Influence of PQ disturbances on operation of PE rich power networks

Deliverable 5.4

Date: 31.12.2018

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Executive summary

This report documents the work that has been carried out from January 2018 to December 2018 by MIGRATE WP5 (Power Quality in Transmission Networks with high PE Penetration) under task 5.4. This report constitutes the deliverable D5.4 – "Influence of PQ disturbances on operation of PE rich power networks", in fulfilment of the requirements defined by the grant agreement No 691800.

European transmission systems already face the challenge of integrating a rising number of power electronic (PE) devices and this trend will proceed in the future. The PE devices are included in most of the new low or high power equipment. Many types of renewable energy sources (RES), such as wind power plants, comprise PE. Also, the flexible AC transmission system (FACTS) devices that support the transmission system for its main function - the transmission of electrical energy, are mostly composed of the power electronic devices. As a consequence, large penetration of RES and other PE-based high power devices introduces new issues to the transmission system and to the power quality at the highest voltage levels.

Wind power plants are characterised by a varying feed-in of active power due to the fluctuating wind speed. Since active power variations lead to frequency variations in the system, wind farms and other RES can deteriorate power quality in the grid. Furthermore, with PE devices replacing directly coupled synchronous machines, the system inertia and primary control reserve decrease. A lower system inertia and primary control reserve, again, lead to higher variations of the system frequency.

Synchronous generators are also responsible for voltage control in the power system. Thus, when replacing synchronous generators with PE devices it is necessary that these devices support the voltage for a secure performance of the transmission system.

One of the main concerns with PE devices are harmonic emissions, generated by all types of devices that comprise the nonlinear switching converter-based elements. These allow for excellent dynamic performance at the fundamental frequency but due to AC-DC converters often produce high harmonic distortions. In practice, the harmonic studies are not done systematically as part of planning. Therefore, the harmonic analyses should become a compulsory part of system planning, operation criteria development, equipment design, troubleshooting, verification of standard compliance, and others. That to be said, the harmonic propagation studies allow for the proper insight in the power system operation which offers benefits to power system operators.

Influence of PE-based RES on PQ

In this deliverable, system frequency variations, voltage variations and harmonic distortion caused by PE devices are analysed. A grid model based on the Irish transmission system for different levels of PE penetration is studied. The presented use cases based on a future energy scenario for Ireland describe operating points at peak load and total PE penetration levels ranging from 60 % to 90 %.
Harmonic load flow simulations are conducted for the investigation of harmonic distortion as well as dynamic time-domain simulations are performed for the analysis of frequency and voltage variations. It is also assessed, under which conditions the frequency limits for normal operation are reached. Another sensitivity analysis for the study of voltage variations is performed, where the effect of different participation ratios of PE-interfaced generation units for voltage support is investigated.

As shown in this deliverable, the voltage variations in the test system are low due to the enabled voltage control by PE devices. However, a sensitivity analysis shows that with a lower share of PE devices participating in voltage control, the voltage variations increase. Nevertheless, the voltage deviations remain within the limits for normal operation.

Regarding system frequency, there is a positive correlation between the level of PE penetration and frequency variations. Even though the deviations from the nominal frequency of 50 Hz are within the admissible limits for normal operation, it becomes clear that the frequency variations are significantly higher than they are for comparable present-day scenarios analysed in MIGRATE D5.3. When referring to a case with 60 % PE penetration as a reference, the standard deviation of the system frequency increases by 145 % for a case with 90 % PE penetration. How frequency variations affect the balancing energy delivered by synchronous generators is further investigated. It is shown that the amount of balancing energy relative to the installed capacity of synchronous generators rises with an increasing level of PE penetration and increases by 200 % for a case with 90 % PE penetration compared to the reference case. Based on the simulation results, it is recommended, that the control of system frequency in normal operation should also include further generation units.

Probabilistic methodology for harmonic propagation studies developed in Deliverable D5.2 [41] and explained in more detail in Deliverable D5.3 [1] is used in the studies presented here to establish the level and significance of harmonic issues in present and future state of power test system considering different operational uncertainties and different penetration levels of power electronic devices.

By applying this methodology on the test network and for simulation cases, the impacts of PE devices on harmonic propagation in the power systems with increasing PE level are evaluated and identified.

The harmonic distortion is not only defined by the injections of individual device and the share of PE devices but also, as it has been proved by additional simulation scenarios, by the topology of the transmission system which is considered to have the most significant impact on harmonic propagation in the power system.

**Influence of PQ on PE devices**

The operation of PE-based RES devices influences the power quality of the network, as explained in this deliverable, mostly on the harmonic distortion, voltage variations and frequency excursions. The deteriorated power quality introduces new operating conditions for the devices that are already or are going to be connected to the network in the future. This can cause the adverse effects of the
power quality on the operation of devices and should be considered in the design stage to define the suitable immunity levels of individual device. Nevertheless, although a device operates within the immunity levels of particular power quality parameter of the grid, it can suffer from the effects that mostly influence the life-time expectancy of a device, influence the reliability or the efficiency during operation. The deliverable elaborates the influences of the deteriorated PQ on different passive and active elements that are contained within the modern PE-based devices.

The most evident effects caused by harmonic distortions are extensive heating of all conducting elements, overvoltages and consequently higher dielectric stress on the insulation layers as well as the negative influence on the frequency measurement and detection devices. The presence of higher harmonic currents causes increased eddy, stray or hysteresis losses. Some losses are frequency dependent, which increases the harmonic losses even more. Effect of harmonics could penetrate also into other magnetic-flux sensitive elements and can cause heating of other nearby elements, as for example heating of bearings of rotating induction machines due to the stray flux.

Beside the effect of harmonics, also the voltage and frequency variations cause some evident effects on the operation of the PE devices. Voltage variation could lead to higher current variation which consequently influences losses and efficiency of the energy transmission. Excessive voltages influence causes the dielectric stress on the elements or lead to the nonlinear operating conditions (e.g. nonlinear magnetization current of transformers). Other effects are in more details described within the deliverable.

PQ legislation overview and survey

The European Energy Supply for Electricity is undergoing fundamental changes, which also influence the Power Quality (PQ) in transmission networks. Important aspect is to understand and establish the state of the art of the approaches regarding requirements and legislation that different network operators and countries have with respect to PQ. A study was made for this deliverable to review existing grid codes and technical documents regarding PQ. This study contains the review of grid codes, relevant technical documents that accompany the grid codes and standards that are either power quality standards and/or have been cited in the grid codes.

Furthermore, a questionnaire to the TSOs was made about PQ requirements and legislation in current transmission networks that was distributed to a number of TSOs in Europe. The main conclusions arising from the analysis of the results of survey of 14 TSOs from all over Europe with all synchronous zones presented are as follows:

- Requirements for PQ in Europe are mostly defined in national legislative acts, followed by TSO lead documentation (either Grid Code as a TSO document or connection agreements).
- The main documents used/followed for defining PQ in respective networks are EN50160 and IEC standards.
• With respect to defining new limits and requirements for PQ in future networks the majority of the respondents see that these should be made and preferred option is that this should be done in Grid Code as a national legislative act.

• The respondents point out that the most important PQ characteristics to be defined in future documents are harmonics, unbalance, voltage flicker, and voltage dips.

More than two-third of the respondents point out that procedures for defining/setting limits for different PQ phenomena, procedure for monitoring, and procedure for verification should be available in these new documents.
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<td>AC</td>
<td>Alternating current</td>
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<td>AHDL</td>
<td>Allocated Harmonic Distortion Limit</td>
</tr>
<tr>
<td>AESA</td>
<td>Alberta Electric System Operator</td>
</tr>
<tr>
<td>ANSI</td>
<td>American National Standards Institute</td>
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<tr>
<td>DC</td>
<td>Direct current</td>
</tr>
<tr>
<td>DCC</td>
<td>Demand Connection Code</td>
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<tr>
<td>DER</td>
<td>Distributed energy resource</td>
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<tr>
<td>DFIG</td>
<td>Doubly-fed induction generator</td>
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<tr>
<td>DFT</td>
<td>Discrete Fourier transform</td>
</tr>
<tr>
<td>DN</td>
<td>Distribution Network</td>
</tr>
<tr>
<td>EDF</td>
<td>Empirical distribution function</td>
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<tr>
<td>EHV</td>
<td>Extra high voltage</td>
</tr>
<tr>
<td>EN</td>
<td>Europäische Norm</td>
</tr>
<tr>
<td>ENTSO-E</td>
<td>European Network of Transmission System Operators for Electricity</td>
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<tr>
<td>FACTS</td>
<td>Flexible AC Transmission System</td>
</tr>
<tr>
<td>FERC</td>
<td>Federal Energy Regulatory Commission</td>
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<tr>
<td>FFT</td>
<td>Fast Fourier transform</td>
</tr>
<tr>
<td>FR</td>
<td>France</td>
</tr>
<tr>
<td>HV</td>
<td>High voltage</td>
</tr>
<tr>
<td>HVDC</td>
<td>High-voltage direct current</td>
</tr>
<tr>
<td>HVDC</td>
<td>High Voltage Direct Current Connections (this is a ENTSOE network code)</td>
</tr>
<tr>
<td>IE</td>
<td>Ireland</td>
</tr>
<tr>
<td>IEC</td>
<td>International Electrotechnical Commission</td>
</tr>
<tr>
<td>IEEE</td>
<td>Institute of Electrical and Electronics Engineers</td>
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<tr>
<td>IHVDL</td>
<td>Incremental Harmonic Voltage Distortion Level</td>
</tr>
<tr>
<td>ISO</td>
<td>Independent system operator</td>
</tr>
<tr>
<td>LV</td>
<td>Low voltage</td>
</tr>
<tr>
<td>LVRT</td>
<td>Low voltage ride through</td>
</tr>
<tr>
<td>MV</td>
<td>Medium voltage</td>
</tr>
<tr>
<td>MPPT</td>
<td>Maximum power point tracking</td>
</tr>
<tr>
<td>NERC</td>
<td>North American Electric Reliability Corporation</td>
</tr>
<tr>
<td>p.u.</td>
<td>Per unit</td>
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<td>PCC</td>
<td>Point of common coupling</td>
</tr>
<tr>
<td>Acronym</td>
<td>Description</td>
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<td>PDF</td>
<td>Probability density function</td>
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<td>PE</td>
<td>Power electronics</td>
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<td>PEIL</td>
<td>PE-interfaced load</td>
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<td>POC</td>
<td>Point of connection</td>
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<td>POI</td>
<td>Point of injection</td>
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<td>RMS</td>
<td>Root Mean Square</td>
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<td>ROCOF</td>
<td>Rate of change of frequency</td>
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<td>RTO</td>
<td>Regional transmission operator</td>
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<td>RVC</td>
<td>Rapid voltage change</td>
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<td>SNSP</td>
<td>System non-synchronous penetration</td>
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<tr>
<td>SOGL</td>
<td>System Operations Guidelines</td>
</tr>
<tr>
<td>TDD</td>
<td>Total demand distortion</td>
</tr>
<tr>
<td>THD</td>
<td>Total harmonic distortion</td>
</tr>
<tr>
<td>TRD</td>
<td>Total rated-current distortion</td>
</tr>
<tr>
<td>TSO</td>
<td>Transmission system operator</td>
</tr>
<tr>
<td>UK</td>
<td>United Kingdom</td>
</tr>
<tr>
<td>VSC</td>
<td>Voltage source converter</td>
</tr>
<tr>
<td>WECS</td>
<td>Wind energy conversion system</td>
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<td>Wind turbine generator</td>
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1 Introduction

The transmission networks of electrical energy represent the backbone of the large synchronous zones of different continents. They are used to transmit the electrical energy from the generating sites to the loads and to support the network with sufficient short circuit power to improve the overall reliability and security of the power transmission and distribution. In order to optimize and to secure the transmission of the electrical energy, the power quality aspects that describe the voltage conditions of the supplying network must be taken into account. The adequate power quality levels are therefore required to allow for safe and normal operation of all devices connected to the grid. Any condition that deviates from the normal conditions can cause malfunction of individual device. This can adversely cause further negative power quality effects that spread from the source of disturbance to other devices through the network, causing severe operating conditions.

