Power Quality in the GB Transmission Network

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A System Operability Framework Document

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Executive Summary

Power quality is critical to the performance of the plant and equipment connected to the power network; poor power quality can reduce the efficiency, cause excessive heating or even damage the assets. Inverter Based Resources (IBR) such as HVDC, wind, solar and battery resources, and their associated devices (such as harmonic filters) may also both contribute to erosion of power quality, or be designed in such a way as to limit this effect. These resources may also respond adversely to certain distortion of power quality as measured and responded to within their control systems.

There is a direct correlation between system strength, traditionally measured by the Short Circuit Levels (SCL), and some of the power quality aspects, including harmonics, voltage unbalance, rapid voltage change and voltage flicker. In addition, IBR resources also respond differently to power quality in comparison to conventional plant and equipment (i.e. there are also control and protection related responses to these voltage distortions), new areas of power quality consideration are expected to become more prominent over time. This report discusses the main power quality aspects in the GB network. It also discusses some of the future concerns with regard to power quality and what we are doing to address them. This report will focus on the power quality aspects of the GB transmission system.

Driven by the Net Zero targets[1], the penetration of IBR will continue to increase which will reduce the system strength in certain areas of the network. Consequently, harmonics, voltage unbalance and voltage flicker levels may deteriorate as system strength drops and might exceed the standard planning limits and Grid Code requirements if no additional remedial work is done.

Currently the power quality aspects are managed by the Network Owners. While operating the National Electricity Transmission System (NETS), the ESO works closely with the Transmission Owners (TOs) to provide support in maintaining a desirable level of power quality. The stability pathfinder project run by the ESO aims to seek economic solutions/products to procure SCL and improve system strength[2]. The ESO is also investigating the suitability of SCL to define system strength with the increased penetration of IBR in the most recent System Operability Framework (SOF) report[3].

We are working with the TOs to understand the additional monitoring requirements and the best ways of utilising the ever-increasing data collected from all around the system, as a significant increase in the monitoring infrastructure is expected by the end of the RIIO-2 period. We will be working closely with the industry to ensure we will be able to operate a zero carbon transmission system with low system strength. We will also ensure that our engagement in the future policy adjustments through code modifications or engineering recommendation panels reflects the expected challenges of zero carbon operation and how these changes, including power quality limits and processes, are required for safe, reliable and cost efficient networks.

We are currently working towards increasing our modelling capability to be able to analyse the phenomena that will require more detailed analysis techniques like electromagnetic transients (EMT) tools. One of our ESO Business Plan[4] deliverables is to enable more advanced EMT modelling by the end of Business Plan 2 in 2025, although the main continuous power quality phenomena are currently sufficiently captured by the steady state and frequency domain analysis.

Background

The term Power Quality (PQ) is commonly used to group certain electromagnetic phenomena that can take place in power systems. It mostly refers to quality of voltage signals. PQ is defined in the International Standard IEC 61000-4-30 [1] as “characteristic of the electricity at a given point on an electrical system, evaluated against a set of reference technical parameters”. These are usually voltage characteristics, e.g. voltage phases balance,

1 https://www.nationalgrideso.com/future-energy/net-zero-explained
2 https://www.nationalgrideso.com/future-energy/projects/pathfinders/stability
3 https://www.nationalgrideso.com/research-publications/system-operability-framework-sof
4 https://www.nationalgrideso.com/our-strategy/riio

and are used to evaluate the compatibility of the connected load to the energy supplied. The deviations from the reference technical parameters are referred to as PQ phenomena.

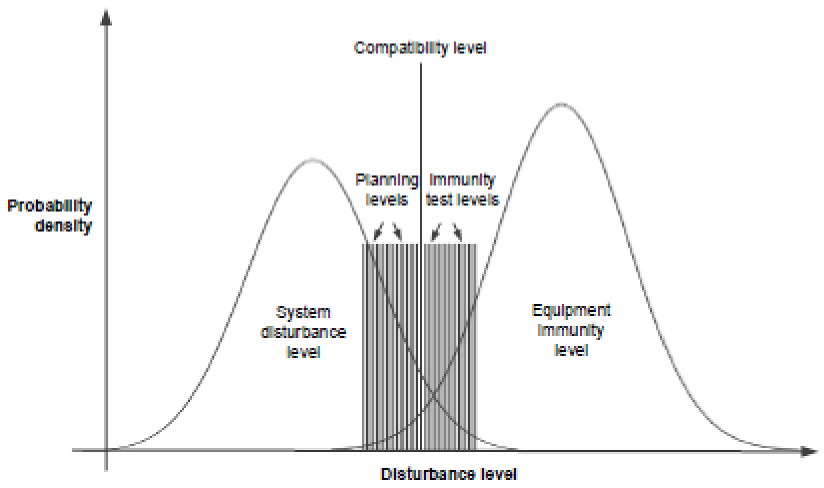
The PQ levels affect the performance of the power system components and especially loads connected to the system. All electrical loads connected to the power system have been designed in such a way that their correct operation and performance rely on an adequate quality of the power supply. The suitability of the power source can be defined in terms of:

- Voltage magnitudes and equal phase shifts (e.g. balanced 3 phases)
- Nominal frequency and its variation
- The shape of the voltage waveform (harmonic content).

The PQ levels on the transmission network are usually assessed by the TOs from the design stage to be within the predefined limits in the relevant codes and standards, e.g. ENA Engineering Recommendation G5 for the harmonic distortion limits [2]. For some of the PQ phenomena, the limits are discussed in two categories: planning levels and compatibility levels. The planning level is the level of the disturbance adopted as a reference value for the limits to be set for the emission from the connection in the system, i.e. the levels that the system is designed not to exceed in the planning stage. On the other hand, the compatibility level is the disturbance level used as a reference for the setting of equipment immunity, i.e. the levels below which all equipment should be able to operate normally as presented in Figure 1 [2]. The figure shows there is a chance for interference between the levels as a recognition that the PQ will not always remain within the planning levels and therefore statistical indices are utilised to describe PQ, as will be discussed in more detail later.

There is a direct correlation between PQ and system strength. In general, the stronger the system, the easier it is to maintain PQ to the required standards. The SCL has been traditionally used as a proxy to system strength, however with the increased penetration of IBR we are currently investigating if it is still the right measure, as discussed in more detail in another SOF report [3]. However, in this report we are investigating and presenting examples of how the expected drop of system strength in future networks will impact some of the main PQ phenomena (driven mainly by the network impedance change rather than the fault infeed drop).

Figure 1: Illustration of the Electromagnetic Compatibility concept [2]



PQ Phenomena and future concerns

For a three-phase balanced power system, any phenomenon, incidental or continuous over a period of time, that changes the voltage waveform from a pure, constant root mean square value and constant frequency sinusoidal, with equal phase shifts can be considered as PQ disturbance. The focus of this report is on the continuous phenomena that usually have an impact on network components in the longer term, and do not cause component trips in normal operational conditions. The continuous phenomena are usually evaluated with statistical measures of a sample of indices (e.g. the 95th percentiles[5]) calculated over a period of time, usually at least a week, and aggregated following the algorithm described in IEC 61000-4-30 [1].

In this report we will discuss the continuous PQ phenomena that are presented in the Grid Code [4] Connection Conditions under the sections of Voltage Waveform Quality and Voltage Fluctuations, i.e.

