

# **Review of Voltage Unbalance Limit in The GB Grid Code CC.6.1.5 (b)**

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## EXECUTIVE SUMMARY

Discrepancy between the voltage unbalance limit in the GB Grid Code for Scotland and England and Wales is presented. According to Grid Code CC.6.1.5 (b), the voltage unbalance limit for all voltage levels in Scotland is 2% whereas the same in England and Wales is 1% for EHV systems. It is further presented that by the virtue of the Grid Code, National Grid is obliged to comply with 1% limit for voltage unbalance at 132kV voltage level whereas the same for Distribution Network Operators is 2%.

It is therefore proposed that a uniform approach based on recommendations by international standards and publications is adopted across the electricity network in Scotland and England and Wales to set the limit at EHV level to 1.5% and lower voltages to 2%. EHV is defined as 400kV and 275kV. Changes in the Grid Code text for CC 6.1.5 (b) and CC 6.1.6 covering the voltage unbalance limit are proposed.

In developing the above revised limit, it is shown that the increase in the Grid Code limit from 1% to 1.5% would not affect equipment connected to the power network any more so than the existing limit. Particular reference is made to rotating machines, namely induction motors and synchronous machines, which are known to be most sensitive to negative phase sequence voltage or voltage unbalance. Modelling exercise using the GB network model was conducted to determine the transfer coefficients for the voltage unbalance from EHV level down to lower voltages. These were then used to apportion the compatibility limit of 2% at 132kV between the voltage unbalance transferred from the EHV network and contribution from DNO networks. This is in line with the recommendations from IEC and CIGRE Working Group.

The main sources of the voltage unbalance in normal operating condition in the EHV system are discussed and the recommendations by international standards in allowing for inherent network unbalance is used to develop the new proposal for the unbalance voltage limit.

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## 1- INTRODUCTION

This proposal is submitted to revise the existing Grid Code criteria applied to Voltage Unbalance at a Point of Common Coupling within CC.6.1.5 (b).

It is stipulated that:

Co-ordination between user's equipment and power supply is needed to avoid overspending on spurious outage cost (consumer cost) or network improvements (utility cost). Before connecting a sensitive device or equipment to the electrical network, it is necessary to assess the compatibility between the device and the supply. Voltage unbalance as other power quality phenomena should be treated as a compatibility problem between equipment and supply.

Grid Code CC.6.1.5 (b) [1] sets the limit for voltage unbalance at any point in the transmission network. The complete CC.6.1.5 and accompanying CC.6.1.6 are shown below.

### Voltage Waveform Quality

CC.6.1.5 All Plant and Apparatus connected to the National Electricity Transmission System, and that part of the National Electricity Transmission System at each Connection Site or, in the case of OTSDUW Plant and Apparatus, at each Interface Point, should be capable of withstanding the following distortions of the voltage waveform in respect of harmonic content and phase unbalance:

#### (a) Harmonic Content

The Electromagnetic Compatibility Levels for harmonic distortion on the Onshore Transmission System from all sources under both Planned Outage and fault outage conditions, (unless abnormal conditions prevail) shall comply with the levels shown in the tables of Appendix A of Engineering recommendation G5/4. The Electromagnetic Compatibility Levels for harmonic distortion on an Offshore Transmission System will be defined in relevant Bilateral Agreements.

Engineering Recommendation G5/4 contains planning criteria which NGET will apply to the connection of non-linear Load to the National Electricity Transmission System, which may result in harmonic emission limits being specified for these Loads in the relevant Bilateral Agreement. The application of the planning criteria will take into account the position of existing and prospective Users' Plant and Apparatus (and OTSDUW Plant and Apparatus) in relation to harmonic emissions. Users must ensure that connection of distorting loads to their User Systems do not cause any harmonic emission limits specified in the Bilateral Agreement, or where no such limits are specified, the relevant planning levels specified in Engineering Recommendation G5/4 to be exceeded.

#### (b) Phase Unbalance

Under Planned Outage conditions, the maximum Phase (Voltage) Unbalance on the National Electricity Transmission System should remain, in England and Wales, below 1%, and in Scotland, below 2%, unless abnormal conditions prevail and Offshore (or in the case of OTSDUW, OTSDUW Plant and Apparatus) will be defined in relevant Bilateral Agreements.

CC.6.1.6 In England and Wales, under the Planned Outage conditions stated in CC.6.1.5 (b) infrequent short duration peaks with a maximum value of 2% are permitted for Phase (Voltage) Unbalance, subject to the prior agreement of NGET under the Bilateral Agreement and in relation to OTSDUW, the Construction Agreement. NGET will only agree following a specific assessment of the impact of these levels on Transmission Apparatus and other Users Apparatus with which it is satisfied.

Grid Code CC.6.1.5 (b) states that the maximum voltage unbalance in National Electricity Transmission system must be below 1% in England and Wales and 2% in Scotland. Connection Condition CC.6.1.6 allows maximum of 2% voltage unbalance in transmission network for short duration provided prior agreement from NGET is sought.

Furthermore, the Grid Code limit of 1% in England and Wales also applies to 132 kV busbars as they are part of the electricity transmission system and hence NGET is obliged to comply with the limit at this voltage level. On the other hand, Distribution Code DPC4.2.3.2 [2] sets the rule in distribution networks to comply with Engineering Recommendation P29 [3]. Part of DPC4.2.3.2 that relates to unbalance states:

- (c) Phase (Voltage) Unbalance shall comply with the levels laid down in DGD Annex 1, Item 10 Engineering Recommendation P29, "Planning limits for voltage unbalance in the United Kingdom for 132kV and below".
- (d) Traction supplies shall comply as appropriate with the requirements of DGD Annex 1, Item 6. Engineering Recommendation P24 "A.C. traction supplies to British Rail".

Under certain circumstances the DNO may agree to other limits or levels.

ENA ER P29 set the limit of 2% for voltages 132 kV and below and allows up to 1.33% to be allocated to one customer, e.g. traction. Distribution Network Owners (DNO) also use BS EN 50160 [4] as a guide for compliance. This standard allows 2% voltage unbalance for voltages of 150 kV and below and in exceptional cases, e.g. radial networks with single phase loads, up to 3% is allowed.

As shown above, the limits for 132 kV busbars seems to be different in the Grid Code and Distribution Code, i.e. the Grid Operator is obliged to comply with 1% phase unbalance limit whereas the Distribution Network Owner is required to comply with 2% limit.

This document objective is to identify the sources of these discrepancies and propose a uniform approach and rational for all voltage levels based on recommendations in international standards and industry practices and technical publications.

## 2- PARAMETERS AND DEFINITIONS

All international standards on definition, assessment of and immunity to the unbalance in power system relate phase unbalance to the level of negative phase sequence (nps) of voltage. This is due to the fact that nps voltage imposes the most detrimental effect on three phase equipment. The main Standards, Technical Reports and CIGRE Working Group reports dealing with nps are BS EN 50160 [4], IEC/TR IEC 61000-3-13 [5], IEC 61000-3-30 [6], Joint Working Group Cigré C4.07 [7] and numerous other references some of which are given in the Glossary. IEC 61000-4-27 provides test procedure for immunity tests on equipment with rated current below 16A. According to these references the unbalance is defined as the ratio of the negative phase sequence voltage to the positive phase sequence (pps) voltage as shown in (1). The ratio is referred to as Unbalance Factor.

$$UBF = \frac{V^-}{V^+} \times 100 \tag{1}$$

Where  $V^-$  : nps voltage

$V^+$  : pps voltage

The pps and nps phasor voltages should be calculated from the measured three phase voltage phasors. Equations (2) and (3) show the conversion from phase coordinate quantities to respectively nps and pps voltages.

$$V^- = \frac{1}{3}(V_r + a^2V_y + aV_b) \tag{2}$$

$$V^+ = \frac{1}{3}(V_r + aV_y + a^2V_b) \tag{3}$$

Where  $V_r$ ,  $V_y$ , and  $V_b$  are red, yellow and blue phases, fundamental frequency component voltages and Operator  $a=1\angle 120^\circ$ .

References [5, 6, 7] also suggest a relationship between UBF and the magnitudes of line voltage as shown in (4):

$$UBF = \sqrt{\frac{1 - \sqrt{3 - 6\beta}}{1 + \sqrt{3 - 6\beta}}} \times 100 \quad (4)$$

$$\text{Where : } \beta = \frac{|V_{ry}|^4 + |V_{yb}|^4 + |V_{br}|^4}{\left(|V_{ry}|^2 + |V_{yb}|^2 + |V_{br}|^2\right)^2}$$

$V_{ry}$ ,  $V_{yb}$  and  $V_{br}$  are the line voltages between respective red-yellow, yellow-blue and blue-red phases. All power quality and other types of monitors use one of the above methods to calculate UBF. Reference [6] which sets the requirement for measurement of power quality parameters states that a Class A monitor should have a tolerance of  $\pm 0.15\%$  of the declared input voltage, e.g. nominal voltage, for measurement of nps. For example, if a Class A monitor is presented with an nps voltage of 1% it shall provide a measurement of V within the range of  $0.85\% \leq V \leq 1.15\%$ . This tolerance excludes the error introduced by the instrument transformers.

For compliance purposes with the network nps limits, [4, 5, 6, 7] state that compliance with the nps limit should be based on the 95-percentile of the 10-minute average measurements over at least one week, which should not include major public holidays. Therefore, these standards recognise that for network compliance purposes long term heating effect of nps should be assessed and therefore transient phenomena such as faults are excluded. In fact [6] has introduced the concept of “flagging”. During a fault or dip, swell, or interruption, the measurement algorithm for other parameters (for example, frequency measurement) might produce an unreliable value. The flagging concept therefore avoids counting a single event more than once in different parameters (for example, counting a single dip as both a dip and a frequency variation) and indicates that an aggregated value might be unreliable. Flagging is only triggered by dips, swells, and interruptions. The flagging concept is applicable for Class A measurement performance during measurement of power frequency, voltage magnitude, flicker, supply voltage unbalance, voltage harmonics, voltage inter-harmonics, mains signalling and measurement of under-deviation and over-deviation parameters. If during a given time interval any value is flagged, the aggregated value including that value shall also be flagged. The flagged value shall be stored and also included in the aggregation process, for example, if during a given time interval any value is flagged the aggregated value that includes this value shall also be flagged and stored. The user may decide how to evaluate flagged data.

Reference [5] also provide a basis for the limit on fast changing nps voltages, such as during bursts or start up condition, based on 99-percentile daily value of UBF over very short time, e.g. 3s period, against the planning level for UBF times a multiplying factor, for example 1.25 to 2 times the planning level, to be specified by the network operator.

### 3- MEASUREMENTS AND NPS PROFILE

CIGRE/CIRED Joint Working Group C4.103 published results of a comprehensive international survey of voltage unbalance [9]. In total 168 EHV, 940 HV, 497 MV and 222 LV sites were considered. EHV levels are defined as voltages above 150kV, HV voltages above 35kV and up to 150kV, MV above 1kV and up to 35kV. The measurements were generally compatible with IEC 61000-4-30 and based on 95-percentile weekly 10-minute average value voltage unbalance.

Figures 1.A, 1.B, 1.C and 1.D illustrate the voltage unbalance for respectively EHV, HV, MV and LV sites. It can be seen that at EHV level, about 83% of sites have voltage unbalance of less than 1%, 94% of sites below 1.5% and 97% of sites below 2%. These numbers of sites for the same range of unbalance voltage for HV sites, i.e. voltages above 33kV and up to 150kV, are 75%, 85% and 90%. About 98% of sites at these voltage levels have unbalance level of less than 3%. For MV and LV sites about 95% of sites the voltage unbalance are below 2%.