The new era of high penetration of renewable energy sources drastically influences the operation of the transmission systems. As a result, the European transmission systems already face the challenge of integrating a rising number of power electronic devices and this trend will proceed in the future [26],[102]. PE devices are equipped with semiconductor based fast-switching power converters that connect a load, generating unit or direct current (DC) transmission system to the alternating current (AC) grid [27]. Many types of renewable energy sources (RES) and FACTS devices comprise PE [27]. Based on installed capacity in Europe, the most common among them are photovoltaic (PV) and wind power plants [28].

The unsteadiness and intermittent nature of renewable power sources lead to higher fluctuations of the generated power which might deteriorate the optimal operating conditions of the grid. For the transmission of the electrical energy, the optimal and stable conditions are one of the major objectives that contribute to the transmission of the energy with the least amount of losses and with the least negative influence on the appliances connected to the grid.

Particularly wind power plants are characterised by a fluctuating power feed-in. Since active power variations lead to frequency variations in the system, RES can deteriorate the power quality in a grid [29]-[31]. Furthermore, with PE devices replacing directly coupled synchronous machines, the system inertia and primary frequency control reserve decrease. A lower system inertia and primary control reserve, again, lead to higher variations of the system frequency [32].

Variations in frequency have a negative effect especially on synchronous generators. If the ratio of non-synchronous to synchronous generation becomes too large, the remaining synchronous generators in the network have to make increased use of primary control in order to keep the power balance in the system. Consequently, the wear and tear of synchronous generators increases and affects the need for maintenance as studies have shown e.g. for hydro turbines [33], [34]. Furthermore, with stronger frequency variations, the system will operate closer to the limits for normal operation. Consequently, the power system becomes more vulnerable to large disturbances.
PE devices can also influence voltage behaviour in the power system if they cause reactive power variations [35]. Therefore, a properly tuned reactive power control or voltage control is crucial for a reliable voltage performance in the transmission system.

Beside the effect on the voltage and frequency fluctuation, the large penetration of PE devices drastically influences the harmonic distortion of the transmission and distribution network. Harmonic studies are becoming an important component of power system analysis and design. Over the past two decades, significant efforts and progresses in the area of power system harmonic analysis have been made. The importance of harmonic analysis with its main characteristics and requirements have been reported in Deliverable D5.3 [1].

This document continues the studies introduced in the deliverable 5.3 [1] and cover present-day scenario analyses. The studies of this document address future cases with further increase of the share of PE devices, which gradually replace the conventional fossil fuel power plants. Three power quality aspects are considered. One aspect includes harmonic distortions, caused by the nonlinear power electronic converters and amplified by the critical network impedances. The second aspect refers to frequency variations, caused by the fluctuating infeed of active power by PE devices and intensified by a reduced inertia and primary frequency control reserve in the system. The last aspect covers voltage variations due to variations of reactive power.

Based on the simulation results it will be assessed whether the existing grid allows such high penetration levels of PE devices, what would be the estimated power quality levels and whether there are any mitigation measures required to keep the power quality within expected or technically required levels.

The condition of the power quality in the future is tightly connected with the currently valid and applied grid codes which normally define the planning or compatibility levels of the network. Some of them also define the limit values and methodologies to allocate the permitted disturbance levels among individual customers.

Since the grid codes and practices diverge within different countries, the expected disturbance levels might reach different values in the future. Also, the electrical grids are highly diverse and the dynamics of the penetration of power electronic devices vary from one country to another. Therefore, the TSOs might consider the PQ issues differently by applying different preventive or mitigation strategies and dynamics of actions in time.

Nevertheless, one of the key points is to improve the awareness of all operators and users of the transmission systems that the preventive strategies to improve or to maintain PQ levels now is better than to mitigate the deteriorated PQ in the future, although it might cause some higher investments earlier in time. To enlighten this topic, the grid codes of PQ phenomena are compared among different countries and the future requirements discussed.
2 Methodology

The study object is a nonlinear dynamic grid model based on the transmission system of Ireland and implemented in DIgSILENT PowerFactory. Its voltage levels include 110 kV, 220 kV and 400 kV. The model used for simulations in MIGRATE D5.4 is based on the 2016 version of the Irish test grid introduced and described as “2016 Baseline Model” in D1.2 [2]. It was adjusted to the specifications of the future scenario “Ireland Slow Change Scenario” for 2040, which had also been introduced in [2]. The adjusted grid model is referred to as “2040 Baseline Model”. For convenience, the installed capacities for 2016 and 2040 presented in D1.2 [2] are shown in Table 2-1.

Power plants with synchronous generators directly coupled to the grid are now limited to types based on gas, waste, biomass and hydro. Coal, peat and oil fired power plants are decommissioned and therefore their installed capacity for 2040 is reduced to zero. In comparison to the 2016 Baseline Model, the 2040 Baseline Model includes additional PE-interfaced generation unit types. Among the installed capacity of these additional units are 400 MW of PV power plants, 40 MW of wave and tidal power stations, 150 MW of battery storage units and 500 MW of offshore wind farms. The installed capacity of onshore wind farms is increased from 2.8 GW in the 2016 Baseline Model to 4.9 GW in the 2040 Baseline Model. Furthermore, a 700 MW high-voltage direct current (HVDC) interconnector between Ireland and France (IE-FR) is integrated in the 2040 grid model in addition to the existing 500 MW HVDC interconnector between Ireland and the United Kingdom (IE-UK).

The specifications for the installed capacity in the power system provide the base for the choice of suitable operating points of use cases for simulation and analysis. Operating points for six use cases are determined in Section 4.1 and analysed in Section 5.1. As it is the primary objective of this study to demonstrate the effects of PE devices on the power quality in the power system, the use cases are characterised by different levels of PE penetration.
Table 2-1: Installed capacity for the Ireland Base Case 2016 and "Slow Change" Scenario 2040

<table>
<thead>
<tr>
<th>Category</th>
<th>2016 Baseline Model</th>
<th>2040 Slow Change Scenario</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coal</td>
<td>860</td>
<td>0</td>
</tr>
<tr>
<td>Gas</td>
<td>4200</td>
<td>5430</td>
</tr>
<tr>
<td>Peat</td>
<td>360</td>
<td>0</td>
</tr>
<tr>
<td>Distillate Oil</td>
<td>310</td>
<td>0</td>
</tr>
<tr>
<td>Heavy Fuel Oil</td>
<td>590</td>
<td>0</td>
</tr>
<tr>
<td>Waste (share fossil)</td>
<td>0</td>
<td>50</td>
</tr>
<tr>
<td>Total fossil fuel generation capacity</td>
<td>6320</td>
<td>5480</td>
</tr>
<tr>
<td>Wind (onshore)</td>
<td>2830</td>
<td>4860</td>
</tr>
<tr>
<td>Wind (offshore)</td>
<td>0</td>
<td>500</td>
</tr>
<tr>
<td>Hydro</td>
<td>240</td>
<td>240</td>
</tr>
<tr>
<td>Biomass/Landfill Gas</td>
<td>0</td>
<td>410</td>
</tr>
<tr>
<td>Solar PV</td>
<td>0</td>
<td>400</td>
</tr>
<tr>
<td>Ocean (Wave / Tidal)</td>
<td>0</td>
<td>40</td>
</tr>
<tr>
<td>Waste (share renewable)</td>
<td>0</td>
<td>50</td>
</tr>
<tr>
<td>Total renewable generation capacity</td>
<td>3070</td>
<td>6500</td>
</tr>
<tr>
<td>Pumped Storage</td>
<td>290</td>
<td>290</td>
</tr>
<tr>
<td>Small Scale Battery Storage</td>
<td>0</td>
<td>150</td>
</tr>
<tr>
<td>Large Battery Storage</td>
<td>0</td>
<td>150</td>
</tr>
<tr>
<td>Demand Side Management</td>
<td>0</td>
<td>500</td>
</tr>
<tr>
<td>DC Interconnection</td>
<td>500</td>
<td>1200</td>
</tr>
<tr>
<td>Conventional Combined Heat &amp; Power</td>
<td>0</td>
<td>150</td>
</tr>
<tr>
<td>Total installed capacity</td>
<td>10180</td>
<td>14420</td>
</tr>
</tbody>
</table>

2.1 Definition of PE penetration

PE penetration in the examined power system is aligned with MIGRATE WP1 scenarios. The PE penetration level is defined as the system non-synchronous penetration (SNSP), expressed in percent. In D1.2, SNSP is described for the 2016 Base Model as [2]:

\[
SNSP = \frac{P_{\text{wind}} + P_{\text{DC,import}}}{P_{\text{load}} + P_{\text{AC,export}} + P_{\text{DC,export}} - P_{\text{AC,import}}} \cdot 100 \%
\]  

(2.1)

Here, \( P_{\text{wind}} \) denotes the total active power feed-in by wind farms, whereas \( P_{\text{load}} \) represents the total active power demand. \( P_{\text{DC,import}} \) and \( P_{\text{DC,export}} \) stand for aggregated active power import and export to external grids via DC lines, respectively. Analogously, \( P_{\text{AC,import}} \) and \( P_{\text{AC,export}} \) express aggregated active power import and export via AC lines.
In the 2016 Baseline Model, PE-interfaced generation, excluding power infeed by DC-inter-connectors, constitutes exclusively of wind power. In comparison, the 2040 Baseline Model includes additional units for battery storage, wave and tidal power plants and PV. Therefore, the variable $P_{\text{wind}}$ in equation (2.1) is generalised and renamed as $P_{\text{PE}}$ for use in D5.4. Here, $P_{\text{PE}}$ comprises the aggregated active power feed-in by wind farms $P_{\text{wind}}$, battery storage $P_{\text{battery}}$, wave and tidal power plants $P_{\text{ocean}}$, and PV $P_{\text{PV}}$.

Furthermore, in the 2040 Baseline Model power exchange to external grids exclusively takes place via DC lines. The terms $P_{\text{AC,import}}$ and $P_{\text{AC,export}}$ in equation (2.1) are thus omitted. Last, aggregated transmission losses $P_{\text{loss}}$ are disclosed separately from $P_{\text{load}}$.

Consequently, equation (2.1) can be converted into equation (2.2) for use in D5.4:

$$SNSP = \frac{P_{\text{PE}} + P_{\text{DC,import}}}{P_{\text{load}} + P_{\text{loss}} + P_{\text{DC,export}}} \cdot 100\% \tag{2.2}$$

Power input of synchronous generators $P_{\text{SG}}$ can be determined by the system power balance, expressed in equation (2.3):

$$P_{\text{SG}} = (P_{\text{load}} + P_{\text{loss}} + P_{\text{DC,export}}) - (P_{\text{PE}} + P_{\text{DC,import}}) \tag{2.3}$$

### 2.2 Indicators for power variations

The volatile feed-in of the wind farms due to a changing wind speed leads to variations in active and reactive power in the power system. These variations are indicated by variations of the system frequency and voltage. In this study, system frequency and voltages at relevant nodes are analysed over a time of ten minutes. The methodology for the analysis is described in the following paragraphs.