- Harmonic Content
- Phase (Voltage) Unbalance also known as Negative Phase Sequence (NPS)
- Flicker

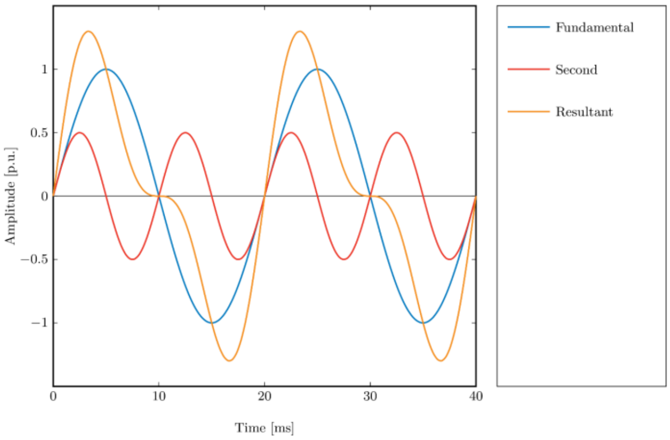
Harmonics

- Harmonic voltage issues may be caused by sources injecting harmonics to the network or amplifying existing background harmonics
- Engineering Recommendation G5 provides the limits and the evaluation process for the connection of harmonic sources
- Future network changes will change the network impedance characteristic causing the traditional mitigation solutions to be less effective.
- New solutions like optimally located and retuned filters and FACTS active filters could mitigate these issues

Harmonics are waveforms of higher frequencies than the nominal frequency, which superimpose on the original waveform, thereby creating an impure waveform compared with the original 50Hz sine wave. Figure 2 (a) shows an example of a distorted waveform due to 50% component of the 2nd harmonic.

Harmonics have an impact on a range of operational aspects. They can cause equipment heating, increased losses, over-voltages under resonant conditions, communication interference, protection relay malfunction and adverse impact on the IBR controller response. Therefore, the TOs ensure that the harmonic distortion limits in Engineering Recommendation G5 [2] are adhered to at the connection design study, while the ESO ensures following up with any harmonic compliance related issues with the users after the connection.

Figure 2: Examples of a harmonic distorted waveform



(a) Basic illustration example with one harmonic frequency imposed

5 The value not exceeded for 95% of the sample (usually time)

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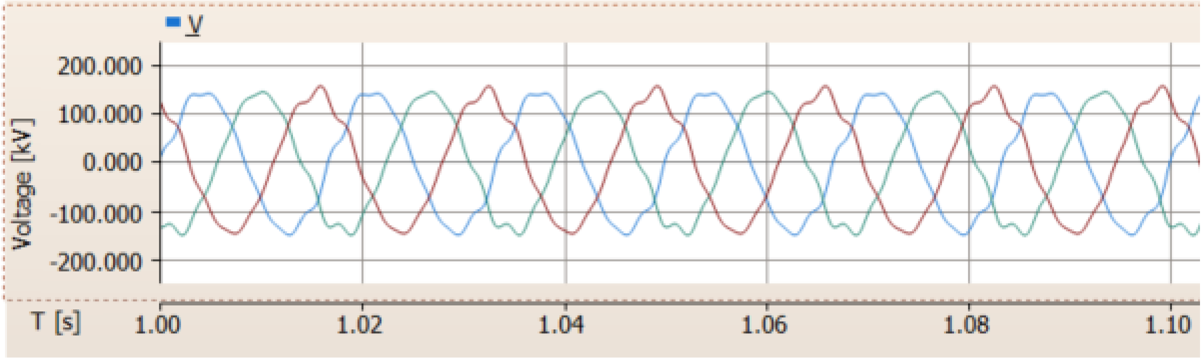


(b) Realistic example of 3 phase voltages with harmonic distortion

There are a number of indices to evaluate harmonic performance. G5 defines the limits for the individual harmonic distortion, which is the rms value of the individual harmonic voltage, i.e. the voltage magnitude with the certain harmonic frequency, expressed as a percentage of the fundamental rms voltage at 50Hz (V_h/V_1%). G5 also defines the limits for the total harmonic voltage distortion (THD_V) which is the square sum of the rms value of the individual harmonic voltages, up to the 100th harmonic, expressed as a percentage of the fundamental rms voltage, as shown in Equation (1) below

$$THD_v = \sqrt{\sum_{h=2}^{h=100} (V_h)^2} \quad (1)$$

where,

THD_V is the total harmonic voltage distortion

h represents the harmonic order

V_h represents the individual harmonic voltage (%h=1)

Table 1 below shows the G5/5 *THDv* planning levels at different voltage levels.

Table 1: THD planning levels

Nominal Voltage (*V*) kV	THD_V %*h* = 1
$V \leq 0.4$	5
$0.4 < V \leq 25$	4.5
$25 < V \leq 66$	3.7
$66 < V \leq 230$	3
$V > 230$	3

The level of harmonic distortion on networks will vary depending on the generation, demand and operation condition, which will vary depending on the time of day, season and between weekdays and weekends. Therefore, G5 states the importance of taking harmonic measurements over a continuous period of at least seven days, and in multiples of seven days, to demonstrate compliance under a range of operation conditions. As mentioned earlier, the measurements are aggregated following the IEC61000-4-30 [1] algorithm, which is taking the measurement over a basic interval of 10 cycles (200 ms), aggregating 200 samples into 10-min intervals. Depending on application the IEC 61000-4-30 recommend different aggregation interval. The aggregations are performed using the square root of the arithmetic mean of the squared input values. The weekly 95th percentile values of the harmonic voltages and THDv (values that are not exceeded for 95% of the time) are then compared with the G5/5 levels to verify compliance. It is also worth noting that G5 recommends adjusting the aggregation period for short-duration bursts or fluctuating harmonic distortion and also adjusting the limits based on factors defined in the document [2].

Voltage variation observed at a particular harmonic frequency is a function of the current injection and the network impedance at that frequency. Although these issues are expected to be assessed and mitigated during the connection design stage by the connecting customer working with the relevant TO and the ESO, there is a risk associated with the unpredictability of the aggregated behaviour of the various current and future technologies that can introduce or modify harmonic content and can also alter system impedance.

Harmonics can be injected or amplified in the system from a number of sources. The most common sources of injection are non-linear loads and power electronic interfaced generation and demand (due to the switching nature of their operation). New connections to the system can amplify existing background harmonics by interacting with the system impedance at certain frequencies and shifting the resonance frequencies. The inductive reactance increases with the frequency (or the harmonic number h) and the capacitive reactance decreases with the frequency (or the harmonic number h) following equations 2.a and 2.b. Therefore, the magnitude of the system impedance can increase or decrease with the frequency depending on the dominant type of reactance, which can be used to create impedance scan plots as shown in Figure 3 (a). The resonance will occur at the harmonics where the system impedance magnitude in the impedance scan is very high (called parallel resonances) or very low (called series resonance), as shown in Figure 3 (a). The resonance will take place if the capacitive and inductive reactance at the point of connection become equal at a certain frequency, as shown in equations (2) – (4) below

$$X_L(h) = h \times X_L \qquad (2.a)$$

$$X_C(h) = {X_C}/{h} \qquad (2.b)$$

$$X_L(h) = X_C(h) \qquad (3)$$

$$h_r = \sqrt{{X_C}/{X_L}} \quad or \quad f_r = f \times h_r = {1}/{2\pi\sqrt{LC}} \qquad (4)$$

where,

X_L the inductive reactance

X_C the capacitive reactance

h harmonic number

h_r resonance harmonic

f fundamental frequency

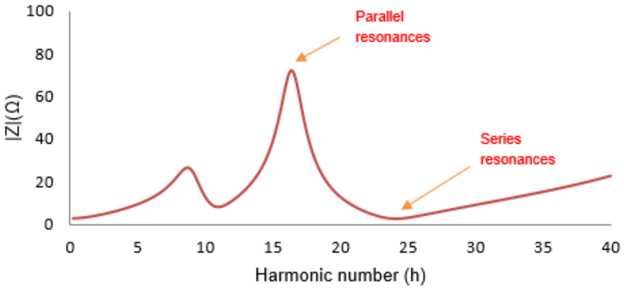
f_r resonance frequency

For example, the connection of high capacitance plant (e.g. wind farm cable array) to a relatively weak area (i.e. high equivalent inductance) might lead to a resonance which can cause magnification of low order harmonic voltages at the connection point [5].