Using the survey result, [9] later proposes limits for different voltage level based on 95% of sites. This will be dealt with later in this report.

Amongst many publications, [9, 10, 11, 12, 13, 14] highlight the impact of rotating loads, e.g. induction motors, on the voltage unbalance level and its propagation across different voltage levels. Therefore for a meaningful analysis of voltage unbalance, the appropriate load model should be considered.

For the compliance with the GB Grid Code purposes and in relation to new connection applications NGET carry out power quality measurements across the 400kV down to 66kV levels and sometimes 33kV and 11kV. Voltage unbalance is part of the measurement. Although exact network configurations during the measurement period is not known measurements have been taken throughout the year and therefore some of them would include outage seasons, when the network is at lower strength compared to high season due to equipment outage or low generation.

The measurements are based on 95-percentile weekly 10-minute average values. Figures 2.A to 2.E illustrate the voltage unbalance in the network in England and Wales over a 10-year period.

Based on 95-percentile weekly 10-minute average values the voltage unbalance at 95% of sites is below 0.52%, 0.42%, 0.67%, 0.68% and 0.86% respectively for 400kV, 275kV, 132/66kV, 33kV and 11kV. If one considers 99-percentile of the weekly values then the voltage unbalance for 95% of sites are below 0.58% (400kV), 0.47% (275kV), 0.83% (132/66kV), 0.80% (33kV) and 0.89% (11kV).

Scottish Power have provided voltage unbalance measurement for a number of sites in England and Wales. The data were in the form of graphs in image format rather than sample data. Therefore, the maximum values were estimated by visual inspection over the measurement period. These are given in Table 1. As can be seen all values are below 2%. Based on 95% of sites the voltage unbalance level is about 1.4% for 33kV and 1.6% for 11kV. Table 2 illustrates the measurement data from Scottish and Southern. These figures are higher than 95-percentile levels in NGET for the same voltage levels, which can be due to a number of reasons including the fact that the NGET measurement nodes are usually close to the HV busbars but the measurements provided by Scottish Power and Southern may be at load nodes further from the 132kV supply points. Higher values at load node far from bulk supply points may indicate that the unbalance factor is mostly influenced by unbalance downstream than transferred from EHV or 132kV networks.

kV	Substation Name	UBF (%)
132	St Asaph	0.46
33	Crewe Grid	0.80
33	Denbigh	0.65
33	Dolgarrog	1.15
33	Four Crosses Grid	1.35
33	Wade Grid	0.35
33	Ince Local	0.40
33	Rhydlydan	0.52
33	Strandgate Generators	0.95
11	Aluminium Power Co	0.75
11	Beaumaris Llanddona fdr	1.10
11	Bethesda-Penrhyn	0.80
11	B R Bankhall	0.55
11	Borough Hospital	1.00
11	Cemmaes Rd Primary	1.40
11	Gateworth Sewage Consumer	0.91
11	Glen-yr-Afon	1.60
11	Grayman Pressings	1.65
6.3	Canada Dock Manweb s/s	0.40

Table 1- Voltage Unbalance Measurement Courtesy of Scottish Power

kV	Substation Name	UBF (%)
33	Greater Torrington	1.54
33	Barnstaple	0.82
33	Rainford	0.39
33	Darracott Moor Windfarm	0.66

