mechanisms.

Under the same premise, if the voltage limits were allowed to be ±7%, then using the same graph it can be noted that 65% of the nodes would have voltages equal to or lower than 0.97pu, assuming no generation on these feeders and thus maximum voltage drop from the upstream primary transformer to the distribution transformer. So, by extending the voltage limits to ±7%, approximately 8% (65% - 57%) of the nodes (i.e. distribution transformers) would require additional voltage regulation mechanisms. For the scenario of ±10% limits, approximately 18% of the nodes would require additional voltage regulation or replacement.

If generation was connected to these circuits, then there would be an associated voltage rise and the permitted voltage drop before additional LV voltage regulation was required would be less than the 6.75% mentioned above. If the maximum voltage rise along the feeder due to reverse power flow was 1%, then the allowable voltage drop would be 5.75%.

Due to the unpredictable nature of DG connections, with regard to location and export capacity, a full assessment of these types of scenarios cannot be undertaken. It should be noted though that the connection of large volumes/capacities of DG would typically be accompanied by reinforcement of the 11kV network, so the requirement for additional voltage regulation would be relatively alleviated.

Overall, the percentage of distribution transformers requiring reinforcement or replacement will depend upon the following:

- The numbers of HV feeders on which the demand is increased to realise the benefits of the widened voltage limits
- The numbers of HV feeders on which generation is installed and the variation in voltage between maximum demand and maximum export is greater than 6.75%

6 VLA Stakeholder Questionnaire

VLA questionnaires were issued to the main industry stakeholders across the UK and Europe, as identified by the Network Equilibrium project team.

The aims of the questionnaires were to:

- Seek information regarding how voltage limits are currently implemented in distribution networks of the UK and EU
- Identify constraints they impose to the relevant stakeholders operating or connecting to the networks
- Explore amendments to existing statutory voltage limits and step change limits in Engineering Recommendations where applicable, highlighting both limitations and opportunities for change

The results from the questionnaire were compiled and presented in a concise manner, which allows the explored issues to be viewed from the different perspectives of the DNOs, regulatory authorities, manufacturer associations, consultants and other technical specialists with long experience in the industry.

The key points from the responses were the following:

- The overall perception of the project scope by the industry was positive with most respondents noting that they find the proposals put forward interesting and in alignment with the recent evolution of distribution networks.
- Some key observations were made on the basis of voltage control and the increased requirement to enhance that aspect as a result of the more complex operation of today's networks, stressed further by a potential widening of voltage limits. The need for wider system voltage coordination was identified.
- Technical considerations regarding the implementation of higher upper limits involved voltage withstand characteristics of distribution equipment, with focus on insulation levels and lifetime. Reactive power levels during periods of low demand, harmonic emissions and potentially higher fault levels were additional issues identified. Benefits regarding minimisation of ohmic losses in networks, due to operation at higher voltages, could counterbalance the above barriers.
- Technical considerations regarding the implementation of decreased lower limits involved potentially increased risks of voltage collapse, implications regarding OC6 provisions and under-performance of sensitive loads such as motors. Protection coordination was seen as a key factor, while the identified benefits were related to the reduction of capacity limitations supporting higher demands, reduction of network losses due to decreased demand and potential improvement of asset life.

- Step change limit amendments were associated with the (mal-)operation of sensitive and protective equipment, possibly resulting in commercial implications for the DNOs. Reference was also made to the proposed GC076 modification proposal on voltage dips within the Grid Code, which includes various areas of technical impact and alignment with other standards such as ER P28 (which is also under review).
- Impact on other voltages, lower and higher than 11kV and 33kV, were identified in the form of more challenging voltage regulation and LV reinforcement requirements associated with the operation of sensitive equipment, such as lighting.

7 VLA Workshop

A VLA workshop was held in IET Birmingham in October 2015, with the attendance of network strategy and planning engineers from all GB DNOs.

The purpose of the workshop was to present the findings from the initial stage of the VLA work and the literature reviews undertaken at the time, to review industry responses to the VLA questionnaire, to discuss the present implementation of existing voltage limits in 11kV and 33kV networks and the scope for a potential amendment of statutory and step change voltage limits, and finally to examine and record views of the DNO representatives.