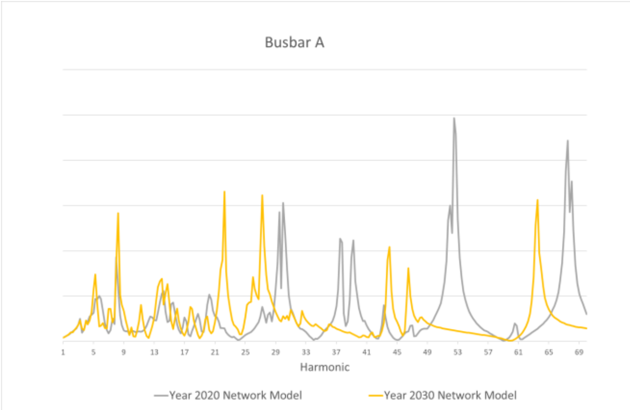
The development and changes of the future networks, including adding more underground cables, deploying more power electronic applications like FACTS and IBRs, will significantly change the network impedance frequency characteristic. Figure 3 (b) and (c) show examples of how impedance characteristics may change across 10 years of network development. Note that these plots are for illustration purposes only, as many factors like future load models and dynamic component impedance characteristics are not taken into account which will impact the characteristics. Currently these areas are under research and investigation by the ESO and the TOs. Moreover, it is also important to ensure the power electronic based components model information includes accurate representation of the impedance characteristics, especially as these characteristics will depend on the control systems and operating conditions of the connected component. For example, it was demonstrated in [5] when the operation of the wind farm changes from 0 to 11 turbines the resonance can move between the 10th

and the 16th harmonic. With such components a complete EMT based frequency scan is required to capture the impedance characteristics.

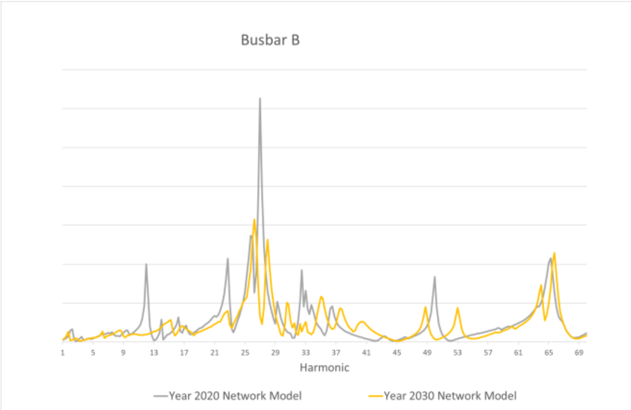
Figure 3: Impedance frequency scan examples



(a) Impedance scan illustrative example



(b) 400 kV bus impedance scan



(c) 275 kV bus impedance scan

Low system strength could deteriorate harmonic voltage distortion: the penetration of IBRs could introduce new characteristics in the network impedance and the closure of traditional synchronous generation means there could be a higher network impedance between the point of interest and the network equivalent. The resonance frequency could shift causing amplification of voltage distortions at different harmonic frequencies. The existing connections could face a different network background to the one during connection application; there could be a risk of non-compliance. Moreover, the existing harmonic filters might become less effective and need to be re-tuned. The need to utilise more advanced mitigation solutions like FACTS devices might become more imminent. Appendix A shows an example of the harmonic performance at a site before and after deploying an advanced harmonic mitigation solution and how it effectively brought the harmonic levels within the limits.

Phase (Voltage) unbalance

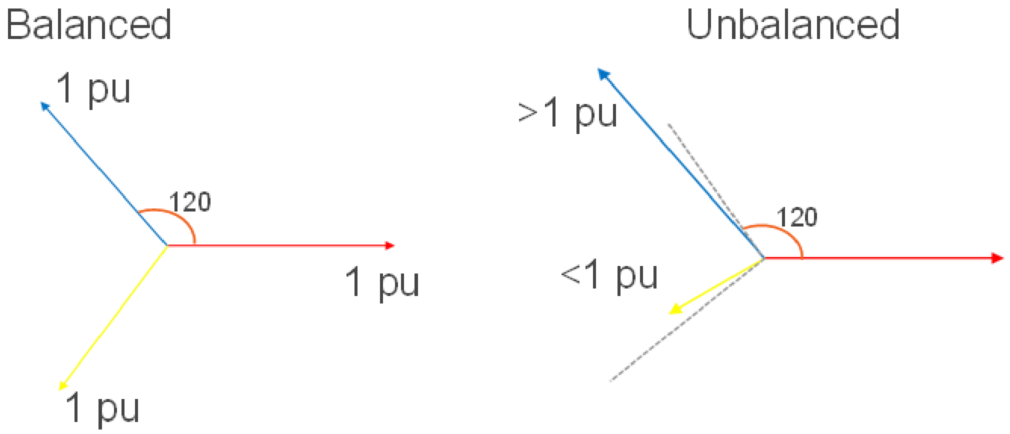
- Voltage unbalance or Negative Phase Sequence NPS in today's network is mainly due to the connection of single phase or two phase loads like the railway traction system and untransposed lines in the transmission systems
- The Grid Code identifies the NPS limits as 1.5% or 2% depending on the location and voltage level and network operating conditions
- Future network changes like drop of system strength and changes in the power flow directions may lead to a rise in the NPS levels that wasn't considered at the design stage

The Grid Code [4] defines the Phase (Voltage) Unbalance as the ratio (in percentage) between the rms values of the negative sequence component and the positive sequence component of the voltage, and it should be calculated in accordance with IEC 61000-4-30 [1]. Therefore, the term Negative Phase Sequence (NPS) is used as well to describe the voltage unbalance, Equation (5).

$$NPS\ (\%) = \frac{negative\ sequence\ voltage\ component}{positive\ sequence\ voltage\ component} \times 100 \qquad (5)$$

In general, the voltage unbalance is the condition in any polyphase system in which the rms values of the line voltages (fundamental component), or the phase angles between consecutive line voltages are not all equal. This will lead to the presence of negative sequence and zero sequence voltages and currents on the network; however, the zero sequence components are not mandated by the Grid Code and are usually neglected because of their minimal impact on generators. Figure 4 shows an example of 3 phase balanced compared to unbalanced phasor diagram.

Figure 4: Balanced vs unbalanced phasors



The main impact of NPS on system operation can be seen on the rotating electrical machines experiencing negative sequence torques. The predominant consequence is machine overheating and pulsating torque which reduces life expectancy of the machine. The Grid Code limits and Engineering Recommendation planning levels take into account the long term impact on the machines while allowing for suitable protection settings for the machines.