Table 2- Voltage Unbalance Measurement Courtesy of Scottish and Southern

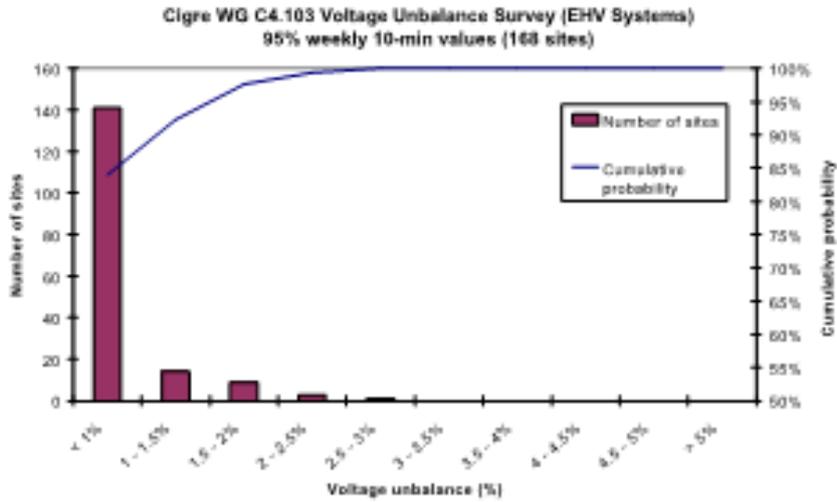


Fig 1.A- CIGRE WG C4.103 Voltage Unbalance Survey, EHV Sites

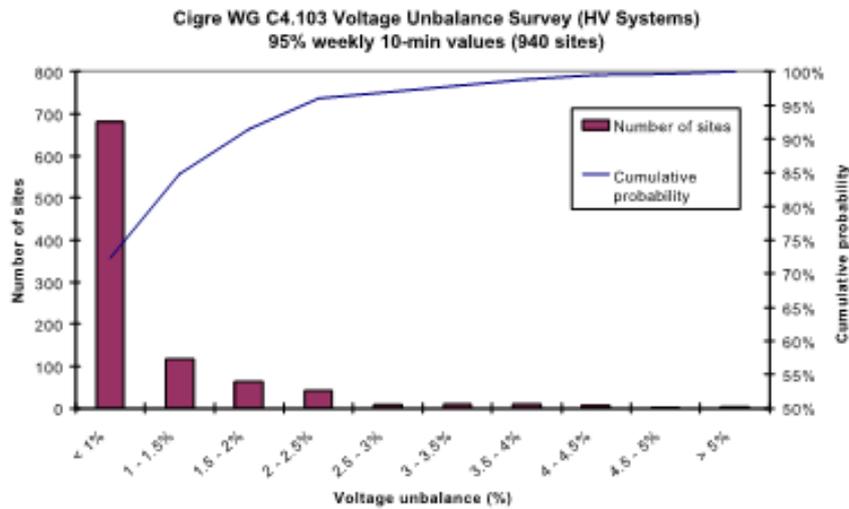


Fig 1.B- CIGRE WG C4.103 Voltage Unbalance Survey, HV Sites

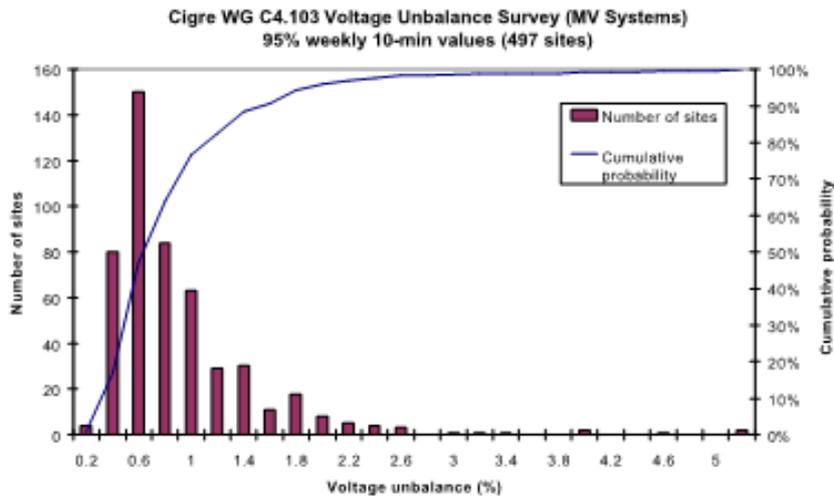


Fig 1.C- CIGRE WG C4.103 Voltage Unbalance Survey, MV Sites

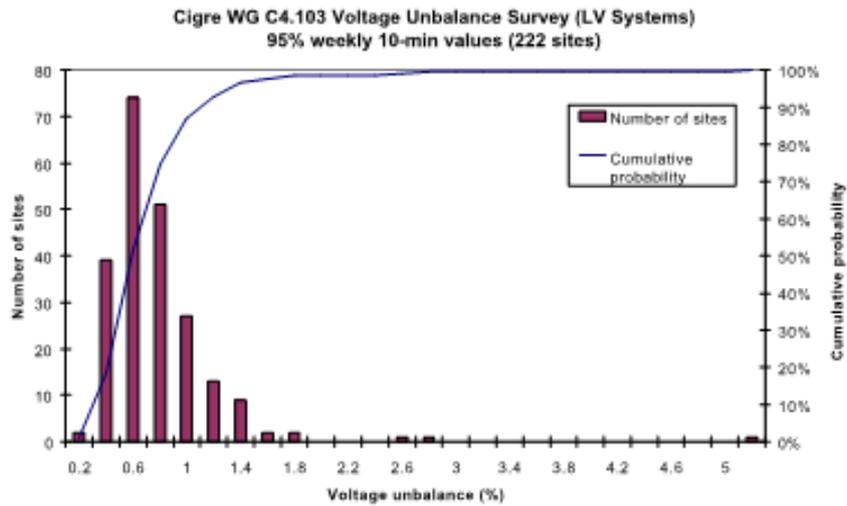


Fig 1.D- CIGRE WG C4.103 Voltage Unbalance Survey, LV Sites

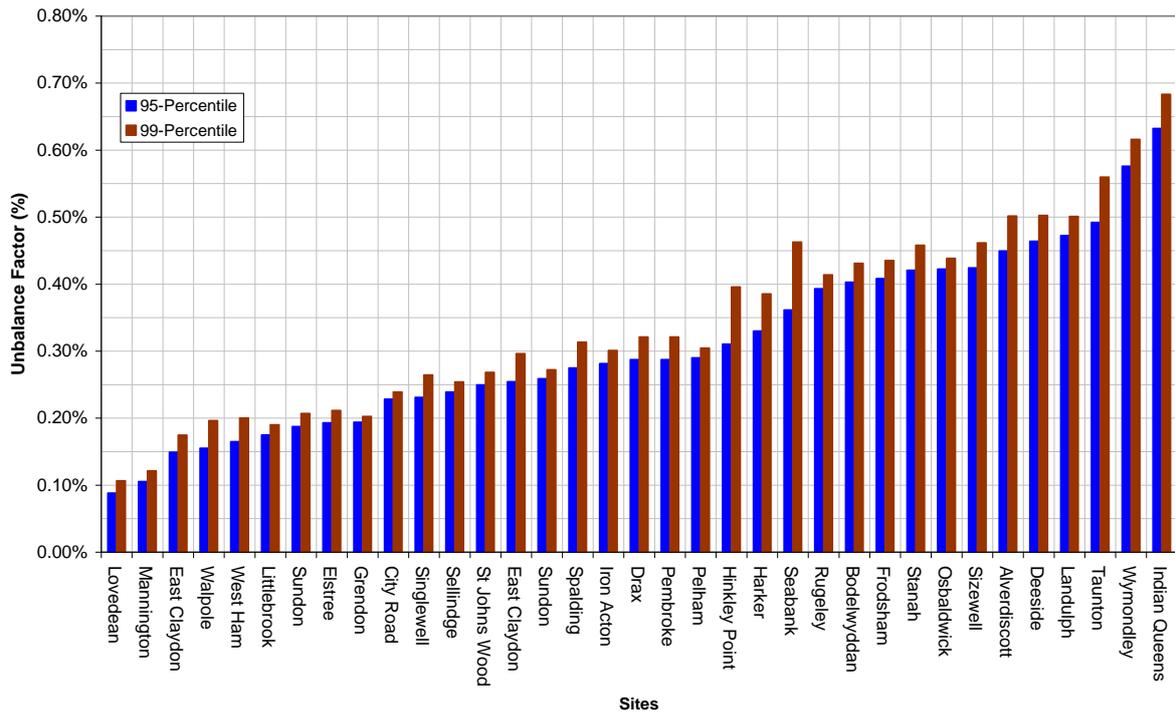


Fig 2.A- Unbalance Profile in England & Wales Network, 400kV Sites

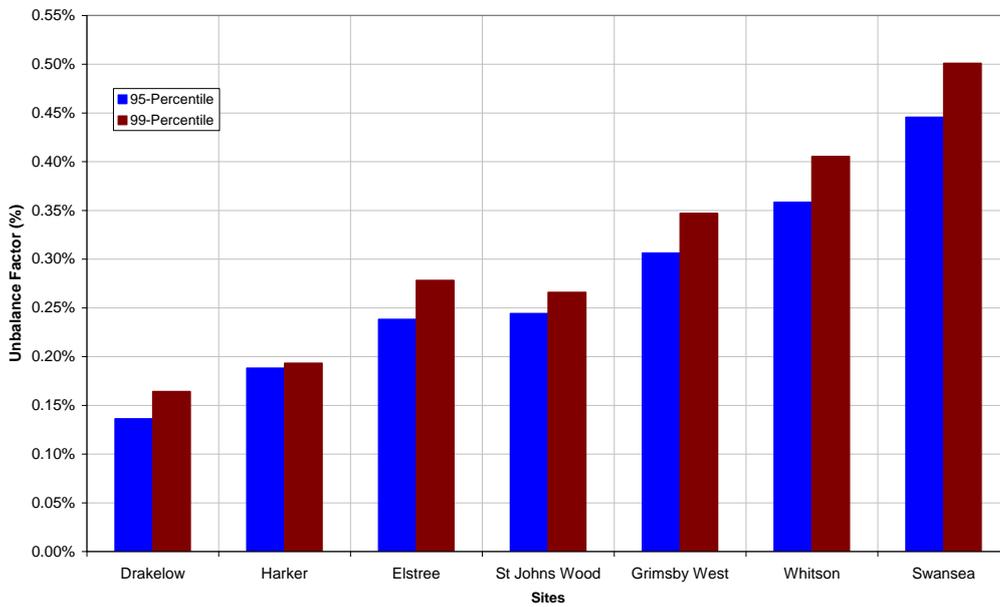


Fig 2.B- Unbalance Profile in England & Wales Network, 275kV Sites

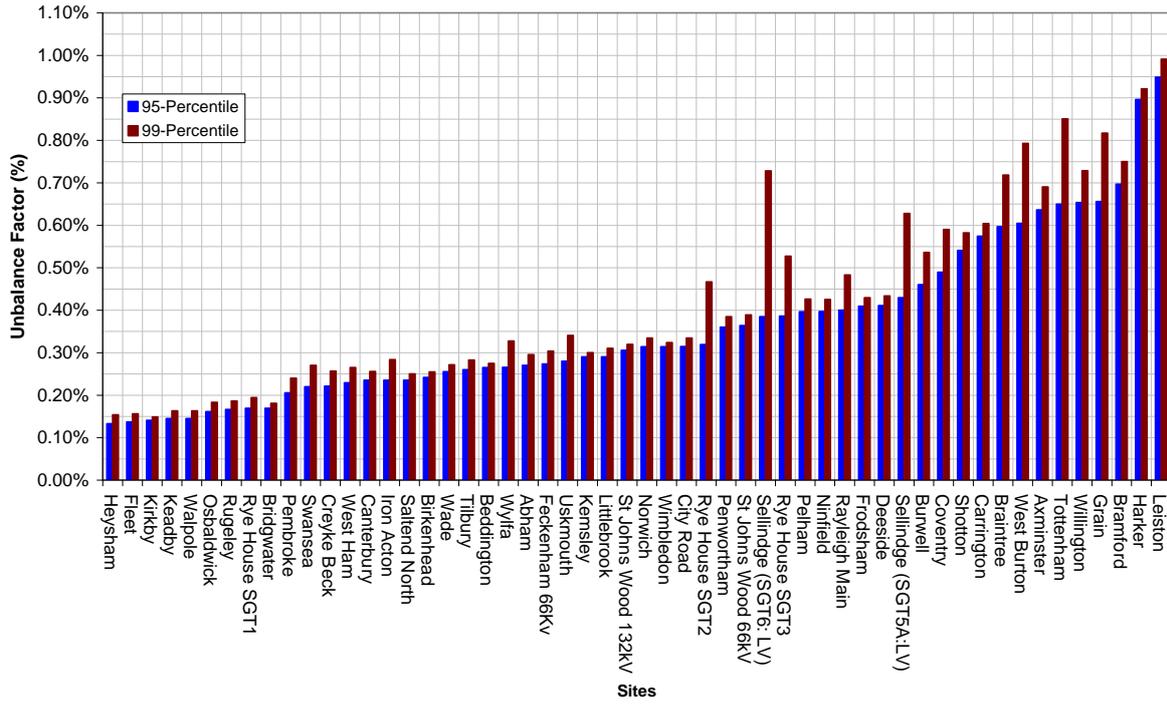


Fig 2.C- Unbalance Profile in England & Wales Network, 132/66kV Sites

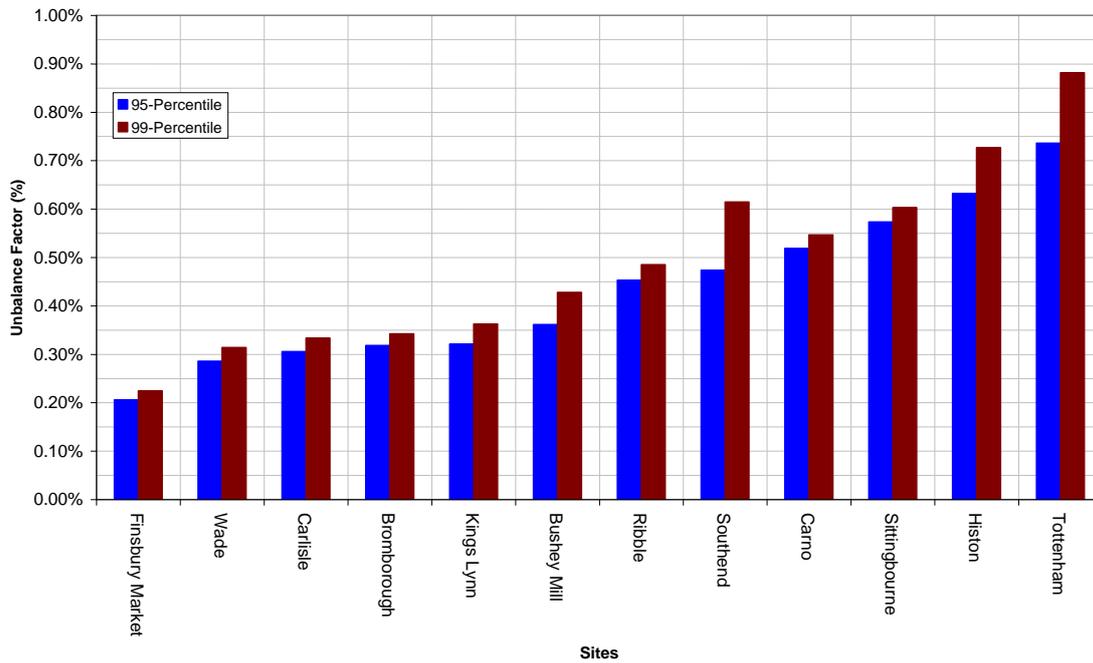


Fig 2.D- Unbalance Profile in England & Wales Network, 33kV Sites

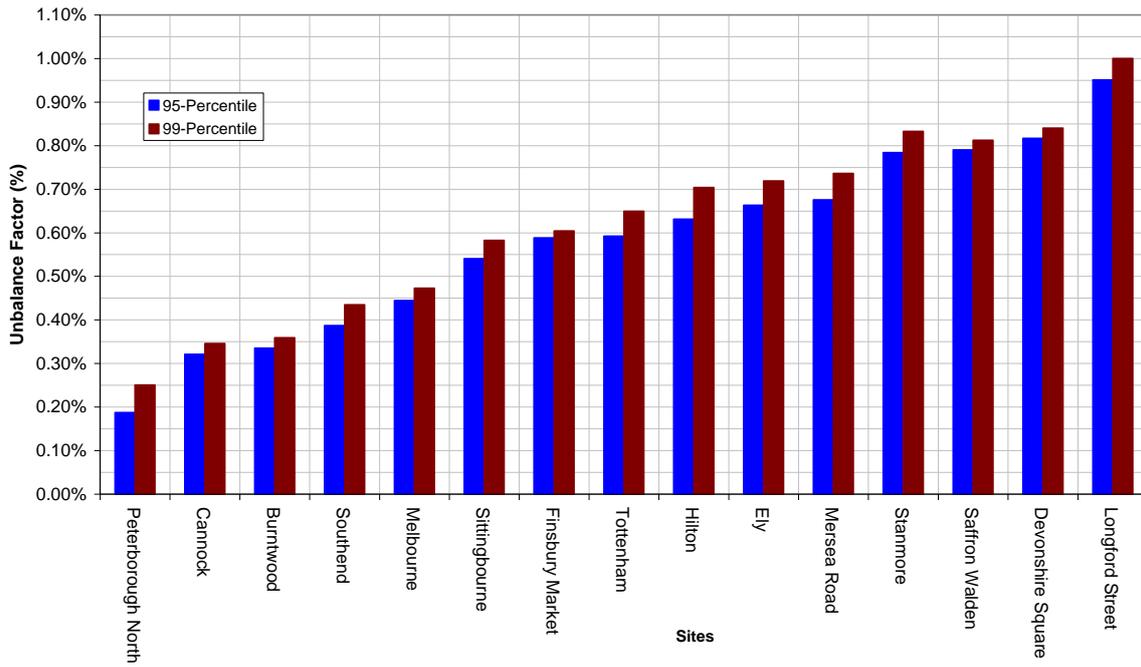


Fig 2.E- Unbalance Profile in England & Wales Network, 11kV Sites

#### 4- COST OF NPS: SUSCEPTIBILITY VS MITIGATION

Power systems contain only pps sources, thus the energy conversion at the source takes place through this component only. However, due to unbalance traction supplies and mainly unbalance impedances, whether originating from the load or network, nps and zps currents flow in the network, which have the following main detrimental impacts. Note that zps current may be blocked by delta connected or unearthed transformers.

- i) Negative phase sequence and zps currents and voltages cause additional losses in the network.
- ii) Zero sequence currents, which by definition have equal magnitudes and phase angle in all three phases, cannot produce significant armature reaction inside rotating equipment such as induction motors or synchronous machines as the stator three phase windings are physically 120° apart and thus the resultant armature reaction in the machine air gap is small. This current however produces extra stator losses and may cause heat spot at the winding ends and rotor bearings. Negative phase sequence current, on the other hand, has significant impact. The rotating field or armature reaction, in the air gap created by the stator nps current rotates in space in opposite direction to the rotor rotation, as shown in Fig 3. This induces voltage in the rotor which causes current to flow in the rotor body. Because the armature reaction rotates in opposite direction to the rotor but with nearly the same speed, it looks to the rotor as if the field is rotating at nearly twice the speed. Therefore the depth of penetration of the field into rotor is not large and thus the induced emf in the rotor produces circulating current on mainly surface of the rotor resulting in increase in the rotor temperature.
- iii) Negative phase sequence current produces pulsating torque due to revers rotating magnetic field and thus additional noise and vibration which may lead to reduction in life or premature breakdown.