#### 2.2.1 Frequency

The electrical system frequency $f_{\text{sys}}$ is measured at the point of common coupling (PCC) of all synchronous generators in the system which are directly coupled to the grid and which are active during the simulation. Upper and lower frequency limits are verified for normal operation. According to the Irish Grid Code, the lower and the upper limits of the normal operating range are 49.80 Hz and 50.20 Hz, respectively [38].

The system frequency behaviour is further analysed to determine the extent of variations. For that purpose, a histogram and an empirical distribution function (EDF) plot are provided in one graph. The histogram states the normalised number of counts of sample values $p_{\text{hist}}(f_{\text{sys}})$ for the single bins at $f_{\text{sys}}$ and is denoted on the left-hand side y-axis. The bins of the histogram have a constant width of 5 mHz. The EDF is denoted as $P_{\text{EDF}}(f_{\text{sys}})$ on the right-hand side y-axis and states the cumulative normalised number of counts at $f_{\text{sys}}$, i.e. the count number of values in the sample that are greater than $f_{\text{sys}}$. 
In addition, a Fourier analysis is performed to describe the frequencies characterising system frequency deviations. The Fourier transform decomposes the system frequency deviations in the time domain into oscillatory components. The amplitudes of these components can then be displayed in a frequency spectrum. In this study, a fast Fourier transform (FFT) algorithm is applied to the system frequency samples in order to compute the discrete Fourier transform (DFT).

From the diagram obtained by FFT, the dominating frequency components of the system frequency deviations can be identified. For a better understanding of the implications of these components for the system frequency control, the influence range of primary control and system inertia is determined in the frequency spectrum. First, the turbine governors for synchronous generators of thermal power plants are investigated. The governor model used in this study is the IEEEG2 standard model. The parameters are listed in the appendix. In Figure 2-1, the Bode diagram for the transfer function $G_{\text{gov}}$ of the generic turbine governor model can be seen. The turbine governors are tuned for frequencies smaller than the cut-off frequency at 4.4 Hz, which is marked by a green dotted line. Therefore, system frequency deviations appearing with frequencies below 4.4 Hz are addressed by primary control.

![Bode diagram of generic turbine governor for thermal power plants](image)

Figure 2-1: Bode diagram of generic turbine governor for thermal power plants

In a next step, the region of influence in the frequency spectrum by system inertia is determined in the same manner. Neglecting the effect of damping by loads, the transfer function relating power and system frequency is described as follows [30]:

$$G_{\text{inertia}}(s) = 2H_{\text{eq}}s = \frac{\Delta P_L}{\Delta f_{\text{sys}}}$$ (2.4)

Where $H_{\text{eq}}$ is the equivalent system inertia constant, $\Delta f_{\text{sys}}$ is the system frequency deviation in per unit (p.u.) and $\Delta P_L$ is the non-frequency-sensitive load change in p.u. The corresponding Bode diagram for an example with $H_{\text{eq}} = 3$ s is shown in Figure 2-2. For this case, it can be seen that the system inertia has a dominating effect on the system frequency variations for frequencies above 26 mHz, i.e. when it crosses the 0 dB mark. For cases with smaller $H_{\text{eq}}$, the intersection with the 0 dB level moves towards higher frequencies and vice versa.
Finally, the Bode diagrams for turbine governor and system inertia are combined with the diagram for the FFT analysis of the system frequency deviations. The aim of this graphical representation is to identify the frequency components with the maximum amplitudes and to facilitate a qualitative evaluation of how they are influenced by primary control and system inertia. Figure 2-3 shows the result for an exemplary set of samples of system frequency deviation. Region A indicates the frequency spectrum, for which the generic speed governors of thermal power plants are tuned. Region B on the other hand marks the frequency spectrum, for which system inertia has a dominating effect on the system frequency variations.

The rate of change of frequency (ROCOF) is not considered in this study. Frequency changes due to the varying feed-in of active power by wind power are slow and lead to small ROCOF. This has been shown for example in the previous MIGRATE WP5 deliverable, D5.3 [1]. Instead, ROCOF is more suitable to describe the fast decline or rise of frequency resulting from faults or sudden large changes in load in frequency stability studies. For more information on frequency stability studies in the Irish test grid, refer to [2].
2.2.2 Voltage

The voltage is measured and analysed at nodes with a nominal voltage level of 110 kV, 220 kV and 400 kV. The voltage magnitudes are compared to the allowed ranges for normal operation in kV, which are listed in Table 2-2 [38]. The respective values are complementarily added in per unit (p.u.). For the description of voltage variations, the standard deviation is determined.

Table 2-2: Voltage deviation limits for normal operation

<table>
<thead>
<tr>
<th>Nominal voltage [kV]</th>
<th>Lower limit [kV]</th>
<th>Upper limit [kV]</th>
<th>Lower limit [p.u.]</th>
<th>Upper limit [p.u.]</th>
</tr>
</thead>
<tbody>
<tr>
<td>110</td>
<td>105</td>
<td>120</td>
<td>0.955</td>
<td>1.091</td>
</tr>
<tr>
<td>220</td>
<td>210</td>
<td>240</td>
<td>0.955</td>
<td>1.091</td>
</tr>
<tr>
<td>400</td>
<td>370</td>
<td>410</td>
<td>0.925</td>
<td>1.025</td>
</tr>
</tbody>
</table>

2.2.3 Harmonics

Harmonic distortion of the voltage at the transmission system nodes is analysed by using the detailed model of the Irish transmission network which comprises the frequency-dependent characteristics of network elements to provide more accurate results of the harmonic analyses in the higher frequency range.

The methodology of the harmonic analyses is based on the probabilistic approach since the detailed tuning of individual operating point for harmonics is practically impossible. Detailed information about the probabilistic methodology on the harmonic load flow analyses has been provided in D5.3 [1]. It is important to emphasize that the results provided in this report are for the illustrative purposes of the potential impact of different PE penetration levels on harmonic propagation only and they do not reflect in any way actual, measured or expected harmonic performance of the Irish transmission network. The Irish network model is used only to illustrate the application of the developed methodology in a realistic transmission network topology and to demonstrate the potential for the application of such methodology for the TSOs in terms of understanding the harmonic propagation in the transmission network. The probabilistic harmonic methodology, as explained in detail in Deliverable D5.3 [1], is here applied for single operating points of the selected case studies. The approach in its full extent, as presented in Deliverable D5.3 [1] and illustrated there on the modified IEEE 68 bus network, could not be directly applied in EirGrid test network (Irish network model) due to unavailability of some data related to yearly operation of the network so that chronological network operation could be simulated. The methodology is used here to demonstrate its suitability for evaluation of the harmonic performance of the large power system or rather changes in expected
harmonic performance of the network, at different levels of penetration PE connected generation. From that point of view, the simulation of harmonic performance of the network over prolonged period of time was not necessary. Finally it is important to note that the comparison of developed probabilistic methodology for harmonic evaluation in the future transmission networks, with very large penetration levels of PE connected devices, with harmonic evaluation approaches currently used by TSO, was out of the scope of this deliverable.
3 Modelling

3.1 Modelling for dynamic simulations

The study object is a nonlinear dynamic system model based on the transmission system of Ireland suitable for phasor-type simulation, which is provided by the Irish transmission system operator (TSO) EirGrid and implemented in the simulation software PowerFactory DIgSILENT.

Modelling of load

The load elements in the system model are divided into 86 % conventional loads and 14 % PE-interfaced loads (PEIL). Conventional loads are modelled as a combination of 50 % static and 50 % non-linear dynamic loads as described in MIGRATE Deliverable D1.2 [2]. PEIL elements are modelled according to the generic PE-based load model suitable for phasor-type simulation, which is introduced in MIGRATE Deliverable D1.3 [39]. This model mimics the characteristics of a full converter-interfaced load model that reduces frequency and voltage dependence on the load-side.

Modelling of synchronous generators

Power plants with synchronous generators are modelled as generic power plant models consisting of an automatic voltage regulator, a turbine governor and the synchronous generator. A more detailed description is given in MIGRATE Deliverable D1.2 [2].

Modelling of non-synchronous power generation units

The following types of non-synchronous power generation units are considered in the power system model: onshore wind farms, offshore wind farms, wave and tidal power plants and battery storage units. Wave and tidal power plants and battery storage units are modelled as static generators. The control scheme of the static generators is based on [27]. The coupling with the transmission grid is at 110 kV, respectively. All units employ voltage control at PCC.

For representing the behaviour of offshore and onshore wind farms, wind turbines are subjected to individual wind speed profiles. The wind speed profiles are modelled as described in MIGRATE D5.3 [1]. The employed wind energy conversion system (WECS) model is described in [40] and has been introduced in MIGRATE D5.2 [41]. It represents a nonlinear WECS model with a type 4 wind turbine and a rated power of 3 MW that is reached at a nominal wind speed of 12 m/s. In order to allow for individual wind speed profiles for each turbine, the values for active power output of the single WECS units in a wind farm are simulated separately and are then aggregated and stored in a
lookup table. The lookup table serves as the input signal for the power output of the static generator representing a wind farm in the grid model. The control scheme of the converter is based on [27].

In the grid model, onshore wind farms are connected at 38 kV or 110 kV. Offshore wind farms are connected at 220 kV. Wind farms connected at voltage levels of 110 kV or above employ voltage control at PCC.

For the simulations of the study cases covered in Sections 4.1 and 5.1, all wind turbines within a wind farm are assumed to be active. Further it is assumed, that all turbines operate in maximum power point tracking (MPPT) mode. This operating mode maximises the power output of the WECS based on the incoming wind speed [42]. Consequently, the MPPT mode leads to active power variations in contrast to operation above rated wind speed, when blade pitch control regulates the power output to its nominal value [42]. Therefore, the simulations in this chapter describe a situation with high active power variations caused by wind farms.
3.2 Modelling for harmonic analyses

The study object is a nonlinear dynamic system model based on the transmission system of Ireland provided by the Irish transmission system operator (TSO) EirGrid and implemented in the simulation software PowerFactory DgSILENT. In general, it is the same grid model as is the one used for fundamental frequency component analyses (phasor analyses) with the addition of more detailed modelling of individual network elements, which are now frequency-dependent as described in [41].

All PE interface connected devices (RES, FACTS and HVDC) in the test network are modelled as harmonic sources. Corresponding magnitude injection ranges for individual frequency component are taken from Deliverable 5.2 [41] while the individual harmonic phase angles were randomly sampled from the range 0-180° assuming uniform distribution in accordance with suggested probabilistic harmonic methodology.

All loads in the network, industrial and distribution network (DN) type load are modelled as a combination of linear and non-linear components. The percentage of nonlinear components of industrial loads was assumed to be 50% and the percentage of nonlinear components of DN type loads was assumed to be 20%. This composition of linear and non-linear load component at different buses is used in all case studies concerning different penetration level of PE connected generation. The same linear/non-linear load split, i.e., percentage of non-linear component of the load at load buses has been used previously in D5.3 [1] where the probabilistic methodology for harmonic propagation studies was introduced and illustrated. Additional case studies were introduced and analysed in this report where different load composition i.e. different share of linear and non-linear loads was considered. These were developed to investigate and illustrate the impact of background harmonic injection on harmonic propagation in the network.