The main sources of the NPS in the networks are the unbalanced connections (single phase loads or generation units or phase to phase loads) and the current flow in unbalanced system impedances (mainly untransposed overhead lines (OHL)). One of the most common phase to phase loads on the transmission network are the supplies to the railway traction system. Engineering Recommendation P24 [6] provides a comprehensive discussion about AC supplies to railway systems including the unbalance quantification using Equation (6).

$$V_{NPS}\% = \frac{line\ to\ line\ load\ MVA}{fault\ level\ MVA\ at\ supply\ busbar} \qquad (6)$$

Another Engineering Recommendation P29 [7] defines the planning levels for voltage unbalance for connections at 132 kV or below. In P29 the voltage unbalance caused by a combination of unbalanced three-phase loads or phase to phase loads can be evaluated by Equation (7).

$$Voltage\ unbalance\ (\%) =$$

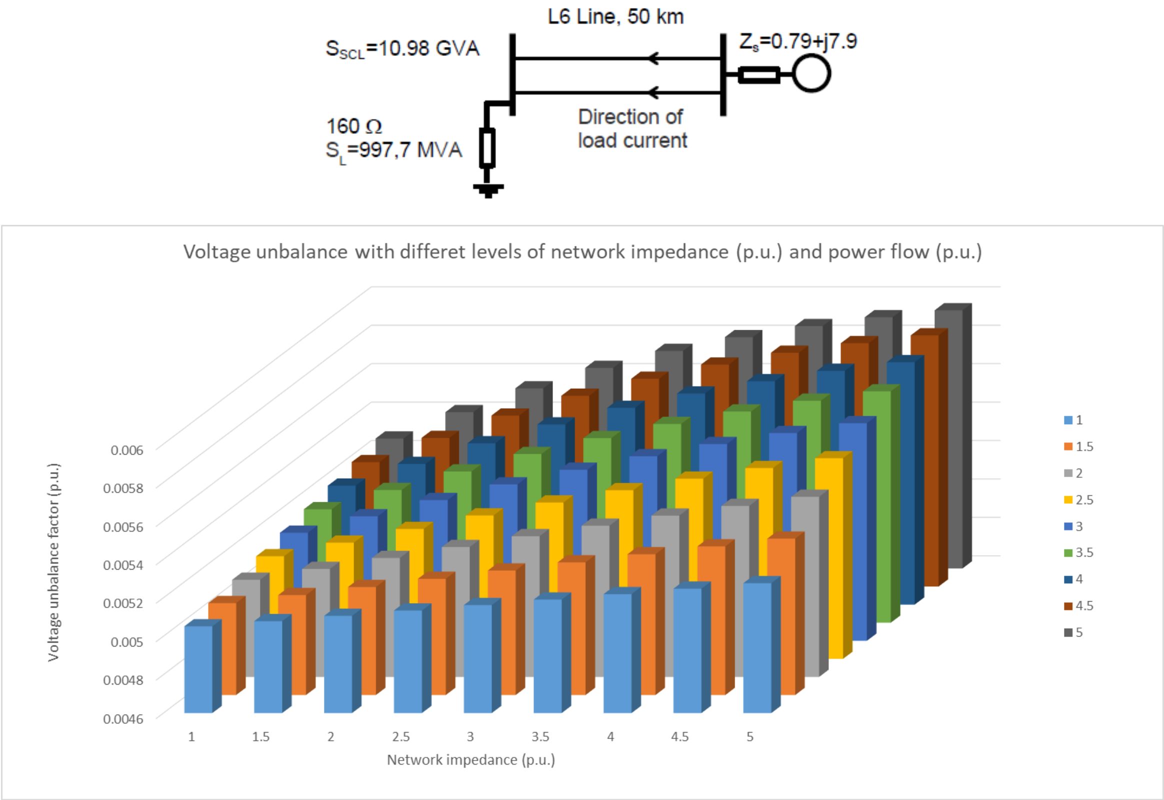
$$\frac{\sqrt{3}\ \times negative\ phase\ sequence\ component\ of\ the\ loads\ (kA) \times Line\ voltage\ (kV)}{three\ phase\ short\ circuit\ level\ at\ pcc\ (MVA)} \times 100\% \qquad (7)$$

Similar to harmonics, voltage unbalance compliance with Grid Code is calculated based on IEC61000-4-30, by comparing the weekly 95th percentile values with the Grid Code. The limits are, for voltages above 150kV, 1.5% in England and Wales and 2% in Scotland. For voltages 150kV and below, the limit is 2% across all of GB.

It is clear from equations 6 and 7 above that the NPS is directly impacted by a drop in system strength. The closure of synchronous plants will also indirectly impact the NPS levels due to the loss of some of the main damping component like generator transformers. Also, as mentioned previously, transmitting power over untransposed OHL will lead to the rise of unbalance levels. Direction of the flows and high magnitude of flow in the OHL circuits may also increase the unbalance levels on receiving nodes. In future networks, due to the increased intermittent generation leading to more variable flows, the unbalance levels estimated at the network design stage will increase. Going forward, wider network monitoring and management of the phenomenon might be required rather than just at the disturbing source locations. In addition, the IBRs are prone to unbalance as it will cause issues for the way the converters are following the network voltages though Phase Locked Loop (PLL) controller. Appendix B provides examples of unbalance performance in different sites in the NETS.

Figure 5 below shows a simple network example and how the voltage unbalance at the demand busbar can increase with both the drop of system strength (network impedance increase) and the increase of the flows on the OHL (increase of the demand at the receiving end).

Figure 5: the impact of system strength and power flows on NPS



Flicker

- Flicker is a voltage fluctuation phenomenon that is traditionally used to measure the unsteadiness of lighting (i.e. changes in the brightness)
- The flicker severity is evaluated by the short term and long term flicker severity indices (Pst and Plt respectively) and can be measured by a flickermeter
- The Grid Code defines the limits for Pst and Plt as 0.8 and 0.6 for the transmission voltage levels
- With the currently available headroom of flicker in the transmission system, it is of less operational concern compared with harmonics and NPS

Flicker is defined in [1] as the impression of unsteadiness of visual sensation induced by lights fluctuating with time. Repetitive voltage fluctuations of sufficient frequency and magnitude can cause this luminance fluctuation in traditional incandescent lamps. Although this type of lighting has been phased out with more modern technologies of lamps like LEDs, the standards including the Engineering Recommendation P28 [8] continue to use the originally developed metrics based on incandescent lamps as a reference. Nevertheless, a key principle in P28, which is the Engineering Recommendation setting the limits for voltage fluctuation in the UK, is that the visual discomfort due to light flicker is the most frequent reason to limit voltage changes due to fluctuating installations. The main sources of flicker in the network can be the connections with continuous variation in their load currents like arc furnaces and motor based loads with frequent start-stop features. Generation with continuous voltage variation due to variable output or continuous switching might also cause flicker injections. It is worth mentioning that P28 also covers the Rapid Voltage Change (RVC) limits, which is another form of voltage fluctuation. The RVC is not a continuous phenomenon and is measured by the number of occurrences of voltage dips and voltage swells. This section will focus only on the Flicker form of voltage fluctuation.

Flicker severity is assessed by two indices, the short term flicker severity (Pst) and the long term flicker severity (Plt). The Grid Code [4] defines the Pst as a measure of the visual severity of flicker derived from the time series output of a flickermeter over a 10 minute period and provides an indication of the risk of customer complaints. The Plt is a value driven from 12 successive measurements of Pst (i.e. over a two hour period) and calculated by Equation (8) below

$$P_{lt} = \sqrt[3]{\frac{1}{N}\sum_{i=1}^{N} P_{st,i}^{3}} \qquad (8)$$

where,

$P_{st,i}$ *(i=1, 2, 3, …)* are consecutive readings of P_{st}

N is the total number of readings to consider (for 2 hours N=12)