When nps current flows in a rotating equipment the machine behaves similar to subtransient condition as the flux created by the armature nps current mostly closes its path through air and surface of the rotor with no significant penetration into iron of the rotor and hence the nps reactance of the machine is similar to the subtransient impedance. Thus:

$$X^- \approx \frac{X_d'' + X_q''}{2} \quad \text{for salient pole machines} \quad (5)$$

$$X^- \approx X_d'' \quad \text{for cylindrical rotor} \quad (6)$$

Where  $X_d''$  and  $X_q''$  are respectively the direct and quadrature axis subtransient reactances. For induction motors, the subtransient reactance can be 5 to 7 times smaller than the motor impedance in normal operating condition.

Therefore, small amount of nps voltage at the rotating equipment terminal can produce significant amount of nps current in the machine resulting in overheating and pulsating torques and thus they should be protected against excessive nps current.

Most induction motors are designed to run at 50% to 100% of their rating, where the maximum efficiency is usually near 75% of rated load. The range of good efficiency varies with individual motors and tends to extend over a broader range for larger motors as shown in Fig 4 [15].

In order to operate efficiently within the supply system statutory voltage and frequency variations and also to meet the starting torque requirement, motors are usually overrated. Furthermore, motors overload capability is specified by its Service Factor, which defines its capability to tolerate overload when the supply system voltage and frequency deviate from the nominal values. For motors up to 150kW Service Factor of 1.15 and for larger motors 1.0 is specified [16]. In the selection of motors for a given mechanical load a safety margin of between 10% and 25% is often considered, depending on the load size [17].

When an a.c. motor is connected to a three phase voltage system having an nps component exceeding 1% of the pps component of the voltages over a long period, (at least the thermal time constant of the machine), the permissible power of the motor is less than the rated power to reduce the possibility of damage to the motor. A typical derating factor for motors of design N within the scope of IEC 60034-12 [18] is given in Fig 5 on the supposition that the pps component of the supply voltage

is close to the rated voltage. Operation of the motor above a 5 % voltage unbalance condition is not recommended [19]. As can be seen from Fig 5, for 2% unbalance the motor should be derated by about 5% or alternatively an oversize motor should be used. Since the nps limit in HV, MV and LV is 2% [2, 3, 4], this has to be considered when selecting a motor. Table 3 gives typical induction motor increase in losses and temperature with respect to unbalance factor [20].

Unbalance value (%)	0	2	3,5	5
Stator current (A)	$I_n$	$1,01 \times I_n$	$1,04 \times I_n$	$1,075 \times I_n$
Loss increase (%)	0	4	12,5	25
Heating (%)	100	105	114	128

Table 3- Effect of Voltage Unbalance on Motor Operating Characteristic

The nps impedance of induction motors at normal slip range is mostly given by the stator and rotor leakage reactances and is in the range of 14% to 20% based on the motor rating.

GEC-Alstom [21] suggests that the unbalance protection of motors should be set at 20% of rating for alarm using definite time relays and 50% of rating for trip using relays with IDMT characteristic. Considering the alarm setting and nps impedance of 14%, the nps voltage which causes alarm would be about 2.8%. The nps voltage causing a trip is 7%. These are above the limits set out by the Distribution Code.

GE [22] recommend rather conservative setting of 10-15% x FLA (full load current) for the unbalance alarm with a delay of 5-10s and 20-25% x FLA with a delay of 2-5s for trip. The assumptions for these setting are nps impedance of 17% and unbalance limit of 1.5% or more in the supply system.

ABB [23] recommend that for unbalance protection a voltage setting of 5% and/or current setting of 20% of rated current is used.

As illustrated above, the statutory limit for the supply system and motor nps withstand capability influence the setting of motor protection.

Unbalanced loading in generators may produce more severe heating than balanced three-phase operation. Series faults close to the generator will cause nps currents. Unsymmetrical faults may produce more severe heating in three-phase synchronous machines than symmetrical faults. Typical conditions and incidents that can cause unbalanced loading are:

- Single-phase loads close to the power plant.
- Untransposed transmission circuits.
- Unbalanced step-up transformers.
- Series faults in the transmission network.
- Series faults on the secondary side of the step-up transformer.
- Series faults on the primary side of the step-up transformer.
- Pole discrepancy in the generator breaker.
- Unbalanced shunt faults close to the power plant.
- Unbalanced shunt faults on the generator busbar.

These voltages cause currents to flow in the rotor and associated windings. Due to the skin effect, these currents flow close to the surface of metallic objects in the rotor. The penetration depth in magnetic steel is less than one millimetre. These currents will quickly heat the rotor body, the slot wedges, the retaining ring and the damper winding if there is one. These components are normally already under great stress in large turbo-generators. If the nps current persists, the metal will melt and damage the rotor structure [24, 25].

The amount of nps current that the machine can tolerate depends on the design of the generator.

#### 4.1. Turbo Generators

Generators without damper winding do not have well-defined paths for the induced double frequency currents. The electromagnetic and thermal utilization increases steadily. This is especially true for the rotors in turbo-generators. This means that the turbo-generators are very sensitive to unbalanced loading [24].

#### 4.2. Hydro Generators

Salient pole generators with damper windings (hydro-generators) have well-defined paths for the induced double frequency currents. The currents flow mainly in the damper windings. Generally, hydro-generators have strong damper windings and they can withstand higher negative-sequence currents than the turbo-generators can. There are very few hydro-generators without damper windings [24].

#### 4.3. Continuous $I^-$ -Capability

Generators can only withstand nps current of usually 8% to 15% of the rated current continuously. When larger values of nps currents occur, these currents produce rapid heating by  $I^{-2} \cdot R$ , where  $I^-$  is the per unit value of the nps current (based on the full load current). The resistance  $R$  is the resistance of the iron in the rotor body and is assumed to be constant. As heat build-up is time dependent, then the heating a rotor receives will depend on  $I^{-2} \cdot R \cdot t$ . As  $R$  is constant, heating is proportional to  $I^{-2} \cdot t$ . Manufacturers state that their generators rotors will have a certain  $I^{-2} \cdot t$  rating, also known as  $K$  Constant. The constant  $K$  corresponds to the time (number of seconds) a machine can withstand an nps current equal to the rated current of the generator and it depends on the size of the generator and the method of cooling. For example, if  $I^{-2} \cdot t$  or  $K$  rating of a generator is 10 and 20% of nps current flows in the generator, using (7) the generator will be damaged in 250s. Therefore, it is essential that generators are protected against nps currents.

$$\int I^{-2} \cdot t = K \tag{7}$$

An alarm is provided which usually operates when continuous  $I^-$  rating of the generator is exceeded, usually 8% to 15% of rated current for large generators and trips when  $I^{-2} \cdot t$  rating is exceeded. Table 4 shows typical continuous negative-sequence current capability for generators with different forms of cooling [24]. Most countries support Table 5, the American suggestion, concerning the continuous  $I^-$  capability [24]. The machine manufacturers can provide accurate values.  $I^-_{max}$  in Tables 4 and 5 refer to maximum nps current based on generator rated current that the machine can tolerate continuously. As can be seen, for larger generators lower  $I^-$  is suggested. Figure 6 shows the requirements on the nps current withstanding capability in graphical form.

The constant  $K$  depends on the size of the generator and the method of cooling. For most generators, the value is from 5 to 30 s, but for some hydro-generators it may be as high as 60 s, as shown in Table 4 [24].

There are industry standards that determine the permissible unbalance for which generator is designed [26]. For generators up to 800MVA, the generators should be designed to have  $K$  of 10 or longer and for larger machines (8) defines the requirement [26].

$$K \geq 10 - \frac{S_n - 800}{160} \tag{8}$$

Where  $S_n$  is the nominal power of the machine in MVA.

Figure 7 shows these requirements in a graphical form. A 500MVA generator should have at least  $K=10s$  and a 1600 MVA generator should have at least  $K=5s$ .

IEC 60034-1 [27] also presents nps current and  $K$ -constant requirements for rotating machines.

To avoid un-necessary loss of generation, [25] suggests that coordination between nps protection of transmission network and power station owner should be made.

Figure 8 illustrates data on the negative-sequence current capability. The ability of large generators to stand negative-sequence current is progressively decreasing because their specific rating is increasing.

Figure 9 illustrates the nps voltage on the HV side of generator transformer. The data, including the generator nps impedances, to calculate nps voltages was obtained from GB model in Power Factory. All data was converted to 100MVA and common voltage bases in order to show them on the same plot. In total 220 generators were considered of which 153, 36 and 31 were respectively connection to 400kV, 275kV and 132kV. In developing Fig 9 it was assumed that the maximum nps current generators can tolerate continuously is 8% of the rated current. Table 6 shows the average and 50, 5 and 1 percentiles. For example, 1-percentile means that 99% of the nps values are above the level. Table 6 also shows that 99% of generators considered are tolerable to nps voltage level of 2% and higher if their continuous nps current rating is 8%. Equation (9) was used to calculate the nps voltage level.

$$V^- = (X_g^- + X_{Tx}^-) \times I^- \quad (9)$$

Where  $X_g^-$  and  $X_{Tx}^-$  are respectively generator and generator-transformer nps reactances.

From Fig 9, it can be seen that for generators above 400MVA the nps voltage at the grid supply point that causes 8% nps current is 2.8% or higher. Between 160MVA and 400MVA this level is 2.3% and for generators smaller than 160MVA the level is 1.9%. The single value below 2% level is for the 155 MVA machine at Indian Queen where the generator transformer has an impedance of 7.5% on 204 MVA transformer rating. This causes lower voltages to drive an nps current of 8% into the machine.

Smaller generators and generators with indirect-cooling often have higher than 8% nps current rating and therefore the curves shown in Fig 9 should be scaled upwards. If generators are of indirect-cooling type then the nps current capability should be considered to be 10% or higher.

Note that Fig 9 has been developed using generic nps current capability and for indication only. The actual generator nps current capability should be used for alarm and protection setting purposes.

Generally, unbalanced protection consists of a dependent time overcurrent relay. A negative-sequence filter energizes the overcurrent relay. The relay shall be set to match the machine characteristic. Setting must be above any normal unbalances that may exist in the network for normal operating condition or the statutory limits imposed by the national standards.

Negative phase sequence voltage also affects HVDC converter stations and variable speed drives. They tend to cause an increase in harmonic emission and generation of non-characteristic harmonics. The designers of such installations must be aware of the maximum nps voltage level that is expected in the network to accordingly rate harmonic filters and also to comply with the harmonic limits.

The American National Standards Institute (ANSI) standard C84.1 [28] was developed by the National Electrical Manufacturers Association (NEMA), which recommends that electrical supply systems should be designed and operated to limit the maximum voltage unbalance to 3% when measured at the electric-utility revenue meter under no-load conditions [28]. The IEC recommends that the maximum voltage unbalance of electrical supply systems at HV, MV and LV be limited to 2% [4, 5].

Concurrently, NEMA, the developer of ANSI C84.1, in the standard NEMA MG1-2009 [29] recommends that for voltage unbalance greater than 1%, induction motors should be derated by the appropriate factor. IEC standards also restrict the permissible voltage unbalance on induction motors to 1% and require a derating of the machines if unbalance is greater [18].