The most significant findings from the workshop are summarised below:

- Voltage limits were recognised to be a significant constraint to DG connections
- DNOs have experience of operating their systems above the existing limits, which are interpreted to only apply at the customer's point of connection, without obvious detrimental effects
- Increasing the upper voltage limit was seen as a way of connecting more DG, while recognising that other constraints, such as thermal and power quality issues, may then become the limiting factor
- Barriers requiring further exploration were identified in a number of areas, such as network equipment, maintaining LV voltages within limits, changes to fault levels, customers' networks, customer reaction etc.
- As it presently stands, the ESQCR permits the agreement of specific supply voltage ranges between the distributor, the supplier and the consumer, which can be utilised where appropriate

8 Overall Conclusions

The main conclusions drawn from the previous sections of the report are summarised below.

- The overall conclusion of the literature review of manufacturing standards and equipment specifications is that the majority of the equipment is characterised by its highest voltage for continuous operation (U_m) and by the power frequency withstand voltage, which typically is applied and tested for 1 minute during the pertinent insulation withstand test. The main series of standards for the purposes of insulation withstand levels is the IEC 60071 series titled "*Insulation Co-ordination*".
- Most of the equipment suitable for installation on systems of a nominal voltage of 11kV has a U_m of 12kV, which is approximately 9% above the nominal system voltage. Similarly, equipment suitable for 33kV nominal system voltages has a U_m of 36kV, which is again approximately 9% higher than the nominal.
- As far as power frequency withstand voltages are concerned, for the test duration of 1 minute, 12kV rated equipment can typically withstand 28kV while 36kV rated equipment can withstand 70kV. Notice is also given to certain testing requirements from BS standards and equipment specifications, pertaining to applying lower test voltages, but over longer periods.
- A VLA questionnaire was issued to industry stakeholders to obtain information and wider perspective on the VLA work. The responses indicated a positive perception of the proposed scope by industry members. Technical considerations were also identified, mainly involving voltage regulation issues, equipment voltage withstand capabilities and lifetime, protection coordination and the impact of wider 11kV and 33kV limits on HV and LV networks.
- The VLA workshop (held in IET Birmingham in October 2015) identified voltage limits as being a significant constraint to DG connections, also recognising that other constraints, such as thermal and power quality issues, may then become the limiting factor. The workshop concluded that barriers, such as network equipment withstand characteristics, maintaining LV voltages within limits, changes to fault levels, impact on customers and customer reaction, require further exploration.
- The study of the WPD South West licence area network showed that if an amendment to the existing statutory steady-state voltage limits was implemented, the fully exploited widened steady-state voltage limits would cause some of the 33kV and 11kV nodes to go outside the existing ±6% limits.
- For example, with limits widened to ±7% and fully exploited, 30.51% of the total studied 11kV nodes went outside the existing limits. At 33kV and considering again full exploitation, 5.81% of the total nodes went either above the existing +6% upper statutory limit or below the existing -6% lower statutory limit.

- However, load and generation would need to increase significantly if the widened voltage limits were to be fully exploited, particularly at 11kV. It would be expected that thermal limits would constrain the ability to fully exploit widened voltage limits.
- • Within the modelled area of the network, only one 33/11kV primary transformer would require replacement or upgrade of its voltage regulating capabilities in order to cope with a +10% limit, while a maximum of 18% of distribution transformers might require OLTC or other types of voltage regulation for the extreme scenario of ±10% statutory voltage limits.
- Based on the results of the modelling study and the review of equipment limitations, it was concluded that the vast majority of equipment connected at 11kV and 33kV would not require replacement, provided that the new range of voltage variation would not be greater than ±10% applied in a probabilistic manner so that operation in the extreme ends of that range would only be allowed for short periods of time.
- Caution should also be exercised regarding ER G59 protection settings, voltage unbalance monitoring and other potential impact on LV of any changes made at HV.
- With regard to voltage step changes and flicker standards, modern lamps are not always less sensitive to voltage variations than traditional incandescent lamps and so careful consideration and extensive research are necessary prior to any possible amendment of the IEC 61000 3 3 flicker curve, the IEC flickermeter or even the ER P28 step voltage change limits.

9 Recommendations

With regard to a potential modification of the steady-state voltage limits, as a provisional recommendation, subject to further investigation and consultation, it would be advisable to adopt a probabilistic approach (similar to the requirements relating to weekly measurements and the differentiation per voltage ranges existing in EN 50160). More restrictive overall limits than the ones stated in EN 50160 would need to be applied, in order to ensure satisfactory conditions of operation for the most sensitive equipment on the 11kV network.

It is acknowledged that constraints other than voltage may be encountered in advance of being able to realise the benefits made available by widening voltage limits. However, emerging technologies are expected to mitigate these constraints.