PE connected devices (WF, SVC and HVDC) are modelled using Norton equivalent with independent sampling of harmonic impedance and current injections, as elaborated previously in D5.3 [1], and within ranges specified in D5.2 [41]. The power system loads are modelled as the ideal current sources with harmonic injections within ranges also specified in D5.2 [41].

The probabilistic approach of the harmonic analyses considers a single operating point for each of the operating scenarios. The harmonic injections were simulated 500 times in each case using Monte Carlo simulations.

Bus numeration differs from original EirGrid model in order to enable publication of these document.
4 Study cases

4.1 Study cases

In this section, the operating points for six study cases for the 2040 Baseline Model are defined and summarised in Table 4-1. The aggregated active power demand $P_{\text{load}}$ of 5.9 GW is the same for each case and represents a winter peak situation. The study cases differentiates based on the SNSP level, which ranges from 60 % to 90 % and is defined in Section 2.1.

The reference case specified in Table 4-1, serves as a base for comparing the simulation results obtained from the remaining use cases. It comprises an SNSP level of 60 % and corresponds to a present-day scenario in Ireland, where 65 % SNSP is the maximum limit [104]. Since there is no installed capacity for offshore wind farms, PV, wave and tidal power stations or battery storage in the present-day Irish transmission grid [37], the respective units in the 2040 Baseline Model are out of service for the reference case. PE-interfaced generation is limited to 3348 MW by onshore wind farms and 350 MW by the HVDC interconnector between Ireland and UK. Synchronous generators feed in 2466 MW.

The other use cases represent future scenarios. The values for SNSP are set to 70 %, 80 % and 90 % for Cases 1, 2 and 3, respectively. As winter peak demand in Ireland usually occurs after sunset [43], the power input $P_{\text{PV}}$ by PV power plants is set to zero for all cases. The operating points for $P_{\text{ocean}}$, $P_{\text{battery}}$, $P_{\text{DCimport}}$, $P_{\text{DCexport}}$ for Cases 1 to 3 are set to 40 MW, 200 MW, 800 MW and 0 MW, respectively. According to equation (2.2), $P_{\text{wind}}$ results in 3285 MW for Case 1, 3892 MW for Case 2 and 4549 MW for Case 3. Application of equation (2.3) for determining $P_{\text{SG}}$ leads to 1854 MW for Case 1, 1233 MW for Case 2 and 621 MW for Case 3. The power infeed $P_{\text{SG}}$ is supplied by synchronous generators with the aggregated installed capacity $S_{\text{SG}}$ given for each case in Table 4-2.

Case 3.1 and 3.2 represent alterations of Case 3 and, therefore, feature an SNSP level of 90 % as well. To show the influence of a higher system inertia and primary control reserve on dynamics, an additional synchronous generator is active in Case 3.1 leading to higher installed capacity of synchronous generators. The other alteration, Case 3.2, employs the same generators as Case 3 but changes the regulation characteristic of the turbine governors of the synchronous generators. This results in a primary control reserve equivalent to that of the reference case.

The bottom row of Table 4-1 states the entries for the equivalent system inertia constant $H_{\text{eq}}$ and the inverse of the equivalent governor speed droop $R_{\text{eq}}$ of the synchronous generators in the system for the respective study cases. As the equation of motion for a synchronous generator in equation (4.1) implies, dynamic changes in the system frequency are inversely proportional to the inertia constant [30].
\[
\frac{d\omega_r}{dt} = \frac{T_m - T_e}{2H} \tag{4.1}
\]

where \( \omega_r \) is the angular velocity of the rotor in per unit, \( T_m \) is the mechanical torque in per unit and \( T_e \) is the electrical torque in per unit. \( H \) is the inertia constant of the synchronous generator in s.

\( R_{eq} \) is the equivalent speed droop for all turbine governors of synchronous generators in operation. The gain \( 1/R_{eq} \) determines the response of the generators towards a load change \( \Delta P_{load} \) in the system. The proportional response, together with the load-damping expressed as \( D \), results in a steady state system frequency deviation of \( \Delta f_{sys} \) as shown in equation (4.2) [30]. Thus, the value of \( 1/R_{eq} \) indicates the primary control reserve of the synchronous generators.

\[
\Delta f_{sys} = -\frac{\Delta P_{load}}{\frac{1}{R_{eq}} + D} \tag{4.2}
\]

As can be seen from Table 4-1, the equivalent system inertia constant \( H_{eq} \) and the inverse of the equivalent governor speed droop \( R_{eq} \) decrease with a rising level of SNSP up to Case 3 and increase again for Case 3.1 and 3.2.

Table 4-1: Operating points for study cases

<table>
<thead>
<tr>
<th>Reference Case</th>
<th>Case 1</th>
<th>Case 2</th>
<th>Case 3</th>
<th>Case 3.1</th>
<th>Case 3.2</th>
</tr>
</thead>
<tbody>
<tr>
<td>SNSP [%]</td>
<td>60</td>
<td>70</td>
<td>80</td>
<td>90</td>
<td>90</td>
</tr>
<tr>
<td>( P_{load} ) [MW]</td>
<td>5894</td>
<td>5894</td>
<td>5894</td>
<td>5894</td>
<td>5894</td>
</tr>
<tr>
<td>( P_{losses} ) [MW]</td>
<td>270</td>
<td>285</td>
<td>271</td>
<td>315</td>
<td>315</td>
</tr>
<tr>
<td>( P_{PV} ) [MW]</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>( P_{ocean} ) [MW]</td>
<td>0</td>
<td>40</td>
<td>40</td>
<td>40</td>
<td>40</td>
</tr>
<tr>
<td>( P_{battery} ) [MW]</td>
<td>0</td>
<td>200</td>
<td>200</td>
<td>200</td>
<td>200</td>
</tr>
<tr>
<td>( P_{DCimport} ) [MW]</td>
<td>350</td>
<td>800</td>
<td>800</td>
<td>800</td>
<td>800</td>
</tr>
<tr>
<td>( P_{DCexport} ) [MW]</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>( P_{wind} ) [MW]</td>
<td>3348</td>
<td>3285</td>
<td>3892</td>
<td>4549</td>
<td>4549</td>
</tr>
<tr>
<td>( P_{SG} ) [MW]</td>
<td>2466</td>
<td>1854</td>
<td>1233</td>
<td>621</td>
<td>621</td>
</tr>
<tr>
<td>( H_{eq} ) [s]</td>
<td>3.01</td>
<td>2.76</td>
<td>1.77</td>
<td>1.21</td>
<td>1.58</td>
</tr>
<tr>
<td>( 1/R_{eq} ) [MW/Hz]</td>
<td>1685</td>
<td>1366</td>
<td>890</td>
<td>677</td>
<td>906</td>
</tr>
</tbody>
</table>

Table 4-2: Installed capacity of synchronous generators in operation

<table>
<thead>
<tr>
<th>Reference Case</th>
<th>Case 1</th>
<th>Case 2</th>
<th>Case 3</th>
<th>Case 3.1</th>
<th>Case 3.2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Installed capacity of synchronous generators in operation ( S_{SG} ) [MVA]</td>
<td>3735</td>
<td>3017</td>
<td>1946</td>
<td>1466</td>
<td>1981</td>
</tr>
</tbody>
</table>
4.1.1 Additional study-cases for harmonic analyses

Variation of the share of PE loads

The harmonic analyses have been performed for the Cases 1 to 3 and the reference one. Additional cases that are evaluated and analysed are the cases that correspond to the Case 1 as presented in Table 4-1 where different load composition in terms of split between linear and non-linear loads is assumed and its impact on harmonic propagation is assessed. The main reason for the selection of Case 1 to be the base for the further analysis is the fact that in this case (i.e., 70% penetration of PE devices) one can observe first increase of 95th THD value over the threshold value specified in the international standards. Different variations of Case 1 for additional harmonic studies are shown in Table 4-3.

Table 4-3: Operating points for Case 1 with different share of loads

<table>
<thead>
<tr>
<th>Cases</th>
<th>Distribution network loads</th>
<th>Industrial loads</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case 1</td>
<td>80% linear, 20% non-linear</td>
<td>50% linear, 50% non-linear</td>
</tr>
<tr>
<td>Case 1.1</td>
<td>50% linear, 50% non-linear</td>
<td>50% linear, 50% non-linear</td>
</tr>
<tr>
<td>Case 1.2</td>
<td>80% linear, 20% non-linear</td>
<td>80% linear, 20% non-linear</td>
</tr>
<tr>
<td>Case 1.3</td>
<td>50% linear, 50% non-linear</td>
<td>80% linear, 20% non-linear</td>
</tr>
</tbody>
</table>

Maintenance scenario

In order to evaluate the impact of variation of the network topology, which corresponds to the network impedance and resonant frequency variations, an additional "maintenance case" (marked as M case) has been analysed. It represents the case where the disconnection of one of the 220 kV lines followed by the disconnection of a 110 kV harmonic filter occurs. Apart from the line and filter disconnection, i.e., topology change, the other settings correspond to the Reference case (marked as Ref case).

By manipulating the network impedance, the frequency-dependent impedance characteristic varies. The resonance impedances can shift to different frequencies that causes high variation of the impedance at particular frequency consequently causing high variations of the resultant individual harmonic distortions.
5 Analysis of frequency and voltage variations

5.1 Simulation and analysis

In this section, the results of the frequency and voltage variations simulations are presented for the same cases described in the previous Section 4.1.

5.1.1 Reference Case: 60 percent of System Non-Synchronous Penetration

Active and reactive power

For the reference case, the aggregated active power demand in the system is depicted in Figure 5-1. The active power demand of the loads is voltage and frequency dependent, which is why the curve is not constant but varies around its initial value. The corresponding graphs for the aggregated active power demand for Cases 1, 2, 3, 3.1, and 3.2 can be found in the Appendix.

The aggregated feed-in of active power PE-interfaced power sources including wind farms is depicted in Figure 5-2. The active power feed-in by wind farms fluctuates because of the non-stationary wind speed that serves as input for the wind farm models. It can be seen from Figure 5-3 that the active power feed-in by synchronous generators acts in the opposite direction of the varying wind power in order to keep the system power balance and to regulate the system frequency at 50 Hz. Neglecting governor dynamics and damping, the active power deviation $\Delta P_i$ in p.u. of a synchronous generator $i$ from its operating point in response to a system frequency deviation can be described by [30]:

$$\Delta P_i = -\Delta f_{sys} \left( \frac{1}{R_i} + 2H_is \right)$$

(5.1)

Here, $\Delta f_{sys}$ is the system frequency deviation in p.u., $R_i$ is the speed droop of the turbine governor for generator $i$ in p.u. and $H_i$ is the inertia constant of generator $i$ in s.

Integrating the curve for active power provided by synchronous generators reveals the resulting balancing energy deployed by synchronous generators over the ten minutes simulation time. Figure 5-4 shows the balancing energy represented by the area between the active power curve and the height of active power feed-in at the initial operating point. For the reference case, the positive balancing energy marked blue is determined as 1.47 MWh. The negative balancing energy is marked red and amounts to 1.43 MWh. Summing up the absolute values and setting this amount in relation with the installed capacity of active synchronous generators results in 2.80 MWs/MVA.