The derating factor graph in Fig 5 also appears in the ANSI/IEEE Std. 141-1993 [30] and ANSI/IEEE Std. 241-1990 [31]. Both the Standards indicate that some electronic equipment, such as computers, may experience problems if the voltage unbalance is more than 2 or 2.5%. They both also state that in general, single-phase loads should not be connected to three-phase low voltage circuits supplying equipment sensitive to phase-voltage unbalance. Instead, a separate circuit should be used [30, 31].

The apparent contradiction in ANSI C84.1 [28], allowing a 3% voltage unbalance on power systems and NEMA MG1 [29], recommending motor derating in the presence of greater than 1% voltage unbalance, can be explained by the following rationalization.

In developing the ANSI C84.1 recommendation for voltage unbalance, economic studies were conducted indicating the following [28, 32]:

- 1) Ultimately, the customer ends up paying for the utility related costs required to reduce voltage unbalance, and the manufacturing related costs required to expand a motor’s unbalanced voltage operating range,
- 2) Utilities’ incremental improvement costs are maximum as the voltage unbalance approaches zero and decline as the unbalance is permitted to increase,
- 3) Manufacturers’ incremental motor related costs are lowest at zero voltage unbalance and increase rapidly as the unbalance increases.

When these costs, excluding motor related energy costs, are combined, curves can be developed as shown in Fig 10, that indicate the annual incremental cost to the customer for various percent voltage unbalance limits. The optimal range of voltage unbalance occurs when the cost to the customer is minimized, which is implied in ANSI C84.1 to be at approximately 3% as shown in Fig 10.

Therefore, the cost of mitigation by utilities to reduce the voltage nps levels in the network should be weighed against the susceptibility level considered in design of equipment. This approach has led to a universally accepted maximum level of 2% for nps voltages in the supply system although in particular networks such as those with long single phase feeders up to 3% is allowed [4, 5]. According to [28] the cost of designing the network for lower nps levels at distribution voltages would be higher than the cost of improving the tolerance level of equipment.

Type of machine	Cooling and cooling medium	$\Gamma_{max}$	$K$
		%	s
Turbo generator	Direct hydrogen 30 lb/in <sup>2</sup>	10	7
Turbo generator	Conventional hydrogen 30 lb/in <sup>2</sup>	15	12
Turbo generator	Conventional hydrogen 15 lb/in <sup>2</sup>	15	15
Turbo generator	Conventional hydrogen 0.5 lb/in <sup>2</sup>	15	20
Salient pole machine	Conventional air	40	60

Table 4- Negative Phase Sequence Current Capability

Cooling Method	$S_n$	$\Gamma_{max}$
	MVA	%
Indirectly cooled		10
Directly cooled	<960	8
Directly cooled	961-1200	6
Directly cooled	>1200	5

Table 5- Suggested Continuous Negative Phase Sequence Capability

	Average	50%	5%	1%
400kV	3.05	3.11	2.36	2.00
275kV	3.17	3.24	2.23	2.22
132kV	2.82	2.71	2.38	2.35

Table 6- NPS Voltage Levels in GB Network for Average and Different Percentiles

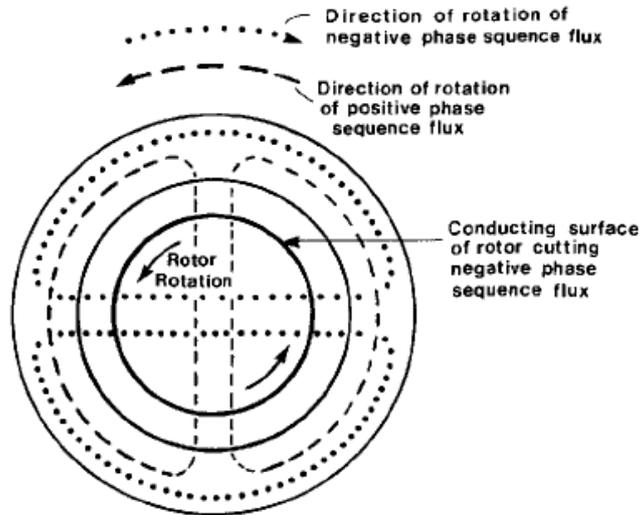


Fig 3- End View of Generator Rotor and Stator Showing Rotor Cutting nps Fluxes

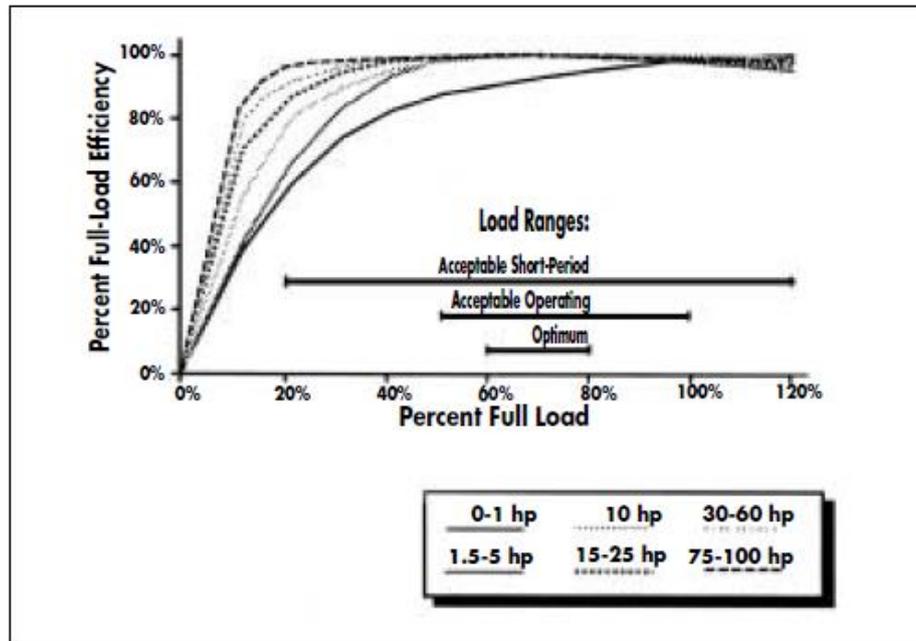


Fig 4- Motor Part Load Efficiency (as a Function of % Full-Load Efficiency)

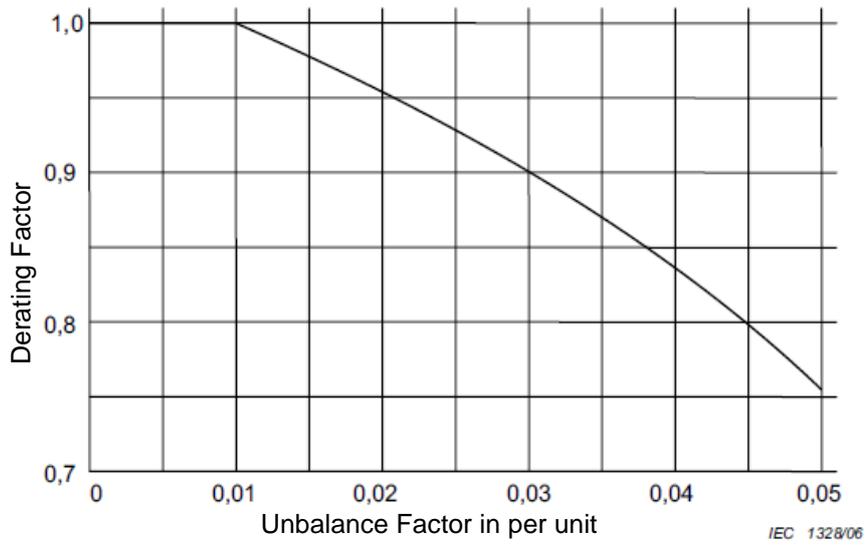


Fig 5- Typical Values of Derating of Design N, Three Phase Cage Induction Motors within the Scope of IEC 60034-12