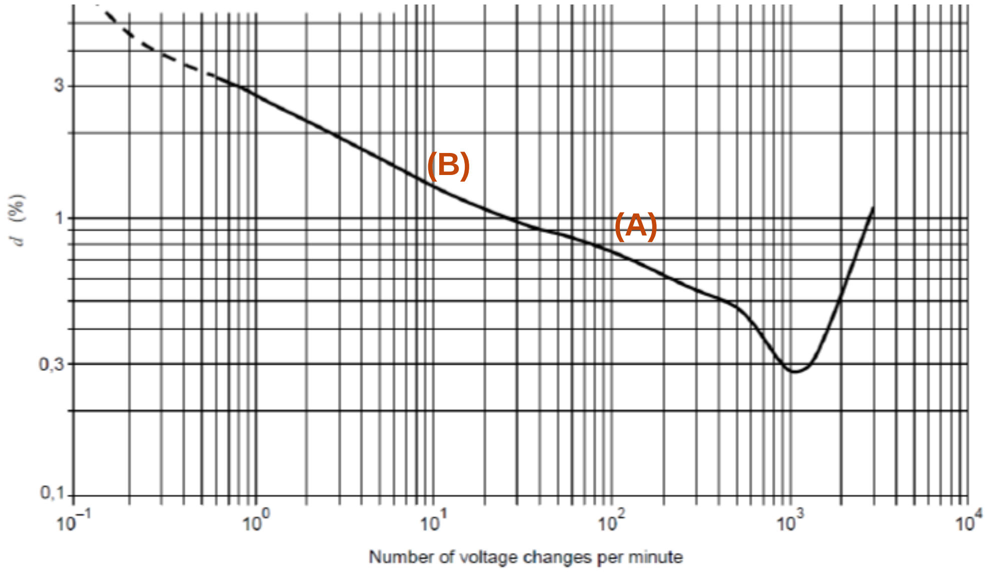
From P28 [8] and the Grid Code [4], the 95th percentile values of Pst and Plt over 1 week should be used to assess flicker against the planning levels, which are reproduced in Table 2 below. In P28, there is also presentation of the typical transfer coefficients, which are used to assess flicker between different voltage levels. For example, the transfer coefficient between 400/275 kV to 132/110 kV levels is 0.85, applied to both the P_{st} and the P_{lt}.

Table 2: Flicker planning levels

Supply system Nominal Voltage	***Planning Level***	
	Flicker Severity Short Term (P_{st})	**Flicker Severity Long Term (P_{lt})**
3.3 kV, 6.6 kV, 11 kV, 20 kV, 33 kV	0.9	0.7
66 kV, 110 kV, 132 kV, 150 kV, 200 kV, 220 kV, 275 kV, 400 kV	0.8	0.6

As stated in P28 [8] the connection of flicker disturbing equipment to the network is usually assessed in three stages. Stages 1 and 2 are usually for discrete LV equipment and for installation with emission at $P_{st} \leq 0.5$. Only at stage 3 where detailed assessment of existing flicker background levels and projected flicker severity should be carried out with the addition of the new disturbing installation. Disturbing equipment with stochastic voltage fluctuations, such as arc furnaces, should be generally subjected to Stage 3 assessment [8]. The IEC 61000-3-7 [9] technical report defines the limits of voltage fluctuation in medium and high voltage power systems. It also provides a number of assessment methods for the P_{st}. These methods are by flickermeter, simulation, analytical or by the use of P_{st} = 1 curve, replicated in Figure 6 below. This flicker curve can be used to correlate the amplitude of rectangular voltage changes with the rate of repetition which correspond to flicker severity of P_{st} = 1, for example for around 1% voltage fluctuation, it will require 22 changes/minute to record a P_{st} = 1.

Figure 6: Curve for P_{st} = 1 for rectangular equidistant voltage changes [9]



The voltage fluctuations should be assessed under the worst case normal operation[6], unless specified otherwise by the Network Operator. Under worst case condition, a simplified voltage change evaluation can be performed by Equation (9):

$$\frac{\Delta V}{V} = \frac{S}{S_k^{"}} \times 100 \qquad (9)$$

Where:

$\Delta V/V$ is Voltage change in percentage (%) (shown as *d* (%) in Figure 6)

S Apparent power change in MVA of the disturbing equipment

S_k" Supply system initial symmetrical short-circuit power MVA

It can be concluded from Equation (9) that a drop in system strength will lead to a higher voltage change percent ∆V/V (or *d(%)* in Figure 6) as a result of the same level of apparent power change *S.* This basically means that fewer numbers of voltage changes per minute can now cause the same level of flicker severity. For example, taking the curve from Figure 6 as a reference, for the same disturbing equipment if the drop in the system strength causes the voltage change percentage to increase from around 0.7% (point A in the figure) to around 1.5% (point B in the figure), it will only require around 10 changes per minute to cause short term flicker severity around 1, compared with more than 100 changes per minute before the system strength drop.

However, a review of flicker background levels in the GB electricity supply system has not found evidence to support apportioning of remaining capacity to prevent planning level exceedances [8]. The flicker headroom is of less operational concern compared to harmonics and voltage unbalance, as shown in the PQ measurements examples in Appendix C.

PQ monitoring and measurements example

PQ monitoring and measurements checks are essential tasks performed by the TOs. The measurements are usually used for background checks for new connections, compliance checks after connection and for general system performance with regard to PQ.

[6] the condition that results in the maximum short-circuit impedance when measured at the PCC for the various normal operating conditions considered (i.e. credible outages and reasonable assumptions on demand and generation)

The PQ monitor types and accuracy should be compliant with the Class A as given in international standard IEC 61000-4-30 [1]. PQ parameters like power frequency, voltage magnitudes, flicker, voltage dips and swells, voltage unbalance and voltage and current harmonics and interharmonics should be measured and recorded through these monitors. Further guidance in monitoring specific PQ phenomena can also be found in separate standards, like IEC 61000-4-7 for harmonics and interharmonics measurements and IEC 61000-4-15 for flicker.

The STC procedure STCP27-01 [10] identifies the GB system performance monitoring requirements. It also sets a target of installing devices for the measurement of Synchronised Data (i.e. data that has been time-stamped at source) at all Grid Supply Points and generators directly connected to the National Electricity Transmission System (NETS) by the end of RIIO-2 (March 2026). The onshore TOs have also set in their RIIO-T2 business plans the intention of deploying additional PQ monitors or monitoring modernisation investment, which will lead to at least an additional 170 monitored site by the end of RIIO-T2. These measurements will increase the visibility of the system performance and can also provide useful insights with regard to some PQ phenomena like NPS.

Appendices A-C show examples of monitored PQ phenomena at different sites on the NETS and with different periods of measurement recorded and provided by the TOs.

PQ mitigation

The different PQ phenomena are assessed by the TOs in detail as part of the connection process. If the assessment indicates possible planning limit exceedances, then the PQ mitigation options will be considered and discussed with the customer.

The harmonics mitigation solutions are usually the harmonic filters. The traditional filters, or passive filters, are a shunt RLC circuit which is tuned to provide a low impedance path to the problematic harmonic and prevent it from being injected into the network. A more modern solution is by using dynamic or active filters. This technology can be applied on existing FACTS devices like STATCOMs by updating their controls to target the problematic harmonic frequency. This solution was successfully applied in South-West Scotland utilising existing wind farm STATCOMs [5]. Appendix A also shows an example of the harmonic performance before and after applying the mitigation solution.

For the NPS, the mitigation solutions can be applied at the design stage, like phase rearrangement of lines connected, selecting appropriate phases pair, connecting at stronger location or higher voltage level, provide operational guidance like changing split arranged substations into solid arrangement and finally introducing phase balancer equipment if the former less costly solutions were not adequate. Similar to harmonic filters, the traditional phase balancing technology involved switching inductors/capacitors whereas the more modern technologies are power electronic based, standalone solutions or embedded within equipment, such as STATCOM, can be utilised. The unbalance filtering has been utilised in three STATCOMs in the South East of England.

Regarding the flicker, and similar to the NPS, the main mitigation can be preventative measures and can be applied at the design stage by for example changing the supply system arrangement, suggesting stronger connection point or reducing the disturbance at the Point of Common Coupling (PCC). Also modification to the disturbing installation by using compensation equipment (like STATCOM) [8].