A maximum limit of ±10% should be considered for the 33kV network (treated as absolute, i.e. relating to 100% of voltage measurements over a specific period). As a consequence of some equipment specifications only requiring a withstand of 9% above nominal voltage for continuous operation, it is recommended that operation above +9% and below +10% is restricted by an appropriate percentile of measurements within a defined period, for example in the order of 99% over the measured period as applied in EN 50160.

As far as voltage limits at 11kV are concerned, a tighter range than at 33kV would need to be considered due to issues pertaining to voltage regulation and equipment sensitivity. A point for consideration, which was raised during the VLA workshop, was that, due to the manner in which LV voltage is regulated via the 11kV network and the tap ratio/settings of the distribution transformers, it would be difficult to realise a higher upper statutory limit at 11kV without concurrent change of the LV upper statutory limit. Some selective adjustments on tap settings of distribution transformers could resolve this issue in problematic areas. A decreased lower 11kV limit would be easier to accommodate after the LV harmonisation to the EU has been implemented (230V -10%). However, it is recognised that any proposed amended limits could not be realised in all parts of the 11kV networks, as is currently the case with the existing ±6% limits.

A modification of steady-state voltage limits at 33kV would not be expected to create problems on the downstream network, due to the larger flexibility of the regulation of voltages across the primary transformers, i.e. wider tapping range and automatic voltage control. A review of AVC target voltages would be required on an individual basis, accounting for the maximum amounts of generation and demand along the associated 11kV feeders.

Voltage unbalance needs to be monitored closely by measuring voltage in all 3 phases, which is something that some DNOs have already begun implementing, in order to avoid excursions of the steady-state voltage beyond the proposed limits in any unmonitored phases.

An amendment to steady-state limits would need to be accompanied by a review of the protection coordination recommendations and the G59/G83 under-voltage and over-voltage protection settings in particular. The ER P28 WG is currently reviewing the voltage step change limits from various perspectives, which include the G59/G83 settings, and is expected to issue recommendations by the end of 2016. Caution should be given to the fact that widening the steady-state voltage limits would require a similar increase/decrease of those settings or re-consideration of the effect of the voltage step change limits.

With regard to voltage step change limits, reference should be given to the draft paper written by Simon Scarbro (WPD) proposing planning limits for RVCs, which has also been a point of discussion for the ER P28 WG[19]. In that, the 3% limit for infrequent planned events is proposed to be maintained; the maximum 10% limit is also to be maintained for infrequent unplanned events, such as faults or energisation of multiple transformers (as per DPC 4.2.3.3 of the Distribution Code) and a probabilistic approach is proposed for events with frequency that sits between that of the aforementioned phenomena. Values of maximum voltage change and residual voltage change (as included in the latest version

[19] DCRP ER P28 Working Group, *Draft Minutes of the Fourth Meeting of the ER P28 Joint GCRP and DCRP Working Group,* (18th June 2015)

of the Grid Code[20]) are proposed to be adopted and implemented in the setting of voltage step change limits, while different limits would be applied for different event durations to ensure coordination with protection settings implemented at 11kV and 33kV networks and avoid unnecessary tripping operations. The recommendations extended in the paper are not to be treated as final at this stage; the final report of the ER P28 WG in 2016 will need to be reviewed and considered within the overall scope of an assessment of voltage limits, both steady-state and step change.

It is recognised that pertinent research is being conducted in areas related to the VLA analytical study and it is anticipated that additional work will be undertaken as part of the formal consultation process, associated with exploring future change, between stakeholders and various working groups concerned with voltage limits. These areas could include the localised examination of distribution networks, particularly the ones experiencing issues of extreme voltages, and further consultation with equipment manufacturers and their representative bodies, such as BEAMA (British Electrotechnical and Allied Manufacturers' Association). Other focus areas could be the consultation with customers connected to the network, liaison with distribution network regulators in the UK and the EU, further system modelling to examine potential impacts in other parts of the UK network and more extensive dissemination of learning between DNOs with regard to particular cases of application of wider voltage levels (potentially through the inauguration of a working group looking specifically at the assessment of voltage limits in 11kV and 33kV networks). Coordination with other working groups such as the ER P28 WG and the LV harmonisation group would be advisable, as well as with other corresponding European bodies.

[20] National Grid Electricity Transmission plc, *The Grid Code, Issue 5, Revision 14* (National Grid, 26 August 2015)