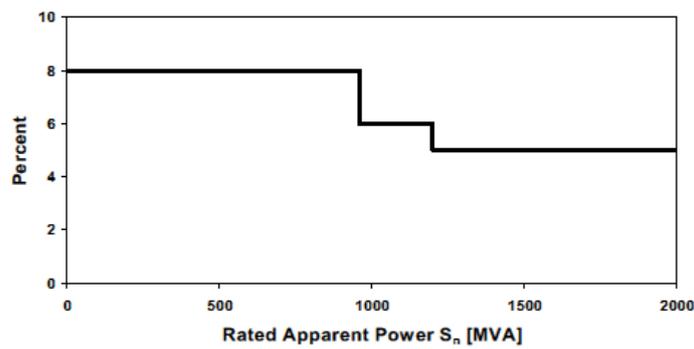


Fig 6- Negative Phase Sequence Current Capability vs MVA Rating

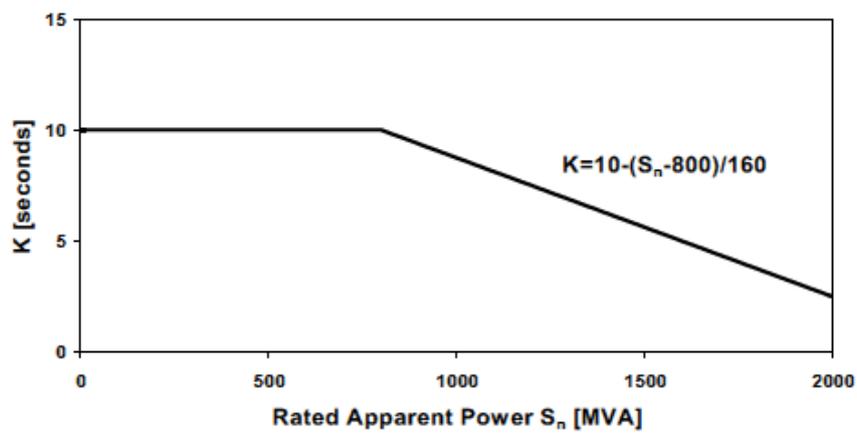


Fig 7- Constant K versus Machine MVA

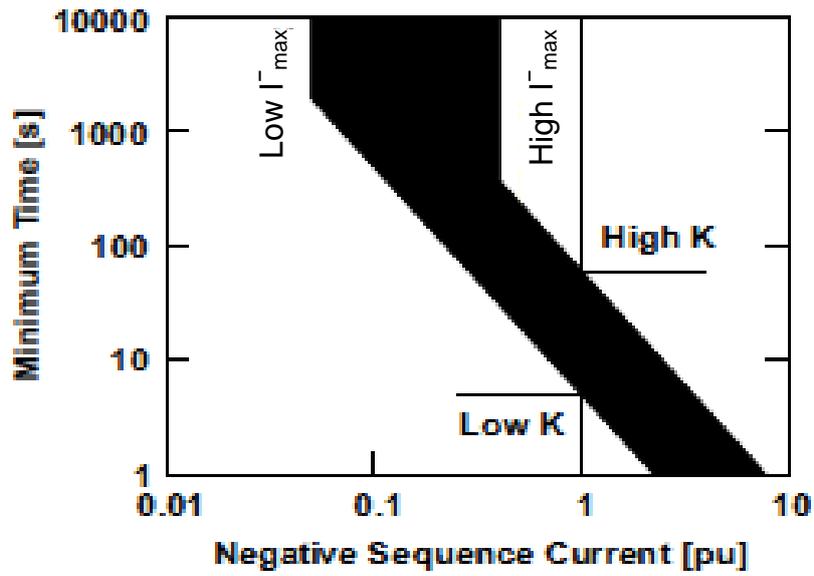


Fig 8- NPS Current-Time Capability for Different K

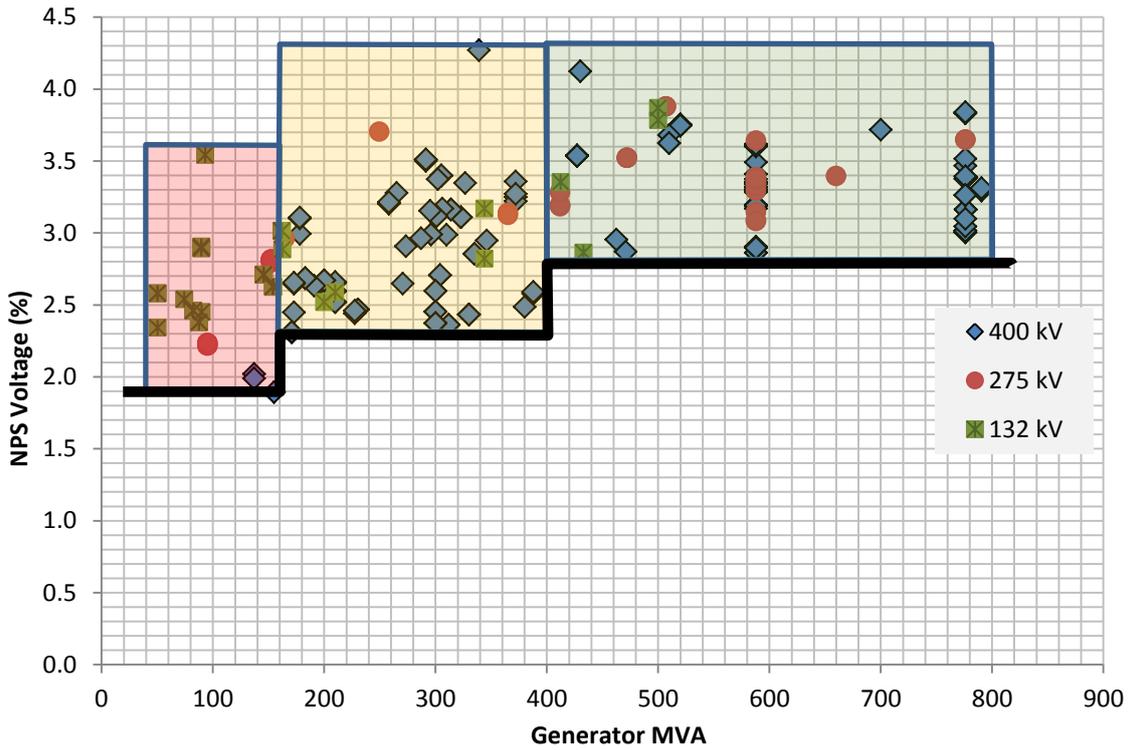


Fig 9- NPS Voltage vs Generator MVA for 8% NPS Current all Referred to HV Side of Generator Transformer

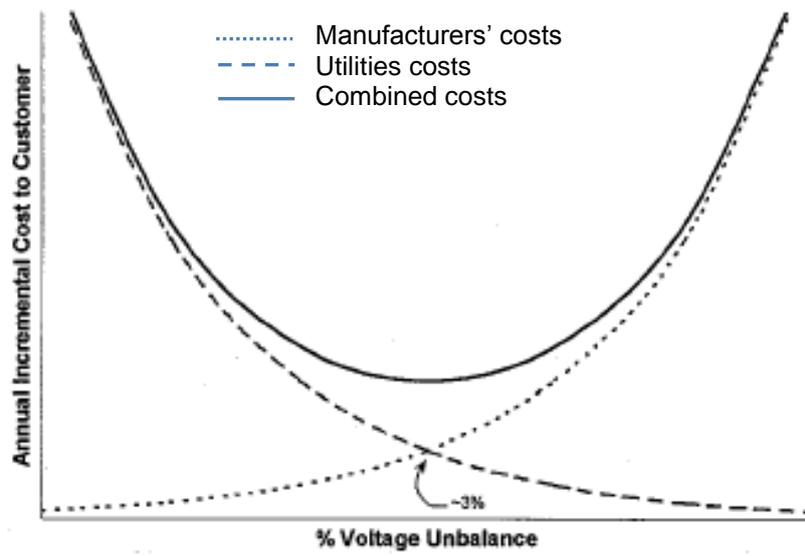


Fig 10- Annual Incremental Cost to the Customer for Various Percent Voltage Unbalance Limits

## 5- SOURCE OF UNBALANCE

At a point of common coupling (PCC) or point of evaluation (POE) the voltage unbalance arises due to one or more of three reasons:

- I. Unbalanced load currents in the three-phase network (unbalanced load or poor apportioning of single-phase loads or single-phase traction).
- II. Unbalanced system impedances (e.g. transmission lines not transposed in upstream network).
- III. Transfer of background nps voltage from one node to another or from one voltage level to another

Fault conditions such as blown fuses or faulty circuit breakers leading to open circuit in one or two phases or short circuit unbalance faults are the other cause of unbalance in power systems. The former are known as series faults and latter shunt faults. As such, these are categorised as faults and therefore not related to the normal system operation and should be detected and cleared in a specified time by protection devices, hence are not the subject of this report which deals with unbalance in the normal network condition.

Due to the geometry and the phase conductor positioning of overhead transmission lines the electrical parameters are different for different phases unless transpositions are used. Even with perfect transposition unequal loading can create unbalance voltages. One cause of unbalance, particularly in residential areas is the uneven distribution of loads across the phases. There is often a tendency for more single-phase connection to be made to some phase due to their position in the junction box or pole cross-arm and hence reach-ability for connection.

As this report is more related to the revision of nps voltage in the transmission network and assumes that the existing limit of 2% is accepted for HV, MV and LV voltage levels, the main focus will be on the sources of the unbalance in the transmission systems.

As stated above, the main source of unbalance in transmission system is untransposed lines. In a perfect transposed line the impedance for all three or six conductors from the sending to receiving ends is equal. The line can be represented by symmetrical matrix where the diagonal elements, the self-impedances, are equal and off-diagonal or mutual impedances between phases are also equal. When this matrix is converted into the symmetrical component impedances using the standard phase coordinate to symmetrical component conversion operator matrix, the sequence networks will be decoupled and hence the mutual impedances between sequence networks is nil, which in turn means that the current in one sequence network does not affect the voltage in another. There is one exception for double circuit lines where there is a mutual coupling between the two circuits zero sequence networks. For untransposed line, on the other hand, this property does not exist and there are mutual effects between the sequence networks of one circuit and between circuits. Appendix A illustrates the relationship between the line impedances and line sequence impedances. It also shows the impedances for a double circuit untransposed L2 type line with the phasing of RYB-BYR.

Equation (10) shows the line impedance matrix for a double circuit, untransposed line. The superscript of impedance terms denotes the sequence impedance and subscripts denote the circuit number. For example,  $Z_{1-1}^{++}$  means the pps impedance of the first circuit,  $Z_{1-1}^{-+}$  the mutual impedance between the nps and pps networks of the first circuit and  $Z_{1-2}^{-+}$  mean the mutual impedance between the nps and pps networks of the two circuits and so on.

$$\begin{bmatrix} V_1^+ \\ V_1^- \\ V_1^0 \\ V_2^+ \\ V_2^- \\ V_2^0 \end{bmatrix} = \begin{bmatrix} Z_{1-1}^{++} & Z_{1-1}^{+-} & Z_{1-1}^{+0} & Z_{1-2}^{++} & Z_{1-2}^{+-} & Z_{1-2}^{+0} \\ Z_{1-1}^{-+} & Z_{1-1}^{--} & Z_{1-1}^{-0} & Z_{1-2}^{-+} & Z_{1-2}^{--} & Z_{1-2}^{-0} \\ Z_{1-1}^{0+} & Z_{1-1}^{0-} & Z_{1-1}^{00} & Z_{1-2}^{0+} & Z_{1-2}^{0-} & Z_{1-2}^{00} \\ Z_{2-1}^{++} & Z_{2-1}^{+-} & Z_{2-1}^{+0} & Z_{2-2}^{++} & Z_{2-2}^{+-} & Z_{2-2}^{+0} \\ Z_{2-1}^{-+} & Z_{2-1}^{--} & Z_{2-1}^{-0} & Z_{2-2}^{-+} & Z_{2-2}^{--} & Z_{2-2}^{-0} \\ Z_{2-1}^{0+} & Z_{2-1}^{0-} & Z_{2-1}^{00} & Z_{2-2}^{0+} & Z_{2-2}^{0-} & Z_{2-2}^{00} \end{bmatrix} \times \begin{bmatrix} I_1^+ \\ I_1^- \\ I_1^0 \\ I_2^+ \\ I_2^- \\ I_2^0 \end{bmatrix} \quad (10)$$

The nps voltage developed at the sending end of say Circuit 1 is given by (11) below:

$$V_1 = Z_{1-1}^- I_1^+ + Z_{1-1}^- I_1^- + Z_{1-1}^0 I_1^0 + Z_{1-2}^- I_2^+ + Z_{1-2}^- I_2^- + Z_{1-2}^0 I_2^0 \quad (11)$$

In a normal operating condition, i.e. no fault, the dominant currents flowing in the line are the pps currents, i.e.  $I_1^+$  and  $I_2^+$ . Hence it can be considered that the other currents are very small compared to the pps currents. Thus:

$$V_1^- \approx Z_{1-1}^- I_1^+ + Z_{1-2}^- I_2^+ \quad (12)$$

Therefore, the induced nps voltage in one circuit is due to the pps currents and the mutual impedances between the nps and pps networks of one circuit and between the circuits.

Similar relationship can be written for the nps voltage developed at the downstream terminal of the second circuit with relevant impedances.

The percentage nps voltage with respect to pps voltage, UBF, at the line downstream (receiving end) terminal can be written in terms of the MVA flow in the line and the short circuit level at the terminal as shown in (13) [32]:

$$UBF = \frac{S_{Load}}{S_{SCL}} \times \frac{Z_{1-1}^+ + Z_{1-2}^+}{Z_S^+} \times 100 \quad (13)$$

Where:

UBF is the percentage nps voltage with respect to pps voltage at the load terminal (downstream)

$S_{Load}$  is the transmitted MVA across the line.

$S_{SCL}$  is the short circuit level at the load terminal (downstream terminal).

$Z_S^+$  is the pps impedance of the network (source impedance) seen from the downstream terminal.

$Z_{1-1}^+$  is the mutual impedance between the nps and pps networks of one circuit.

$Z_{1-2}^+$  is the mutual impedance between nps and pps networks of two parallel circuits.

If only one circuit exists between the two ends of the line then  $I_2^+$  will be zero and thus  $Z_{1-2}^+$  should be removed from the equation, which also applies if one circuit is out of service since there is no contribution from the other circuit. Note that in a double circuit line with RYB and BYR or similar format, there is some cancellation of the nps voltage due to the nearly opposite phase angle of the mutual impedances  $Z_{1-1}^+$  and  $Z_{1-2}^+$ . If the current in one circuit is in opposite direction (counter-flow) to the current in the other then the induced nps voltage will be maximum.

The other main source of the unbalance is single phase supply to traction loads. If it is assumed the current in one phase flows towards the load terminal and returns via another phase and the current in the third phase is zero then at the traction load terminal the current can be resolved into symmetrical components. The nps current is then given by (14).

$$I^- = \frac{\sqrt{3}}{3} I \angle 30^\circ \quad (14)$$

Where  $I$  is the phase current taken by the traction load. Note that  $I$  is a phasor.