The future network changes might raise the need to address PQ mitigation differently, for instance with drop of system strength and topology changes global solutions to address PQ levels at wider regions might prove more economic to deploy rather than at the connection locations. Also, the active filter solution mentioned earlier is a good example of coordinating solutions tuning at different locations to ensure the maximum benefit at all the affected substations [5]. Future policy adjustments through code modifications or engineering recommendation panels can also ensure that the PQ limits and evaluation processes are updated to address future system challenges and to ensure the best mitigation practices are agreed on.

Conclusions

Our previous system operability framework publications show that system strength will keep declining as inverter-based resources (IBRs) are increasingly connected to the system and replace the existing traditional synchronous generation. Lower system strength means more volatile response of the system to a disturbance and it is more challenging to manage PQ phenomena. In this report, we discussed:

- The frequency resonance would be altered and could move to lower frequency order levels (nearer 50Hz) as the system strength decreases and also due to the connection of new components with atypical impedance response. The existing connections could face a different network background from the one assumed during connection application; there could be a risk of non-compliance. Moreover, the existing harmonic filters might become less effective and need to be re-tuned.
- Voltage unbalance could increase in the future networks. The drop in system strength, the higher power flow, the concentration of generation in one part of the network and the changes in flow directions could cause deterioration in the voltage unbalance levels.
- A drop in system strength will lead to higher flicker severity, by causing $\Delta V/V$ to increase. Since currently there is a large headroom between the current flicker level and the planning limit, voltage flicker is of less concern than the harmonics and voltage unbalance.
- The IBRs will have different types of interactions with the PQ phenomena, the deterioration in PQ levels will impact their performance, if not tuned properly they can themselves have a negative impact on the PQ levels and also they can provide new PQ mitigation solutions.
- Uncertain power flow directions and amounts will also impact the PQ performance in parts of the network. These changes in future networks may drive a need of system wide PQ monitoring and solutions, rather than localised PQ monitoring and mitigation driven by customer connections studies.

Traditionally TOs are responsible for managing the PQ in the transmission network, working with the users from the design stage to ensure the PQ compliance. The rapid decrease of system strength as we move to a zero carbon system might not be covered by the current power quality management processes. The ESO will work closely with all the stakeholders to maintain the required quality of supply and to ensure secure and compliant operation of the system with regard to PQ:

- The stability pathfinder project run by the ESO aims to seek economic solutions/products to provide dynamic voltage support, short circuit current and system inertia. These services will help to increase the system strength, mitigating the deterioration of PQ.
- In the STC procedure STCP27-01 [10], we worked with the TOs to identify the GB system performance monitoring requirements. TOs target to install measurement devices providing Synchronised Data at all Grid Supply Points and transmission generators by the end of RIIO-2 (March 2026). These measurements will increase the visibility of system performance and can also provide useful insights with regard to some PQ phenomena like NPS. Sometimes it is also important for validation and root cause analysis to collect measurements from users or DNOs monitors, in such cases the ESO will collaborate with the relevant stakeholders and support the required analysis.
- The ESO indicated its target of enhancing its EMT modelling capability during the RIIO-2 period. This would enable accurate modelling of some of the PQ phenomena in the IBR dominated low carbon network by the end of Business Plan 2 in 2025, although currently the main steady state PQ phenomena are sufficiently captured by the steady state and frequency domain analysis. We are also working closely with all the stakeholders through Grid Code modifications and innovation projects to ensure the availability of accurate and compatible models to facilitate the required future networks modelling and analysis. The ability to deliver EMT analysis with credible results is contingent on getting the more detailed models, for example the impedance characteristics of active components in the network.

- We will be collaborating with the TOs and the relevant stakeholders to further understand impact from future network operation and configuration on PQ levels, for example switching in/out filters to maintain voltages and how it will affect harmonic levels. We are engaging with industry to identify the best practices for utilising the new and evolving technologies like Grid Forming Converters. We will be working closely with all the stakeholders through innovation and consultations to address the future PQ operability risks and will be sharing our findings through future SOF reports.
- Future policy adjustments will include possible code modifications or engineering recommendation panels to ensure that the limits and evaluation processes are updated regularly to address the future system challenges and to ensure the secure and efficient operation of the network.

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Glossary

EMT	Electromagnetic Transients
ESO	Electricity System Operator
ETYS	Electricity Ten Year Statement
FACTS	Flexible AC Transmission Systems
IBR	Inverter-Based Resource
NETS	National Electricity Transmission System
NPS	Negative Phase Sequence
PCC	Point of Common Coupling
PQ	Power Quality
RVC	Rapid Voltage Change
STATCOM	Static synchronous Compensator
STC	System Operator Transmission Owner Code
STCP	System Operator Transmission Owner Code Procedure
THD	Total Harmonic Distortion
TO	Transmission Owner

References

1. Electromagnetic compatibility (EMC) – Part 4-30: Testing and measurement techniques – Power quality measurement methods. IEC Standard 61000-4-30, 2003
2. Engineering Recommendation G5 - Harmonic voltage distortion and the connection of harmonic sources and/or resonant plant to transmission systems and distribution networks in the United Kingdom. Issue 5 2020
3. Provision of Short Circuit Level Data - A System Operability Framework (SOF) Document – February 2022 (https://www.nationalgrideso.com/document/238741/download)
4. The Grid Code (https://www.nationalgrideso.com/industry-information/codes/grid-code)
5. J. Campión, E. O. Oregi and C. Foote, "Active Harmonic Filtering in STATCOMs for Enhanced Renewable Energy Integration," 2019 IEEE Energy Conversion Congress and Exposition (ECCE), 2019
6. Engineering Recommendation P24 - AC supplies to railway systems. Issue 2 2020
7. Engineering Recommendation P29 – Planning limits for voltage unbalance in the United Kingdom for 132 kV and below. Issue 1 1990 (under revision)
8. Engineering Recommendation P28 – Voltage fluctuations and the connection of disturbing equipment to transmission systems and distribution networks in the United Kingdom. Issue 2 2019
9. Electromagnetic compatibility (EMC) – Part 3-7: Limits – Assessment of emission limits for the connection of fluctuating installations to MV, HV, and EHV power systems. IEC/TR 61000-3-7, 2008.
10. STCP27-01 Issue 002 System Performance Monitoring Requirements (https://www.nationalgrideso.com/document/138506/download)