Figure 5-5 displays the aggregated reactive power input of all PE-interfaced power sources and Figure 5-6 shows the reactive power input of synchronous generators. Both generator types adapt their reactive power feed-in in order to regulate the voltage at their respective PCC. The figures representing the reactive power behaviour in Cases 1, 2, 3, 3.1, and 3.2 are listed in the Appendix.
Figure 5-1: Reference case – Aggregated active power demand

Figure 5-2: Reference case – Aggregated active power feed-in of PE-interfaced generation units

Figure 5-3: Reference case – Aggregated active power feed-in of synchronous generators
Figure 5-4: Reference case – Aggregated balancing energy provided by synchronous generators

Figure 5-5: Reference case – Reactive power feed-in of PE-interfaced generation units

Figure 5-6: Reference case – Reactive power feed-in of synchronous generators
**Frequency**

In Figure 5-7, the frequency measured at the synchronous generator terminals is shown for the reference case. It is visible that the frequency is subject to variations over time. The maximum reaches 50.04 Hz, whereas the minimum lies at 49.95 Hz. The deviations from the nominal frequency of 50 Hz are thus within the acceptable limits of 49.80 Hz and 50.20 Hz for normal operation.

The characteristics of frequency deviations can be determined by depicting the frequency distribution with a normalised histogram and the empirical distribution function of the frequency values as visualised in Figure 5-8. The distribution reveals a mean of 50.00 Hz and a standard deviation $\sigma$ of 16.8 mHz. The histogram shape has a negative skew, i.e. the left tail is longer. This implies that the system frequency follows a Weibull distribution. The shape can be explained with the active power output of WECS. While wind speed turbulences are normally distributed [42], the pitch-angle control of the wind turbines limits the power output above rated wind speed. Therefore, only wind speed variations below rated wind speed lead to variations in power output of the wind turbine and, in turn, in the system frequency. The consequence is a negative skew in the frequency distribution. This observation is also valid for the other presented use cases.

In Figure 5-9, a Fourier analysis identifies the frequencies that inhere in the system frequency deviations. In the plot, two regions are marked. Region A indicates the frequency spectrum, for which the generic speed governors of thermal power plants are tuned. Therefore, system frequency deviations appearing with frequencies in Region A are addressed by primary control. Region B on the other hand marks the frequency spectrum, for which system inertia has a dominating effect on the system frequency variations. As can be seen from the graph, the maximum amplitude in the Fourier spectrum appears at 6 mHz, which is out of range of the influence spectrum of system inertia. Consequently, future efforts to address the frequency variations should focus on supporting the primary control ability of the power system. For that purpose, e.g. wind farms can be utilised.

**Voltage deviation**

Figure 5-10 depicts the voltage deviations from their nominal value in p.u., measured at all nodes with a nominal voltage level of 110 kV or above. As stated in Table 2-2, the p.u. limits for normal operation differ for the nominal voltage levels of 110 kV, 220 kV and 400 kV. However, with a maximum standard deviation of 0.001 p.u., the recorded deviations are close to zero and there is no noticeable difference in the voltage deviation characteristics for the nodes at different voltage levels. Therefore, in order to present the respective figures in a compact manner, only the strictest limits are depicted. According to Table 2-2, the strictest lower limit is at 0.955 p.u. for 110 kV and 220 kV and the strictest upper limit is at 1.025 p.u. for 400 kV. For deviations from 1 p.u., these values then correspond to -0.045 p.u. and 0.025 p.u., respectively.

As can be seen in Figure 5-10, the voltage deviations are close to zero and the limits for admissible voltage deviation for normal operation are not violated. The reason for the small voltage deviations is the voltage support enabled by PE-interfaced generation units that are connected at a voltage level of 110 kV or higher at PCC. The voltage is regulated by injecting reactive power, which is also visible
from Figure 5-5 and Figure 5-6. The corresponding generator units are widely distributed in the transmission system providing well-regulated voltage conditions throughout the grid.

![Figure 5-7: Reference case – System frequency](image)

![Figure 5-8: Reference case – Normalised histogram and empirical distribution function of system frequency](image)
5.1.2 Case 1: 70 percent of System Non-Synchronous Penetration

The aggregated feed-in of active power from PE-interfaced power sources is depicted in Figure 5-11. It can be seen that the absolute power variations due to wind power feed-in are higher than in the corresponding Figure 5-2 of the reference case and appear within a span of 149 MW between the minimum and maximum value.

The graph showing the aggregated feed-in of active power by synchronous generators is given in Figure 5-12. From this graph, the balancing energy provided by synchronous generators can be derived in Figure 5-13 with positive balancing energy marked blue and negative balancing energy marked red. For Case 3, the positive and negative balancing energy amount to 1.47 MWh and 1.48 MWh, respectively. The sum of the absolute values corresponds to 3.52 MWs per MVA installed.
capacity of active synchronous generators. The relative strain for the synchronous generators for providing balancing energy is therefore increased by 26% compared to the reference case.

**Frequency**

The system frequency for Case 1 is shown in Figure 5-14. The minimum and maximum values are 49.94 Hz and 50.06 Hz, respectively. The frequency deviations are thus within the limits of 49.80 Hz and 50.20 Hz for normal operation.

The histogram and empirical distribution function of the frequency values are depicted in Figure 5-15. The distribution has a mean value of 50.00 Hz and a standard deviation $\sigma$ of 20.7 mHz. The value for the standard deviation is therefore 23% higher than in the reference case.

The Fourier analysis of frequency deviations is shown in Figure 5-16. As can be seen, the red line marking the region of influence of the system inertia in the Fourier spectrum has moved towards higher frequencies. This is due to the fact that the system inertia constant in Case 1 is lower than in the reference case. The border marking the responsive spectrum of the turbine governors on the other hand remains the same, since the controller parameters are constant throughout the study. In comparison to the reference case, the magnitude of the Fourier spectrum frequencies has generally increased. For the maximum peak at 6 mHz, the increase is 25%.

**Voltage deviation**

Figure 5-17 depicts the voltage deviations from their nominal value in p.u. measured at all nodes with a nominal voltage level of 110 kV or above. The deviations are close to zero with a maximum standard deviation of 0.001 p.u.

![Figure 5-11: Case 1 – Aggregated active power feed-in of PE-interfaced generation units](image)
Figure 5-12: Case 1 – Aggregated active power feed-in of synchronous generators

Figure 5-13: Case 1 – Aggregated balancing energy provided by synchronous generators

Figure 5-14: Case 1 – System frequency
Figure 5-15: Case 1 – Normalised histogram and empirical distribution function of system frequency

Figure 5-16: Case 1 – Fourier spectrum of system frequency deviation

Figure 5-17: Case 1 – Voltage deviation
5.1.3 Case 2: 80 percent of System Non-Synchronous Penetration

The representation of aggregated active power feed-in from PE-interfaced power sources is shown in Figure 5-18. As can be seen, the absolute power variations increase further with a span of 160 MW between the minimum and maximum value. The active power feed-in from synchronous generators is depicted in Figure 5-19. The balancing energy provided by synchronous generators is visualised in Figure 5-20 and is composed of 1.45 MWh of positive balancing energy, marked blue and 1.42 MWh of negative balancing energy, marked red. The sum of the two absolute values amounts to 2.87 MWh resulting in 7.04 MWs per MVA of installed capacity of active synchronous generators. Compared to the reference case this marks an increase by 89 %.

**Frequency**

The system frequency for Case 2 is shown in Figure 5-21. It can be seen that the variations are higher than in the reference case and in Case 1. The maximum deviation is at 50.09 Hz, whereas the minimum lies at 49.90 Hz. The deviations are thus within the accepted boundaries of 49.80 Hz and 50.20 Hz.

The characteristics of frequency deviations are again expressed with the histogram and the empirical distribution function of the frequency values and are shown in Figure 5-22. For Case 2, the mean frequency is 50.00 Hz and the standard deviation is 34.4 mHz. Compared to the reference case, the standard deviation has increased by 105 %.

Figure 5-23 shows the results for the Fourier analysis of the frequency deviations. In conformity with the cases with 60 % and 70 % of SNSP, the maximum magnitude appears at 6 mHz. Again, the magnitudes generally increase compared to the reference case. For the maximum magnitude, the increase is 95 %. This is due to the decrease in system inertia and primary control reserves of the remaining synchronous generators while at the same time, active power variations caused by wind farms are higher.

**Voltage deviation**

Figure 5-24 depicts the voltage deviations from their nominal value in p.u. measured at all nodes with a nominal voltage level of 110 kV or above. With a maximum standard deviation of 0.002 p.u., the values are close to zero and, therefore, the limits for normal operation are not violated.
Figure 5-18: Case 2 – Aggregated active power feed-in of PE-interfaced generation units

Figure 5-19: Case 2 – Aggregated active power feed-in of synchronous generators

Figure 5-20: Case 2 – Aggregated balancing energy provided by synchronous generators
Figure 5-21: Case 2 – System frequency

Figure 5-22: Case 2 – Normalised histogram and empirical distribution function of system frequency

Figure 5-23: Case 2 – Fourier spectrum of system frequency deviation
5.1.4 Case 3: 90 percent of System Non-Synchronous Penetration

In the following subsections 5.1.4, 5.1.5 and 5.1.6, study cases with a level of 90 % SNSP are investigated. The characteristics of the use cases are stated in Table 4-1. For convenience, the information regarding $1/R_{eq}$ and $H_{eq}$ are repeated in Table 5-1.

**Table 5-1: Characteristics of Case 3 and its variations**

<table>
<thead>
<tr>
<th></th>
<th>Reference Case</th>
<th>Case 3</th>
<th>Case 3.1</th>
<th>Case 3.2</th>
</tr>
</thead>
<tbody>
<tr>
<td>SNSP [%]</td>
<td>60</td>
<td>90</td>
<td>90</td>
<td>90</td>
</tr>
<tr>
<td>$1/R_{eq}$ [MW/Hz]</td>
<td>1685</td>
<td>677</td>
<td>906</td>
<td>1685</td>
</tr>
<tr>
<td>$H_{eq}$ [s]</td>
<td>3.01</td>
<td>1.21</td>
<td>1.58</td>
<td>1.21</td>
</tr>
</tbody>
</table>

Figure 5-25 shows the curve for the aggregated active power feed-in from PE-interfaced power sources. Among the presented cases, the power variations of wind farms are the highest in the Case 3, with a span of 177 MW between the minimum and maximum value. Figure 5-26 illustrates the aggregated feed-in of active power from synchronous generators. In Figure 5-27, the area representing the balancing energy provided by synchronous generators can be seen. The negative balancing energy component of 1.42 MWh is marked red and the positive balancing energy component of 1.45 MWh is marked blue. For the Case 3, the sum of the absolute values for the deployed balancing energy is 2.87 MWh. Setting this amount in relation to the given installed capacity of active synchronous generators in the system delivers 7.04 MWs/MVA, which is an increase of 151 % in comparison to the reference case.

**Frequency**

With 90 %, the Case 3 introduces the highest level of SNSP of the presented use cases. As to be expected, the frequency deviates the most from its average value of 50.00 Hz. The standard deviation is 41 mHz, which corresponds to the 145 % increase compared to the reference case. The
characteristics of frequency variations are also described in Figure 5-30, where the Fourier transform of the frequency deviations is depicted. In comparison to the reference case, the maximum peak has increased by 175 %.