The pps current of the load is given by (15).

$$I^+ = \frac{\sqrt{3}}{3} I \angle -30^\circ \quad (15)$$

The nps current produced by the traction load then flows into the system nps impedance producing nps voltages at different terminals with the highest at the point of traction connection.

The percentage nps voltage with respect to pps voltage at the load terminal is given by (16):

$$UBF = \frac{S_{Load}}{S_{SCL}} \left| \frac{I^-}{I^+} \right| \times 100 = \frac{S_{Load}}{S_{SCL}} \times 100 \quad (16)$$

Where  $S_{Load}$  is the MVA of the phase-phase load and  $S_{SCL}$  is the short circuit level at the point of connection. Note that the magnitude of the ratio of nps to pps currents is unity.

The phase pairs to supply traction loads are selected such that reduction of nps current across adjacent traction supply points and background network nps voltage is achieved

The other main source of unbalance is originated from low voltage (LV) networks when distribution of single phase loads across three phases is not perfectly uniform and that not all loads are in service at the same time. The distribution network should be designed according to the nps voltage statutory requirement in the Distribution Code. The leakage of the nps current originating from LV into the EHV system is of less importance since it has to go through several stages of transformation where they exhibit relatively high balance impedances to the current.

## 6- NPS LIMITS

As a result of the opening up of the electricity markets, system operators are being increasingly encouraged to report more and more to external parties, namely users and regulators, information relating to power system performance. Whereas in the past, power quality was often seen as an implicit duty on system operators, today quality objectives have become more and more explicit either in the form of contracts negotiated with customers, or in the form of definite objectives agreed with the regulator. Indeed a number of regulators already have defined, or plan to establish, power quality objectives (e.g. supply continuity and voltage quality) to be met by the electricity supply systems. In a number of countries, regulators may even impose penalties in cases of non-observance of the power quality objectives, i.e. limits. It is an important feature of meeting power quality targets that the interested parties agree on the method(s) of gathering and presenting power quality data.

Considering the scope of this report, the following overview relates to unbalance limit of the power quality indices and objectives in its application in the Grid Code. Power quality indices and objectives may be defined in the form of so-called "voltage characteristics" that apply to public networks from LV to EHV [3, 4, 5, 6]. In addition, various existing other countries national limits addressing unbalance are quoted, with the aim of highlighting the most common denominator among them.

Guidelines for developing voltage unbalance emission limits for installations connected to EHV, HV, and MV power systems have recently been published as a technical report by the IEC. These guidelines, based on the work of Joint Working Group CIGRE/CIRED C4.103, are intended to provide a common basis for the development of similar guidelines or standards in specific countries [5, 7].

Particular reference is made to the inherent network unbalance caused by untransposed lines and cables [5, 12, 32, 34]. Coefficient  $k_{UE}$  was introduced in [5] to define contribution to voltage unbalance that can be allocated to unbalanced installations. Conversely  $1-k_{UE}$  represents the fraction that accounts for system inherent asymmetries. Reference [5] states that an equitable share of emissions should be allowed between the unbalanced installations and the various system inherent sources of imbalance present in the considered power system [7, 32, 33, 34].

A single value for  $k_{UE}$  or  $1-k_{UE}$  cannot be given and it should be determined by the *System Operator* or owner depending on the system characteristics, line length and configuration, etc [5, 12, 13, 14, 35, 36]. It can be different at different voltage levels, and will in most cases be less than 1. Table 7 gives indications of possible values [5].

In setting power quality indices or limits, in addition to the immunity of equipment two other main points should be considered. Transfer of the disturbance, in this case unbalance or nps voltage, from one voltage level to another and aggregation of the transferred nps voltage with that originating or already existing locally [5, 7, 9, 12, 13, 14]. For example, nps voltage originated from EHV network is propagated to HV (132kV) and aggregated with the nps voltages originated in 132 kV and lower voltages.

Reference [5] recommends that the aggregation of nps voltages with different sources is carried out with the summation exponent of 1.4. Hence:

$$V^- = \sqrt[1.4]{(V_L^-)^{1.4} + (T_{RL} V_R^-)^{1.4}} \quad (17)$$

Where:

$V^-$ : is the aggregated nps voltage.

$V_L^-$ : is the locally generated nps.

$T_{RL}$ : is the transfer coefficient from remote (upstream) to local (downstream) nodes.

$V_R^-$ : is the nps voltage at remote node.

In developing a method to allocate contributions from different sources of unbalance, [5] considers transfer coefficient of 0.9 from MV to LV and 0.95 from HV to MV and equal share unbalance contribution at each voltage level.

An extensive study of the GB network was conducted to determine transfer coefficient across different voltage levels. This was carried out by performing unbalance load flow in Power Factory which is basically a three phase load flow analysis. In National Grid all studies related to unbalance is carried out using this feature in Power Factory. The lines in-field phasing is incorporated in the model.

The model used in unbalance studies is a 50 Hz model that is also used for balance load flow. The algorithm used for unbalance load flow is well established phase-coordinate model. It does not assume balance network and considers the full line matrices. The model is used in all nps assessments for new connection and it gives the background nps voltages as well as the incremental increase in the nps voltage due to a new connection. As such, the procedures in [5] or other references for aggregating background nps voltage and new connection are not necessary as the nps assessment adopted by National Grid gives the aggregated voltages directly.

It is important to note that load model affects the calculated nps voltages. Considering constant power load model, i.e. constant P and Q, leads to transfer gains of unity or sometimes greater than unity [9, 36]. Motor loads at lower voltages on the other hand reduce the nps levels and transfer coefficients. In order to obtain more accurate unbalance load flow results, the loads at every demand point were changed to include motor type. For load apportionment into P, Q and motor type, the procedure and scaling factors given in [37] was used. DCHFRR load model, was originally developed through measurement and modelling by electricity industry in early 80s for harmonic studies. It recognises that a portion of the load in distribution systems is of motor type and hence apportions the load into P, Q and motor type which in turn is represented by start-up impedance. As already mentioned in this report, the motor nps impedance is the same as the start-up impedance. The load scaling factors are given in [37] for different network seasonal loads. It is to be noted that the DCHFRR load scaling factors reflect the fact that the motor load portion does not have strong seasonal variation, since the motor loads are mostly related to industry and thus approximately constant.

The study to determine the transfer coefficient from EHV network down to HV (132kV) and lower resulted in the generic transfer coefficients given in Table 8. These values are based on 99-percentile of cases considered.

Reference [5] states that although unbalance factor (UBF) of 2% for voltage levels of up to HV level has been accepted and used as a norm of industry worldwide the limit for UBF for EHV level and above varies from 1% to 2%.

A survey of nps limit in other countries was also conducted. Table 9 illustrates the limits for unbalance that are enforced in other countries.

CIGRE Working Group C4.07 [7] published their final report in 2004. It recommends that the limit for voltage unbalance factors is set at 2% for LV, MV and HV and 1.5% for EHV and above. It also allows in some areas at LV and MV, unbalances up to 3% occurring in cases where predominantly single-phase loads are supplied. The report also suggests indicative planning level of 2%, 1.5% and 1% for unbalance respectively for MV/LV, HV and EHV voltage levels.

System characteristics	Indicative values of the fraction $\{1-k_{UE}\}$ accounting for system asymmetries
<ul style="list-style-type: none"> <li>• Highly meshed system with generation locally connected near load centres.</li> <li>• Transmission lines fully transposed, otherwise lines are very short (few km).</li> <li>• Distribution systems supplying high density load area with short lines or cables and meshed systems.</li> </ul>	0,1 – 0,2
<ul style="list-style-type: none"> <li>• Mix of meshed system with some radial lines either fully or partly transposed. Mix of local and remote generation with some long lines.</li> <li>• Distribution systems supplying a mix of high density and suburban area with relatively short lines (&lt;10 km)</li> </ul>	0,2 – 0,4
<ul style="list-style-type: none"> <li>• Long transmission lines generally transposed, generation mostly remote.</li> <li>• Generally radial subtransmission lines partly transposed or untransposed.</li> <li>• Distribution systems supplying a mix of medium and low density load area with relatively long lines (&gt;20 km).</li> <li>• 3<math>\phi</math> motors account for only a small part of the peak load (e.g. 10 %).</li> </ul>	0,4 – 0,5 <sup>a</sup>
<sup>a</sup> Coefficient $k_{UE}$ or $\{1-k_{UE}\}$ should allow an equitable share of emissions between the unbalanced installations and the various system inherent sources of imbalance present in the considered power system.	

Table 7- Portion of Unbalance for Accounting for the System Inherent Asymmetries

	From EHV to HV	From EHV to MV33	From EHV to MV11	From HV to MV33	From HV to MV11	From MV33 to MV11
Study	0.86	0.76	0.59	1.00	0.77	0.95
Rounded	0.9	0.8	0.6	1.0	0.8	1.0

Table 8- Transfer Coefficients Based on 99% of Cases

Country	UBF (%)	Comments
Scotland	2	[1], GB Grid Code.
Germany	2	[38], At transmission and distribution levels.
Australia	2	[39], At transmission and distribution levels, for short duration 3%.
France	2	[40], RTE. At transmission level.
South Africa	2	[41], For HV, MV and LV. EHV is not mentioned. Increase to 3% is being considered
Hydro Quebec	1	[42], In transmission level, based on 2 hour average (1.5% for HV and 2% for MV and LV all based on 2 hour average).
New Zealand	1	[34], Electricity Governance Rules 2003, Part C Common Quality.
Brazil	2	[7], at all voltage levels

Table 9- Limits for UBF in other Countries

## 7- THE PROPOSAL

Extensive search of CEGB archive (as far back as 60s, 70s and 80s, Chief engineer conferences/recommendations) and NGET Policies, Technical Specification and Technical Notes did not reveal any proposal, justification, recommendation or study as to why the limit set in the GB Grid Code is 1% in England and Wales and 2% in Scotland.

In June 1975, Electricity Council published ER P16 entitled; EHV or HV Supplies to Induction Furnaces to outline the limits for connecting arc furnaces to the EHV and HV system. It recommended that 1% unbalance is allowed for each connection at the planning stage for voltages of 33 kV and above. This implied that the overall limit may have been allowed to be higher [43]. Clause 4.2 in [43] entitled Voltage Unbalance (single outage condition) states that 1% at 33kV and above or 1.3% below 33kV should be allowed assuming “an initially symmetrical system at this point and based on supply system single outage conditions and winter minimum generation” and “based on the consumer’s worst sustained negative phase sequence component of current”. The statement implies that the asymmetry introduced by the unbalance in the supply system is not accounted for within the above 1% limit.

Scottish Network designers/operators have been considering a compatibility level of 2% for UBF in accordance with the Grid Code and this has not led to any published technical and design issues.

As mentioned before in this report, a low limit has cost implications and a balance between the immunity of equipment and mitigation in the supply system has to be made. Below are some practical examples:

- i) Assuming all other design criteria are the same, a low UBF limit may affect connection of a new generator to the grid, e.g.
  - A double turn-in may be adopted because of high UBF.
  - A double turn-in is approximately 35% more expensive than a double Tee.
  - A single turn-in is 25% less expensive than a double Tee connection and it is favoured if UBF is within the Grid Code limit.
- ii) In parts of the network the power flow in transmission circuits are increasing to their limits, East Anglia and South Wales corridors are good examples. The UBF might approach the existing Grid Code limit of 1% even for intact condition.
- iii) High unbalance due to high power flow may impose inter-trip schemes on power stations that add to complexity of operation and affect security of supply. Inter-trip schemes have been imposed on a number of projects around Bramford.
- iv) If all projects contemplated to connect around Pembroke substation are realised then unbalance at around Walham, Rassau and Cilfynydd will exceed the limit.
- v) A number of traction schemes have or will have limits on their demand directly because of unbalance limit.