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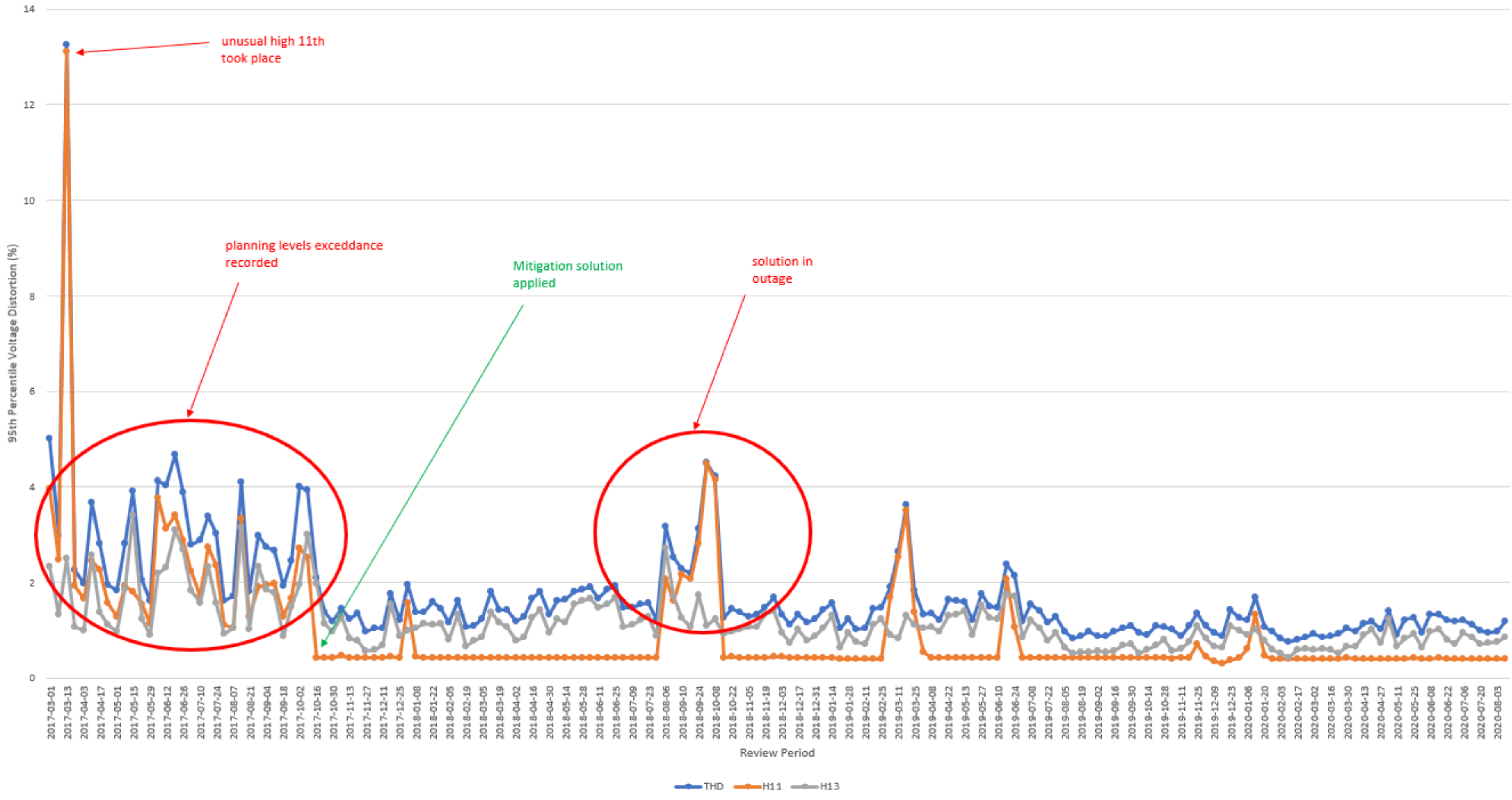
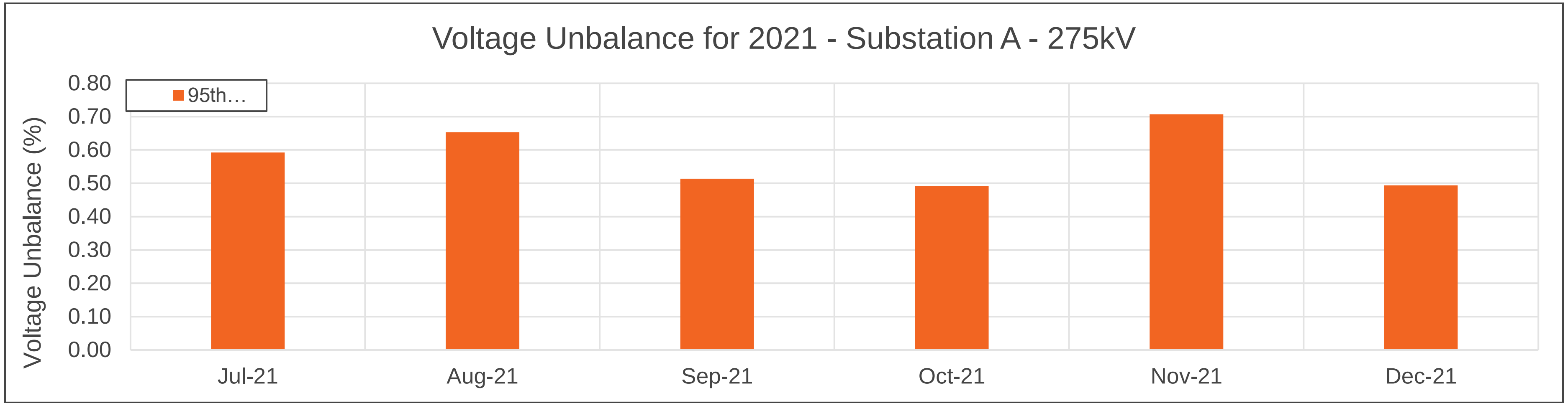
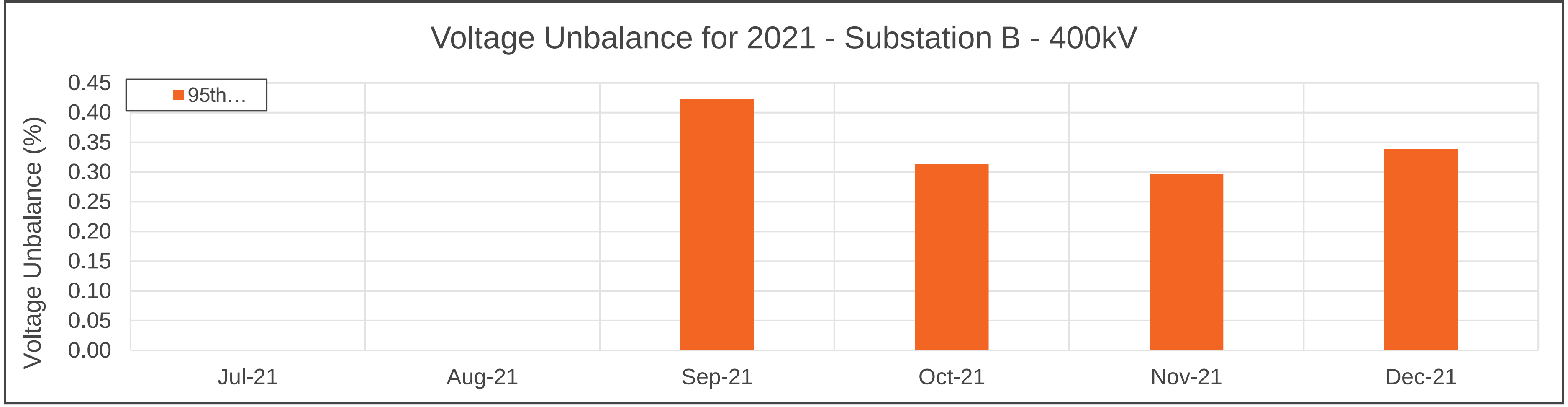
Appendices

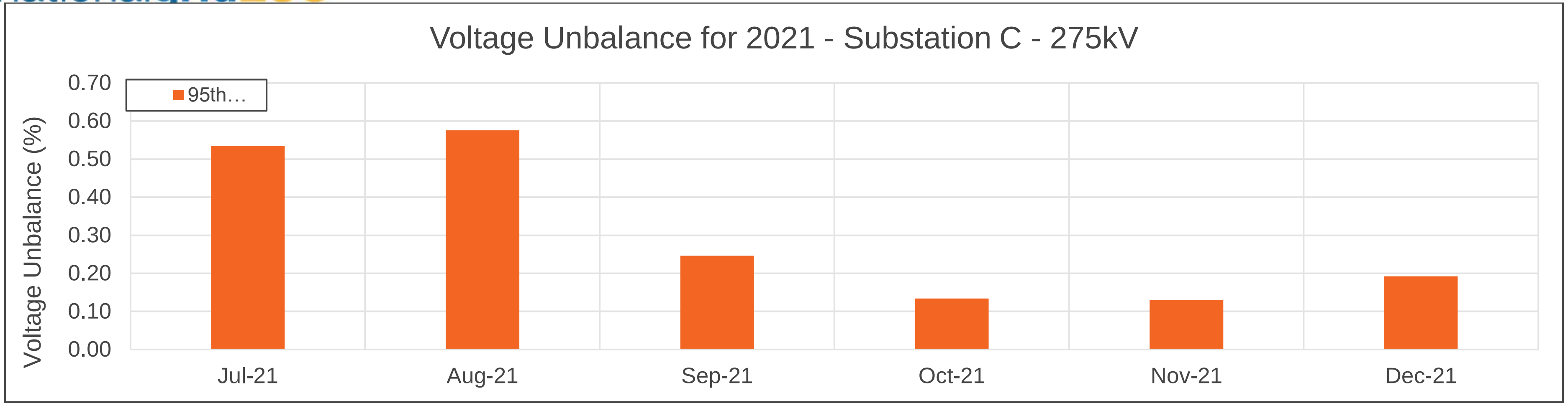
Appendix A: Example of harmonic measurements for a long period and the effectiveness of the mitigation solutions (33 kV connection site)