The minimum and maximum system frequency is 49.84 Hz and 50.14 Hz, respectively, as shown in the Figure 5-28. Thus, the registered minimum of 49.84 Hz approaches the lower admissible limit of 49.80 Hz by 80 %. Even though the limits for normal operation are not violated, it has to be mentioned that this deviation is of significance for the frequency stability of the power system. When the system frequency is already close to its limits for normal operation, the power system is vulnerable to potential further disturbances. If the disturbance, e.g. a generator outage, line tripping or sudden load change, is too large, the momentary and primary reserves of the power system might not be sufficient for keeping the system frequency within admissible limits.

**Voltage deviation**

Figure 5-31 depicts the voltage deviations from their nominal value in p.u. measured at all nodes with a nominal voltage level of 110 kV or above. The maximum standard deviation is 0.002 p.u., which marks a slight increase compared to the Cases 1, 2 and the reference case. However, it can be seen that the voltage deviations remain close to zero.

![Graph of aggregated active power feed-in of PE-interfaced generation units](image)
Figure 5-26: Case 3 – Aggregated active power feed-in of synchronous generators

Figure 5-27: Case 3 – Aggregated balancing energy provided by synchronous generators

Figure 5-28: Case 3 – System frequency
Figure 5-29: Case 3 – Normalised histogram and empirical distribution function of system frequency

Figure 5-30: Case 3 – Fourier spectrum of system frequency deviation

Figure 5-31: Case 3 – Voltage deviation
5.1.5 Case 3.1: 90 percent of System Non-Synchronous Penetration with alternative choice of synchronous generators

Frequency

While the operating points of all other generation units and loads are the same as in Case 3, Case 3.1 deploys more and larger synchronous generators. As a consequence, the inverse of the equivalent speed droop of the turbine governors of the synchronous generators $R_{eq}$ rises from 677 MW/Hz in Case 3 to 906 MW/Hz in Case 3.1 as stated in Table 5-1. For comparison, the reference case is listed with 1685 MW/Hz. Furthermore, the equivalent system inertia constant $H_{eq}$ changes from 1.21 s in Case 3 to 1.58 s in Case 3.1. The equivalent inertia constant for the reference case is 3.01 s.

This relationship of higher system inertia and primary control reserve explains the difference between the frequency simulation results for Case 3 and Case 3.1. In general, the depiction of the system frequency in Figure 5-35, the distribution of system frequency samples in Figure 5-36 and the Fourier analysis of system frequency deviations in Figure 5-37 show that the frequency variations are smaller compared to Case 3. The minimum frequency is now 49.89 Hz and the maximum frequency reaches 50.10 Hz. The standard deviation of 35 mHz for the system frequency constitutes a reduction of 15 % in comparison to Case 3 with 41 mHz standard deviation. The highest peak in the Fourier spectrum is reduced by 28 %.

The higher primary control reserve introduced by the alternative choice of synchronous generators increases the provided balancing energy as visible in Figure 5-34. With 1.53 MWh for positive balancing energy and 1.52 MWh for negative balancing energy, the sum of the absolute values amounts to 3.05 MWh for Case 3.1. However, since there are more synchronous generators in operation than in Case 3, the amount of balancing energy in relation to the installed capacity of active synchronous generators decreases and is given as 5.54 MWs/MVA.

It can be concluded that with increased system inertia and especially primary control reserve, the system frequency variations can be reduced. However, in Case 3.1, the additional momentary and primary control reserve is supplied by the synchronous generator of a large gas-fired power plant. Furthermore, all synchronous generators are running close to their lower admissible power limits. Therefore, this choice constitutes an inefficient use of resources since the synchronous generators are overdimensioned for the given operating point. On top of that, the gas turbines substitute the power provided by smaller hydro power plants, which are usually more cost-efficient than gas-fired power plants [44] and produce no CO$_2$ or other emissions harmful to the environment.

A more efficient method for increasing the system inertia and improving the primary control ability is to utilize kinetic energy stored in the rotating masses of PE-interfaced generating units that have
not been exploited to this point. Wind power plants belong to this category as they dispose of turbine and generator inertia that is decoupled from the grid by a converter. Therefore, one possibility to mitigate frequency variations is to emulate inertia in wind farms and provide momentary reserve for the power system when needed. This mitigation method will be investigated further in MIGRATE deliverable D5.5.

**Voltage deviation**

The usage of the additional synchronous generator does not have a considerable effect on the voltage performance in the system and voltage deviations are again close to zero as can be seen in Figure 5-38. The maximum standard deviation of voltage is 0.002 p.u.

![Figure 5-32: Case 3.1 – Aggregated active power feed-in of PE-interfaced generation units](image)

![Figure 5-33: Case 3.1 – Aggregated active power feed-in of synchronous generators](image)
Figure 5-34: Case 3.1 – Aggregated balancing energy provided by synchronous generators

Figure 5-35: Case 3.1 – System frequency

Figure 5-36: Case 3.1 – Normalised histogram and empirical distribution function of system frequency
5.1.6 Case 3.2: 90 percent of System Non-Synchronous Penetration with increased primary control reserve

Case 3.2 represents another variation of Case 3. The aim of this use case is to estimate the additional balancing energy that is needed if the SNSP level reaches 90% and the primary control reserve is the same as for the reference case. For the presented use cases, balancing energy is provided by synchronous generators. Thus, the frequency control ability by the synchronous generators is altered by setting the inverse of the equivalent speed droop by the turbine governors equal to the settings of the reference case, i.e. 1685 MW/Hz. All other settings remain the same as in Case 3.

The aggregated active power infeed by PE-interfaced generation units is shown in Figure 5-39. Due to the settings described above, the power curve matches the corresponding Figure 5-25 for Case 3. On the other hand, the synchronous generators react to frequency deviations with a higher intensity.
than in Case 3 because of the increased $1/R_{eq}$. This can be seen from the feed-in of active power by synchronous generators in Figure 5-40 and the visualisation of the balancing energy provided by synchronous generators in Figure 5-41. The absolute values for the positive and negative balancing energy each amount to 1.68 MWh. The total of 3.37 MWh marks an increase of 16 % compared to the reference case. Furthermore, the amount of balancing energy in relation to the installed capacity of active synchronous generators is determined as 8.27 MWs/MVA, which is an increase of 195 % compared to the reference case.

**Frequency**

It can be seen from Figure 5-42, Figure 5-43 and Figure 5-44 that system frequency variations are reduced compared to Case 3. This can also be determined from the standard deviation of 24.2 mHz, which is 41 % lower for Case 3.2. Furthermore, the peak of the Fourier spectrum is 51 % lower for Case 3.2. However, the variations are still higher than the results of the reference case where there is a standard variation of 16.8 mHz. The different frequency results for Case 3.2 and the reference case can be explained by the lower system inertia in Case 3.2 and the higher active power variations caused by wind farms as already mentioned in Section 5.1.4.

**Voltage deviation**

As shown in Figure 5-52, voltage deviations are close to zero. The maximum standard deviation is 0.002 p.u.

![Graph](image.png)

Figure 5-39: Case 3.2 – Aggregated active power feed-in of PE-interfaced generation units
Figure 5-40: Case 3.2 – Aggregated active power feed-in of synchronous generators

Figure 5-41: Case 3.2 – Aggregated balancing energy provided by synchronous generators

Figure 5-42: Case 3.2 – System frequency
Figure 5-43: Case 3.2 – Normalised histogram and empirical distribution function of system frequency

Figure 5-44: Case 3.2 – Fourier spectrum of system frequency deviation

Figure 5-45: Case 3.2 – Voltage deviation
5.2 Frequency Limit Assessment

For the test cases described in Section 4.1 and analysed in Section 5.1, the system frequency remains within the specified limits for normal operation of 50 Hz ± 0.2 Hz. However, in Case 3, the system frequency approaches the lower limit already by 80%. In this section, it is assessed, under which condition the system frequency actually violates the limits for normal operation for the specific cases.

As shown in Section 5.1, the active power variations by wind farms are the cause for variations of the system frequency in the transmission system model of this study. In Section 5.1 it is also established that the height of primary control reserves is mainly responsible for the height of the deviation of the system frequency from its nominal value of 50 Hz. Thus, one option for assessing constellations that violate the frequency limit is to change the primary control reserve by adjusting the speed droop of conventional power plants. Table 5-2 lists the inverse of the equivalent speed droop $R_{eq}$ of the turbine governors of power plants, which lead to a frequency limit violation for normal operation. Figure 5-46 to Figure 5-50 show the corresponding simulation results for the system frequency for all study cases. Here, Case 3.2 is covered by the frequency limit assessment for Case 3 since the two cases only differ from each other regarding the equivalent speed droop. From the figures, it can be seen that the lower frequency limit of 49.8 Hz for normal operation is reached at $t = 4$ minutes for the respective cases.
Table 5-2: Study cases violating frequency limits for normal operation

<table>
<thead>
<tr>
<th>Case</th>
<th>$1/R_{eq}$ [MW/Hz]</th>
<th>Standard settings</th>
<th>Limit assessment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reference Case</td>
<td>1685</td>
<td>253</td>
<td></td>
</tr>
<tr>
<td>Case 1</td>
<td>1366</td>
<td>241</td>
<td></td>
</tr>
<tr>
<td>Case 2</td>
<td>890</td>
<td>320</td>
<td></td>
</tr>
<tr>
<td>Case 3</td>
<td>677</td>
<td>450</td>
<td></td>
</tr>
<tr>
<td>Case 3.1</td>
<td>906</td>
<td>450</td>
<td></td>
</tr>
</tbody>
</table>

Figure 5-46: Reference Case – Violation of frequency limits for normal operation

Figure 5-47: Case 1 – Violation of frequency limits for normal operation

Figure 5-48: Case 2 – Violation of frequency limits for normal operation

Figure 5-49: Case 3 – Violation of frequency limits for normal operation

Figure 5-50: Case 3.1 – Violation of frequency limits for normal operation
5.3 Voltage Control Sensitivity Analysis

In the analysed cases introduced in Section 4.1 and investigated in Section 5.1, the simulated voltage deviations at nodes with nominal voltage above 110 kV are close to zero. This result is achieved because the synchronous generators, the converters of HVDC interconnectors and the PE-interfaced generation units connected at 110 kV or above enable voltage control at their terminals. Based on the installed capacity, 85 % of the PE-interfaced generation units participate in voltage control. The remaining 15 % regulate their reactive power feed-in at $Q = 0 \text{ VAr}$.

In the following section, a sensitivity analysis is performed for demonstrating the effect of different participation ratios of PE-interfaced generation units for voltage control. For the sensitivity analysis, three variations of Case 3 are chosen. First, the voltage simulation results are repeated for the base settings, i.e. 85 % of the PE-interfaced generation units participating in voltage control. The first variation, referred to as Variation A, assumes a distribution of 50 % voltage control and 50 % reactive power control with a zero VAr reference among PE-interfaced generation units. The second variation, Variation B, assumes that 35 % of the PE-interfaced generation units control voltage while 65 % regulate reactive power at zero VAr. In the third variation, Variation C, none of the PE-interfaced generation units enables voltage control. However, the converters contribute a steady amount of reactive power for stability reasons.