It is therefore prudent to review the limit in the GB Grid Code to allow a limit that is more in line with international standards recommendations and worldwide practices as well as considering its practicality and cost implications. The proposal to review the GB Grid Code limit for unbalance is based on the followings:

- i) The proposal does not intend to change the compatibility limit above the immunity level of equipment. The immunity level for all equipment is considered to be above 2%.
- ii) The compatibility level for DNOs for voltages at 132kV and below is 2%. It is not intended to propose changes to this.
- iii) Extensive GB system study revealed that the transfer gains from EHV (400kV and 275kV) to 132kV, 33kV and 11kV are below 0.9, 0.8 and 0.6 respectively based on 99-percentiles of sites, as shown in Table 8.
- iv) The above implies that any unbalance whose source is at EHV level will be transferred through the above gains to the lower voltages.
- v) IEC 61000-3-13 recommends that equitable share of emission between unbalanced installations and various systems inherent sources of unbalance present in the system are allowed.

- vi) This provides provision for the equal contribution to the total compatibility limit of 2% from sources in the lower voltages (DNO) and in the transmission network.

It is proposed that the compatibility limit in Grid Code CC.6.1.5 is changed from 1% to 1.5% for 400kV and 275kV and 2% for 132kV.

The proposed limit of 2% for 132 kV is in line with the present limit used by DNOs in accordance with P29 and EN 50160, which allows 2% for voltages up to 150kV.

The compatibility level of 1.5% for 400kV and 275kV is based on the recommendation in IEC 61000-3-13 that allowance to be made for inherent network unbalance created by un-transposed lines.

If 2% is considered to be the aggregated emission limit at 132kV and 1.5% to be the compatibility level at 400/275kV then the available headroom for emissions from unbalance sources at 132kV and DNOs is 1.08%, just more than 50% of the limit. The rationale for considering 1.5% for nps limit is illustrated by (18). If equitable share of compatibility level of 2% is assumed at 132kV for sources at EHV levels and imposed from lower voltages as well as 132kV itself, then the allowance for the EHV can be calculated as shown below:

$$\text{Limit for UBF}\% = \frac{\sqrt[1.4]{2^{1.4} - 1^{1.4}}}{0.9} = 1.58\% \quad (18)$$

Where 1.4 is the exponent for aggregation of nps voltages from different sources recommended by [5], 2% is the compatibility level at 132kV, 1% is the 50% of the compatibility level allowed for the contribution from 132kV and lower voltages and 0.9 is the transfer coefficient from EHV to 132kV as given in Table 8. The compatibility level allowed for UBF at EHV network given by (18) is rounded down to 1.5%. The allowance for contribution from 132kV and lower voltages is thus given by (19).

$$\text{Contribution from unbalance sources in DNO} = \sqrt[1.4]{2^{1.4} - (0.9 \times 1.5)^{1.4}} = 1.08\% \quad (19)$$

For lower voltages more headroom is available for sources in the MV and LV as the transfer gains for unbalance from EHV network to MV and LV are lower.

The proposed change is in the interest of transmission network operator, all connectees directly connected to the transmission system and ultimately the consumer. Un-necessarily tight limit leads to extra cost for remedies, such as transpositions, building new substations and lines, balancers, limiting flows in circuits and requiring inter-trip. It is likely that all generators and railway network owners support the proposal. The proposal will allocate at the most, 50% of the compatibility level at 132kV to EHV transferred emission and therefore reduces the headroom availability for the distribution network operators compared to existing compatibility level.

Therefore, it is recommended that the limit in the GB Grid Code is changed from 1% to 1.5% and the text of the Grid Code Connection Condition CC.6.1.5 (b) and CC.6.1.6 are changed to that given below. When marked as (No change) it means that no change to the existing text in the Grid Code is proposed. Conversely, the texts in red highlight the proposed new insertions and changes.

#### Voltage Waveform Quality

CC.6.1.5 All Plant and Apparatus connected to the National Electricity Transmission System, and that part of the National Electricity Transmission System at each Connection Site or, in the case of OTSDUW Plant and Apparatus, at each Interface Point, should be capable of withstanding the following distortions of the voltage waveform in respect of harmonic content and phase unbalance: **(No change)**

(a) Harmonic requirement **(No change)**

(b) Phase Unbalance

Under Planned Outage conditions, **the weekly 95 percentile** of Phase (Voltage) Unbalance, **calculated in accordance with IEC 61000-4-30 and IEC 61000-3-13**, on the National Electricity Transmission System for **voltages above 150kV should remain, in**

Scotland, England and Wales, below 1.5%, and for voltages of 150kV and below, below 2%, unless abnormal conditions prevail and Offshore (or in the case of OTSDUW, OTSDUW Plant and Apparatus) will be defined in relevant Bilateral Agreements.

The Phase Unbalance is calculated from the ratio of root mean square (rms) of negative phase sequence voltage to rms of positive phase sequence voltage, based on 10-minute average, in accordance with IEC 61000-4-30.

- CC.6.1.6 In Scotland, England and Wales, under the Planned Outage conditions stated in CC.6.1.5 (b) infrequent short duration peaks with a maximum value of 2% are permitted for Phase (Voltage) Unbalance for voltages above 150 kV, subject to the prior agreement of NGET under the Bilateral Agreement and in relation to OTSDUW, the Construction Agreement. NGET will only agree following a specific assessment of the impact of these levels on Transmission Apparatus and other Users Apparatus with which it is satisfied.

It is noted that the proposed change results in a reduction from 2% to 1.5% in Scotland. In order to follow the recommendations in [5] and other publication for the need for coordination between limits in EHV and lower voltages it is prudent that the GB Grid Code voltage unbalance limit for EHV network in Scotland is reduced.

## 8- CONCLUSIONS

It was shown that no sources for discrepancies in the unbalance voltage limit in the GB Grid Code for Scotland and England and Wales was found. A thorough review of standards and other relevant publications showed that the nps voltage limit at EHV level is set by regulators and grid operators in other countries from 1% to 2%. A CIGRE Working Group has recommended that the compatibility for voltage nps is set at 1.5%.

Using network analysis, existing background measurement data, recommendations in international standards and publications and immunity level of equipment, in particular induction motors and synchronous generators, it was proposed that the voltage unbalance limit in Scotland, England and Wales is set to 1.5%. This results in an increase of from 1% in England and Wales and a reduction from 2% in Scotland. It was also shown that this reduces the need for mitigation at design stage and therefore leads to more cost effective designs without impairing reliability and quality of supply.

Change in the GB Grid Code text was proposed.

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## 11- APPENDICES

### 11.1. Appendix A

Line impedance matrix of a double circuit fully transposed line is given by (A.1).

$$Z = \begin{bmatrix} Z_s & Z_m & Z_m & Z_m & Z_m & Z_m \\ Z_m & Z_s & Z_m & Z_m & Z_m & Z_m \\ Z_m & Z_m & Z_s & Z_m & Z_m & Z_m \\ Z_m & Z_m & Z_m & Z_s & Z_m & Z_m \\ Z_m & Z_m & Z_m & Z_m & Z_s & Z_m \\ Z_m & Z_m & Z_m & Z_m & Z_m & Z_s \end{bmatrix} \quad (\text{A.1})$$

Where  $Z_s$  and  $Z_m$  are self and mutual impedances of the line respectively. The symmetrical component operator, H, for a double circuit line is defined as given by (A.2).

$$H = \begin{bmatrix} 1 & 1 & 1 & 0 & 0 & 0 \\ 1\angle -120 & 1\angle 120 & 1 & 0 & 0 & 0 \\ 1\angle 120 & 1\angle -120 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 1 & 1 \\ 0 & 0 & 0 & 1\angle -120 & 1\angle 120 & 1 \\ 0 & 0 & 0 & 1\angle 120 & 1\angle -120 & 1 \end{bmatrix} \quad (\text{A.2})$$

The symmetrical component impedances of the line is given by (A.3)

$$Z^{+,-,0} = [H]^{-1} \times [Z] \times [H] \quad (\text{A.3})$$

$$Z^{+,-,0} = \begin{bmatrix} Z^+ & 0 & 0 & 0 & 0 & 0 \\ 0 & Z^- & 0 & 0 & 0 & 0 \\ 0 & 0 & Z^0 & 0 & 0 & Z_m^0 \\ 0 & 0 & 0 & Z^+ & 0 & 0 \\ 0 & 0 & 0 & 0 & Z^- & 0 \\ 0 & 0 & Z_m^0 & 0 & 0 & Z^0 \end{bmatrix} \quad (\text{A.4})$$

Where  $Z^+$ ,  $Z^-$  and  $Z^0$  are respectively the line pps, nps and zps impedances of the two circuits and  $Z_m^0$  is the zero sequence mutual impedance between the two circuits.

As it can be seen the symmetrical component networks are mutually decoupled as the mutual impedances between sequence networks are all zero except for mutual coupling between the zero sequence networks of the two circuits. This means that zero sequence current in one circuit induces a voltage proportional to the mutual zero sequence impedance,  $Z_m^0$ , in the other circuit.

If the line is not transposed then the self and mutual impedances of the lines, as shown in (A.1), are not the same for and between different phases and therefore the off-diagonal impedances representing the mutual coupling between the sequence networks in (A.4) are not zero. This means that the current in one sequence network, e.g. pps, would induce a voltage in the other such as nps which in turn produces an nps current in the nps network.

Equation (A.5) shows the sequence impedances of a L2 line  $\Omega$  per km if it were fully transposed.

$$Z^{+,-,0} = \begin{bmatrix} 0.315\angle 83.79 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0.315\angle 83.79 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0.79\angle 79.38 & 0 & 0 & 0.476\angle 76.54 \\ 0 & 0 & 0 & 0.315\angle 83.79 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0.315\angle 83.79 & 0 \\ 0 & 0 & 0.476\angle 76.54 & 0 & 0 & 0.79\angle 79.38 \end{bmatrix} \quad (\text{A.5})$$

Equation (A.6) shows the impedance matrix of a L2 line  $\Omega$  per km with phasing of RYB-BYR for the two circuits.

$$Z^{+,-,0} = \begin{bmatrix} 0.302\angle 83.34 & 0.028\angle 151.64 & 0.023\angle -103.35 & 0.012\angle -93.25 & 0.017\angle -31.80 & 0.017\angle -87.95 \\ 0.028\angle 27.38 & 0.302\angle 83.34 & 0.024\angle -73.27 & 0.017\angle 151.79 & 0.013\angle -91.48 & 0.017\angle -81.32 \\ 0.024\angle -73.47 & 0.022\angle -104.38 & 0.817\angle 79.75 & 0.017\angle 29.09 & 0.017\angle 155.99 & 0.476\angle 76.54 \\ 0.013\angle -91.29 & 0.017\angle -31.66 & 0.017\angle 155.94 & 0.302\angle 83.34 & 0.028\angle 148.20 & 0.024\angle 166.73 \\ 0.017\angle -151.68 & 0.012\angle -93.39 & 0.017\angle 29.09 & 0.028\angle 30.36 & 0.302\angle 83.34 & 0.023\angle 16.65 \\ 0.017\angle -83.86 & 0.017\angle -90.71 & 0.450\angle 75.71 & 0.023\angle 16.254 & 0.024\angle 166.06 & 0.450\angle 75.71 \end{bmatrix} \quad (\text{A.6})$$