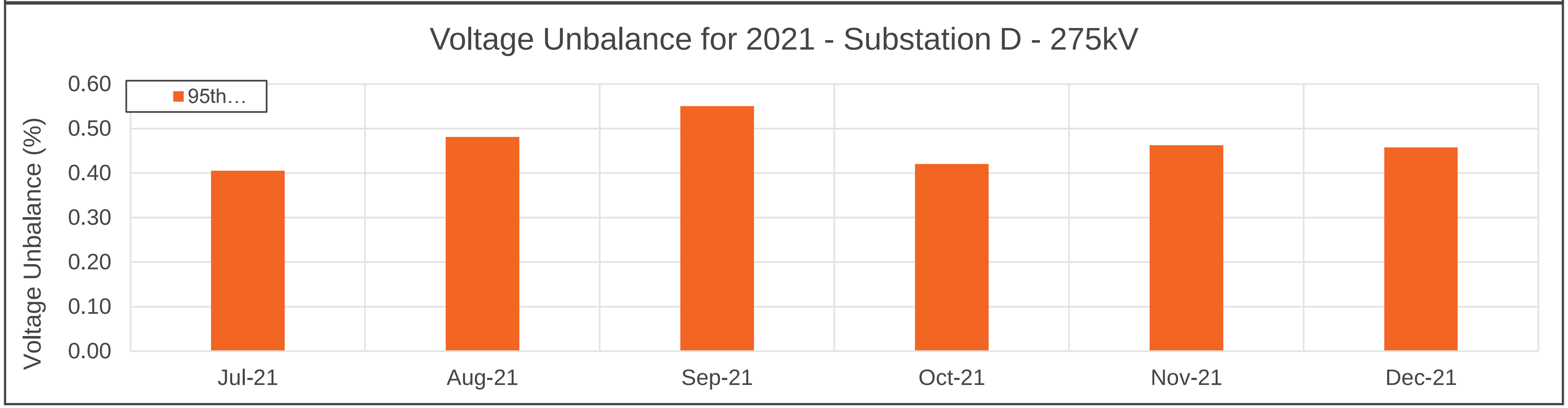


Appendix B: Examples of NPS values for 6 months for 400kV and 275kV sites (*Note: the July and August data for Substation B were not available – rather than a 0% NPS recorded)*

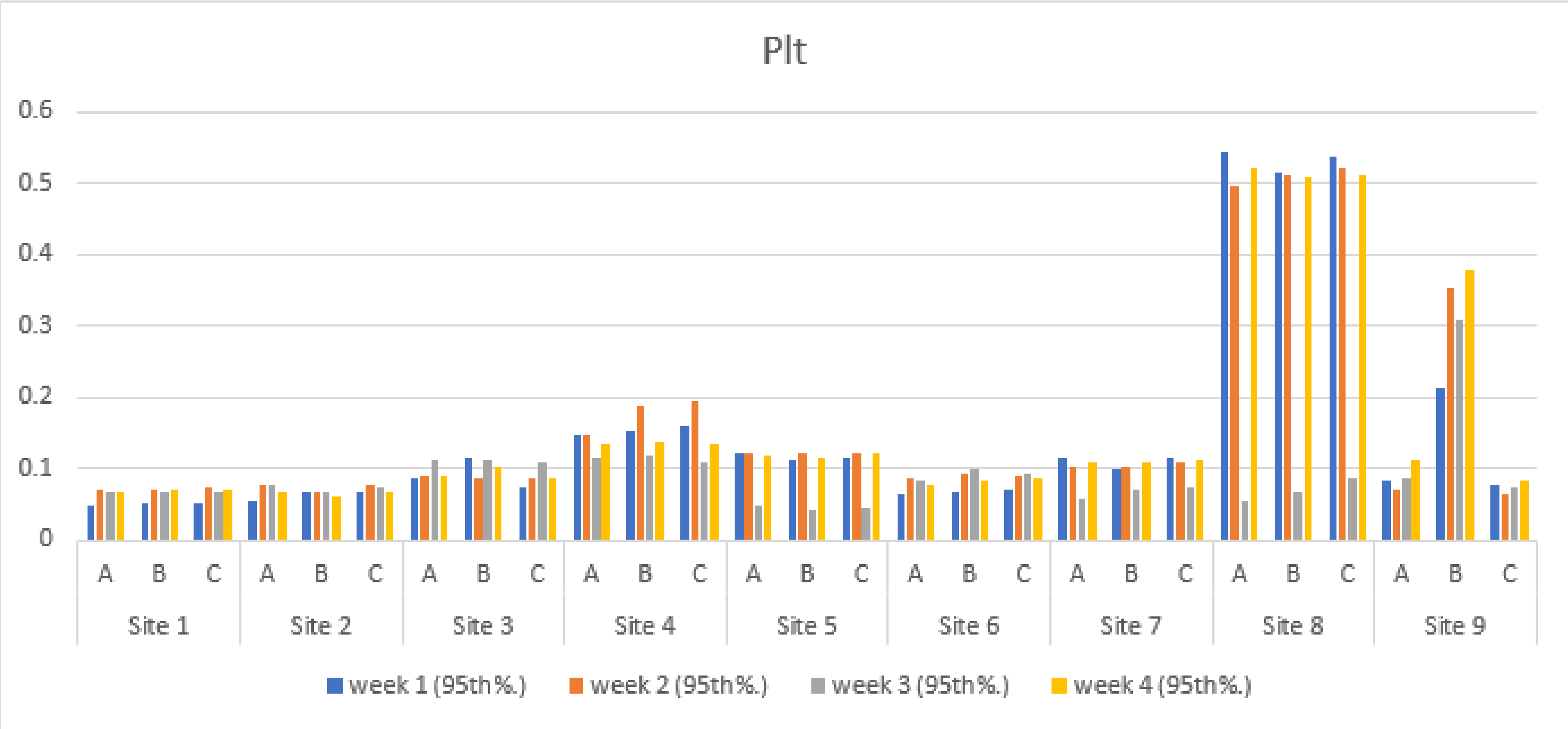





Voltage Unbalance for 2021 - Substation C - 275kV
95th…
Voltage Unbalance (%)
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
Jul-21
Aug-21
Sep-21
Oct-21
Nov-21
Dec-21


Voltage Unbalance for 2021 - Substation D - 275kV
95th…
Voltage Unbalance (%)
0.60
0.50
0.40
0.30
0.20
0.10
0.00
Jul-21
Aug-21
Sep-21
Oct-21
Nov-21
Dec-21

Appendix C: Flicker long term (Plt) weekly measurements in May 2022 for 400kV, 275kV and 33kV sites



Faraday House, Warwick Technology Park,
Gallows Hill, Warwick, CV34 6DA

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