5.3.1 Initial setting: 85 % of PE-interfaced generation units with voltage control enabled

For comparison with Variations A, B and C, the simulation results for voltage for the initial settings for Case 3 are shown in Figure 5-51, Figure 5-52 and Figure 5-53. The figures display the voltage for nodes with nominal voltage level of 110 kV, 220 kV and 400 kV, respectively. Table 5-3 sums up the simulation results.

<table>
<thead>
<tr>
<th>Nominal voltage [kV]</th>
<th>110</th>
<th>220</th>
<th>400</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average standard deviation [p.u.]</td>
<td>&lt; 0.001</td>
<td>&lt; 0.001</td>
<td>&lt; 0.001</td>
</tr>
<tr>
<td>Maximum standard deviation [p.u.]</td>
<td>0.002</td>
<td>0.001</td>
<td>0.001</td>
</tr>
<tr>
<td>Maximum $\Delta v$ [p.u.]</td>
<td>0.007</td>
<td>0.004</td>
<td>0.004</td>
</tr>
<tr>
<td>Minimum $\Delta v$ [p.u.]</td>
<td>-0.007</td>
<td>-0.004</td>
<td>-0.004</td>
</tr>
</tbody>
</table>
Figure 5-51: Case 3 – Voltage deviation for nodes with a nominal voltage of 110 kV

Figure 5-52: Case 3 – Voltage deviation for nodes with a nominal voltage of 220 kV

Figure 5-53: Case 3 – Voltage deviation for nodes with a nominal voltage of 400 kV
5.3.2 Variation A: 50 % of PE-interfaced generation units with voltage control enabled

For achieving a distribution of 50 % voltage control and 50 % reactive power control among PE-interfaced generation units, the following rules are applied: as in the standard settings of Case 3, PE-interfaced generation units connected at a voltage level below 110 kV enable reactive power control only. PE-interfaced generation units connected at 110 kV enable voltage control if their installed capacity exceeds 170 MW. Otherwise, they control reactive power. Last, PE-interfaced generation units connected at a voltage level above 110 kV, enable voltage control regardless of the installed capacity. Table 5-4 summarizes the rules described above.

Table 5-4: Conditions for voltage control of PE-interfaced generation units for Variation A

<table>
<thead>
<tr>
<th>Nominal voltage at PCC [kV]</th>
<th>Installed capacity [MW]</th>
<th>Form of control at PCC</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt;110</td>
<td>n/a</td>
<td>Active and reactive power</td>
</tr>
<tr>
<td>110</td>
<td>≤ 170</td>
<td>Active and reactive power</td>
</tr>
<tr>
<td>&gt;110</td>
<td>&gt; 170</td>
<td>Active power and voltage</td>
</tr>
</tbody>
</table>

The simulation results for the voltage at nodes with nominal voltage of 110 kV, 220 kV and 400 kV are shown in Figure 5-54, Figure 5-55 and Figure 5-56, respectively, and evaluated in Table 5-5. As can be seen, the limits for normal operation are not violated but the deviations are larger than for the setting with 85 % of PE-interfaced generation units.

Table 5-5: Results for voltage analysis of Case 3, Variation A

<table>
<thead>
<tr>
<th>Nominal voltage [kV]</th>
<th>110</th>
<th>220</th>
<th>400</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average standard deviation [p.u.]</td>
<td>0.001</td>
<td>0.001</td>
<td>0.001</td>
</tr>
<tr>
<td>Maximum standard deviation [p.u.]</td>
<td>0.005</td>
<td>0.002</td>
<td>0.002</td>
</tr>
<tr>
<td>Maximum Δv [p.u.]</td>
<td>0.012</td>
<td>0.005</td>
<td>0.005</td>
</tr>
<tr>
<td>Minimum Δv [p.u.]</td>
<td>-0.012</td>
<td>-0.005</td>
<td>-0.004</td>
</tr>
</tbody>
</table>
Figure 5-54: Variation A – Voltage deviation for nodes with a nominal voltage of 110 kV

Figure 5-55: Variation A – Voltage deviation for nodes with a nominal voltage of 220 kV

Figure 5-56: Variation A – Voltage deviation for nodes with a nominal voltage of 400 kV
5.3.3 Variation B: 35 % of PE-interfaced generation units with voltage control enabled

Variation B features a distribution of 35 % voltage control and 65 % reactive power control among PE-interfaced generation units. The constellation is achieved by applying the same rules for participation in voltage control as described for Variation A. The only difference is that the minimum installed capacity limit for the participation in voltage control is increased to 200 MW. Table 5-6 summarizes the rules for Variation B.

Table 5-6: Conditions for voltage control of PE-interfaced generation units for Variation A

<table>
<thead>
<tr>
<th>Nominal voltage at PCC [kV]</th>
<th>Installed capacity [MW]</th>
<th>Form of control at PCC</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt;110</td>
<td>n/a</td>
<td>Active and reactive power</td>
</tr>
<tr>
<td>110</td>
<td>≤ 200</td>
<td>Active and reactive power</td>
</tr>
<tr>
<td>&gt;110</td>
<td>&gt; 200</td>
<td>Active power and voltage</td>
</tr>
</tbody>
</table>

The simulation results for the voltage at nodes with nominal voltage of 110 kV, 220 kV and 400 kV are summarised in Table 5-7. Figure 5-57, Figure 5-58 and Figure 5-59 show the voltages at nodes with nominal voltage of 110 kV, 220 kV and 400 kV, respectively.

Table 5-7: Results for voltage analysis of Case 3, Variation B

<table>
<thead>
<tr>
<th>Nominal voltage [kV]</th>
<th>110</th>
<th>220</th>
<th>400</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average standard deviation [p.u.]</td>
<td>0.001</td>
<td>0.001</td>
<td>0.002</td>
</tr>
<tr>
<td>Maximum standard deviation [p.u.]</td>
<td>0.006</td>
<td>0.003</td>
<td>0.002</td>
</tr>
<tr>
<td>Maximum $\Delta v$ [p.u.]</td>
<td>0.013</td>
<td>0.007</td>
<td>0.006</td>
</tr>
<tr>
<td>Minimum $\Delta v$ [p.u.]</td>
<td>-0.018</td>
<td>-0.008</td>
<td>-0.006</td>
</tr>
</tbody>
</table>
Figure 5-57: Variation B – Voltage deviation for nodes with a nominal voltage of 110 kV

Figure 5-58: Variation B – Voltage deviation for nodes with a nominal voltage of 220 kV

Figure 5-59: Variation B – Voltage deviation for nodes with a nominal voltage of 400 kV
5.3.4 Variation C: 0 % of PE-interfaced generation units with voltage control enabled

For Variation C, none of the PE-interfaced generation units applies voltage control. Consequently, the voltage deviations and variations are the largest for the analysed constellations, as can be seen from Table 5-8. Figure 5-60, Figure 5-61 and Figure 5-62 show the simulated voltage at nodes with nominal voltage of 110 kV, 220 kV and 400 kV, respectively.

Table 5-8: Results for voltage analysis of Case 3, Variation C

<table>
<thead>
<tr>
<th>Nominal voltage [kV]</th>
<th>110</th>
<th>220</th>
<th>400</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average standard deviation [p.u.]</td>
<td>0.007</td>
<td>0.006</td>
<td>0.008</td>
</tr>
<tr>
<td>Maximum standard deviation [p.u.]</td>
<td>0.012</td>
<td>0.009</td>
<td>0.008</td>
</tr>
<tr>
<td>Maximum $\Delta v$ [p.u.]</td>
<td>0.026</td>
<td>0.02</td>
<td>0.019</td>
</tr>
<tr>
<td>Minimum $\Delta v$ [p.u.]</td>
<td>-0.032</td>
<td>-0.024</td>
<td>-0.022</td>
</tr>
</tbody>
</table>

Figure 5-60: Variation C – Voltage deviation for nodes with a nominal voltage of 110 kV

Figure 5-61: Variation C – Voltage deviation for nodes with a nominal voltage of 220 kV
5.4 Conclusions and Recommendations

In order to analyse the effect of high penetration levels of PE devices on the power quality in a transmission system, a future scenario for 2040 was implemented in a nonlinear dynamic grid model based on the transmission system of Ireland. Six use cases were analysed with regard to frequency and voltage variations as indicators for active and reactive power behaviour in the system. In accordance with MIGRATE WP1, the amount of PE in the system was defined in terms of system nonsynchronous penetration (SNSP) levels and ranges from 60% to 90% for the presented cases. The fact that the wind farms operate in MPPT mode guarantees a worst-case environment for the chosen operating points in terms of active power variations. Therefore, the presented simulations describe relevant use cases.

From the analysed simulation results, it can be seen that the voltage variations in the system are small. The standard deviation reaches a maximum of 0.002 p.u. for a case with 90% SNSP. The small voltage variations are linked to the voltage control employed by the PE-interfaced generation units with a PCC at 110 kV or higher. A sensitivity analysis reveals, however, that voltage variations increase if fewer converters of PE-interfacced generation units control the voltage. It is shown that the standard deviation for voltage reaches a maximum of 0.012 p.u. if voltage control is disabled for all PE-interfaced generation units for a case with 90% SNSP.

Regarding system frequency variations, the following conclusions can be made. First, the frequency limits for normal operation are not violated in the studied use cases. However, there is a positive correlation between the level of SNSP and frequency variations. When referring to a level of 60% SNSP as the reference case, the standard deviation of the system frequency increases by 145% for a use case with 90% SNSP.

One reason for these frequency variations is the fluctuating feed-in of active power by wind farms. Furthermore, PE-interfaced generation units replace synchronous generators, which contribute to
primary control and system inertia. At the same time, the remaining synchronous generators are forced to vary their active power output more in order to regulate the system frequency. This is also pointed out by the simulation results showing that the amount of provided balancing energy per MVA of installed capacity of operating synchronous generators grows with a rising level of SNSP. It becomes clear that under such an operating condition also the wear and tear of synchronous generators increases.

It has to be noted that higher frequency variations are not an inevitable consequence of high PE penetration in transmission grids. As it was shown in this chapter, the frequency variations primarily depend on active power variations on one side and on the primary control reserve on the other side. For the presented study cases, the latter declines for higher SNSP because PE-interfaced generation and storage units do not contribute to frequency control. This setting corresponds to today’s general practice where synchronous generators deliver most of the balancing energy. However, some TSOs already allow other power sources like batteries to contribute to frequency control. In fact, many kinds of PE-interfaced generation and storage units have the potential to participate in frequency support with a suitable control scheme. This is why it is necessary to investigate the possibilities of mitigating frequency variations with the help of PE-interfaced units further.

From the study, three recommendations can be made. First, the control of system frequency in normal operation should also include further generation units in the power system. As wind farms play an increasingly important role in the power system, they should be involved in frequency support in the future.

Second, with Fourier transform it was shown that the system frequency deviations are dominated by frequency components below 50 mHz, i.e. in the time range of seconds to minutes. Therefore, the mitigation methods aiming at smoothing the system frequency should support primary control.

Third, the characteristics of eligible mitigation methods lead to different requirements for their implementation. The mitigation method can follow a global coordination scheme or a local approach, for which the method would be implemented at specific units individually. The chosen approach determines how it can be realised, e.g. if it needs to be formulated as a general grid code requirement or if it should be specified on an individual basis. Thus, the approach of how to implement the mitigation methods has to be investigated.
6 Analysis of harmonic propagation

The subject of this chapter is to illustrate the results of harmonic propagation studies in future grids with different, increasing, levels of PE penetration. The studies were carried out in accordance with the scenarios developed for the nonlinear dynamic grid model based on the transmission system network of Ireland which was used as a test network.

Probabilistic methodology for harmonic propagation studies developed in the Deliverable D5.2 [41] and explained in detail in the Deliverable D5.3 [1] is used in the studies presented hereafter to establish the level and significance of potential harmonic issues in current and future power systems considering different operational uncertainties and different penetration levels of power electronic devices.

The probabilistic harmonic methodology, as explained in detail in Deliverable D5.3 [1], is applied for different operating points of the selected case studies. The approach in its full extent, as presented in Deliverable D5.3 [1] and illustrated there on the modified IEEE 68 bus network, could not be directly applied in EirGrid test network (Irish network model) due to unavailability of some data related to yearly operation of the network so that chronological network operation could be simulated. The methodology is used to demonstrate its suitability for evaluation of the harmonic performance of the large power system, or to show the expected changes in harmonic performance of the network, at different levels of penetration of the PE based generation. From that point of view, the simulation of harmonic performance of the network over prolonged period of time was not necessary.

Finally, it is important to note that the final results of the harmonic studies of the current harmonic situation in the test grid could be verified by comparing the simulation results with the existing and available harmonic measurements from the test grid. However, to do that, the simulation model would need to be modelled much more in details by means of existing harmonic injections from lower voltage levels to the transmission system. The scope of such work exceeds the scope of this deliverable, but it would be the necessary part of detailed system studies.

6.1 Simulation and analysis

The following sections present illustrative results of the analysed cases. The results of harmonic load flow analysis enable observation of harmonic performance of the network. Main performance indicator, as suggested by international standards, will be 95th percentile of calculated THD at each bus. Additionally, calculated average THD values are also presented for the purpose of comparison. Comparison of average 95th THD values obtained for whole test network and specific voltage levels is given in the following figure. Note that the 95th percentile values calculated and discussed throughout this document are based on calculating 95th percentile of the values obtained from numerous Monte Carlo simulations of each individual case, i.e., 95th percentile of all samples. They are not the values that would have been observed for the 95 percent of the time during the harmonic monitoring period or considering harmonic performance for
different system operating conditions over period of time. As can be seen from the Figure 6-1 the 95th THD value increases with the increase of share of PE device in total network on all transmission voltage levels for the simulated cases. Figure 6-2 gives the comparison of average THD values for whole test network and specific voltage levels.

Figure 6-1: 95th THD value in total test network and on specific voltage levels for different simulation cases

Figure 6-2: Average THD value in total test network and on specific voltage levels for different simulation cases
Based on the assumption that the share of RES increases hence, the share of PE interface connected devices, which are considered as main harmonic sources in the network, it would be expected to have an increase of THD values across the network. This however is not the case and does not occur at all buses uniformly, as can be seen from following figures in Figure 6-3. The overall harmonic level at different buses depends on network topology and characteristics and injected harmonics, harmonic angles in particular.

Figure 6-3: THD performance of 400 kV buses in test network a) 95th THD values, b) average THD values – simulation results for illustration purpose only.
As can be seen from the Figure 6-3, there are no buses exceeding the harmonic limit threshold value (3% value of 95th THD). Percentage share of 400 kV buses is given in the following figure Figure 6-4.

Figure 6-4: Percentage share of 95th THD values of 400 kV buses in test network

Next figure represents the percentage share of 220 kV buses having particular value of THD according to the 95th THD values. As can be seen from the figure, there are no buses exceeding the harmonic limit threshold value (3% value of 95th THD) for 220 kV buses, but in case of 110 kV that the limit value is exceeded (Case 2 and Case 3). The main reason for this is the network structure (impedance characteristics) and the location of the harmonic sources (propagation on lower transmission voltage network levels).
From the Figure 6-7 and Figure 6-8, representing the 95th THD values and average THD values of individual study case at 220 kV and 110 kV network level respectively, it can be concluded that the 95th THD value for the most busses increases with the higher penetration level of PE devices in the network. For buses where this conclusion is not applicable, the reason for such behaviour can be found in the location of harmonic sources or the network topology (i.e. location of the loads, filters, etc.).
Figure 6-7: THD performance of 220 kV buses in test network a) 95th THD values, b) average THD values – simulation results for illustrative purpose only
Figure 6-8: THD performance of 110 kV buses in test network a) 95th THD values, b) average THD values – simulation results for illustrative purpose only
Figure 6-9: THD performance of some 110 kV buses in test network a) 95th THD values, b) average THD values – simulation results for illustrative purpose only
As can be seen from Figure 6-9, there are only few buses where 95th THD value exceeds the threshold value of 3% in Case 2 and Case 3.

Following tables give the results for five buses of transmission voltage levels based on maximum obtained values of THD. Based on the results presented it could be said that occurrence rate of the buses with the highest 95th THD values remains the same in case of increase of RES share.

Table 6-1: 400 kV 95th THD values, top 5 buses

<table>
<thead>
<tr>
<th>400 kV</th>
<th>95thTHD</th>
<th>MAX</th>
<th>MIN</th>
<th>AVG</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reference case</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>400_1</td>
<td>0,39</td>
<td>0,50</td>
<td>0,12</td>
<td>0,29</td>
</tr>
<tr>
<td>400_2</td>
<td>0,39</td>
<td>0,36</td>
<td>0,08</td>
<td>0,21</td>
</tr>
<tr>
<td>400_16</td>
<td>0,30</td>
<td>0,36</td>
<td>0,08</td>
<td>0,21</td>
</tr>
<tr>
<td>400_17</td>
<td>0,30</td>
<td>0,36</td>
<td>0,08</td>
<td>0,21</td>
</tr>
<tr>
<td>400_18</td>
<td>0,30</td>
<td>1,18</td>
<td>0,37</td>
<td>0,74</td>
</tr>
<tr>
<td>Case 1</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>400_1</td>
<td>0,97</td>
<td>1,18</td>
<td>0,37</td>
<td>0,74</td>
</tr>
<tr>
<td>400_2</td>
<td>0,97</td>
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### 220 kV 95th THD values, top 5 buses

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</thead>
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### 110 kV 95th THD values, top 5 buses

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<th>110_17</th>
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Variation of the share of PE loads

Case 1 is analysed further as the harmonic threshold gets exceeded for the first time when the penetration of RES exceeds 70%. The analysis was performed considering different levels of background "noise", i.e., different level of harmonics being injected into transmission network from distribution network. These different harmonic levels are modelled by considering different share of linear and non-linear loads (Table 4-3) and its impact on the harmonic propagation in the network. Following figures show the both 95th percentile and average values of total harmonic distortions and individual harmonics for 400 kV, 220 kV and 110 kV buses for these four additional cases as given in Table 4-3 (changes in share of linear and non-linear loads).

Figure 6-10: THD performance of 400 kV buses in test network with different share of linear and non-linear loads as harmonic sources a) 95th THD values, b) average THD values – simulation results for illustration purpose only
Figure 6-11: Individual harmonic performance of 400 kV buses in test network with different share of linear and non-linear loads as harmonic sources a) 95th THD values, b) average THD values – simulation results for illustration purpose only
Based on the results presented in Figure 6-11, changes in share of linear and non-linear loads in the power system affect highly the values and dominant harmonic even in the network of the same voltage levels i.e. we do not have a uniform situation occurring on the buses of the 400 kV network. This applies to all other observed voltage levels as presented in the following figures (i.e. dominant harmonic in 220 kV network is 7th harmonic and in 110 kV network it is the 11th harmonic which has the highest values of THD).

Figure 6-12: THD performance of 220 kV buses in test network with different share of linear and non-linear loads as harmonic sources a) 95th THD values, b) average THD values – simulation results for illustration purpose only
Figure 6-13: THD performance of 110 kV buses in test network with different share of linear and non-linear loads as harmonic sources a) 95th THD values, b) average THD values – simulation results for illustration purpose only
Figure 6-14: Individual dominant 7th harmonic performance of 220 kV buses in test network with different share of linear and non-linear loads as harmonic sources

Figure 6-15: Individual dominant 11th harmonic performance of 110 kV buses in test network with different share of linear and non-linear loads as harmonic sources
If we compare individual network performance with respect to different share of linear and non-linear loads at load buses, we see strong influence of modelling of load non-linearity on each transmission voltage level even though the location of loads in the network is the same. The increase in the share of nonlinear load clearly introduces larger harmonic sources (hence higher magnitude of injected harmonics) in the network at numerous locations and the overall propagation and attenuation of harmonics across the network becomes different. The increase in the size of harmonic sources and their location in the network clearly contributes to higher harmonic distortion at numerous buses in the network.

Figure 6-16: Percentage share of 95th THD values in test network with different share of linear and non-linear loads as harmonic sources

Table 6-4 gives the list of the HV buses with the highest 95th THD values and its corresponding dominant harmonics. As we can see, different cases with different share of linear and non-linear loads have different impact on harmonic values in the observed network.
Table 6-4: HV buses with the highest 95\textsuperscript{th} THD value and corresponding dominant harmonic

<table>
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<tr>
<th>Bus</th>
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<th>Case 1.1</th>
<th>Case 1.2</th>
<th>Case 1.3</th>
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<td></td>
<td>total</td>
<td>dominant harmonic</td>
<td>total</td>
<td>dominant harmonic</td>
</tr>
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<td>110_177</td>
<td>2.73</td>
<td>5\textsuperscript{th} 2.70</td>
<td>3.48</td>
<td>5\textsuperscript{th} 3.27</td>
</tr>
<tr>
<td>110_108</td>
<td>2.35</td>
<td>7\textsuperscript{th} 2.30</td>
<td>4.85</td>
<td>7\textsuperscript{th} 4.78</td>
</tr>
<tr>
<td>110_177</td>
<td>2.74</td>
<td>5\textsuperscript{th} 2.70</td>
<td>3.48</td>
<td>5\textsuperscript{th} 3.27</td>
</tr>
<tr>
<td>110_108</td>
<td>2.35</td>
<td>7\textsuperscript{th} 2.30</td>
<td>4.85</td>
<td>7\textsuperscript{th} 4.78</td>
</tr>
</tbody>
</table>

According to the results presented in Table 6-4 when distribution network (DN) loads are 20\% non-linear dominant harmonic is 5\textsuperscript{th} harmonic, and when DN loads are 50\% non-linear dominant is 7\textsuperscript{th} harmonic.

For the purpose of different visualization, the PDFs of the harmonic distortions values (total harmonic and specific harmonic distortions) obtained during the 500 iterations within the probabilistic harmonic methodology are presented for the analysed cases (Figure 6-17 and Figure 6-18). The PDFs can be made for each individual bus in the network as an output result of the simulations. While analysing the parameters of PDF’s it can be said that as penetration level of RES in the network increases, mean and variance (spread) are also increasing. Hence, higher penetration of uncertain renewable generation will result in both higher average (or 95\textsuperscript{th} percentile values) harmonic distortion in the network as well as higher variation of harmonic distortion. The increase of the share of non-linear loads in the network results in similar effect though the change in variance is not as pronounced as the increase in the background harmonic distortion (change of ratio of linear and non-linear loads) is comparatively smaller than the considered increase of penetration level.
Figure 6-17: PDFs of buses with the highest 95th THD values (Reference case, Case 1, Case 2 and Case 3 correspond to 60, 70, 80 and 90 SNSP with 80% linear, 20% non-linear of DN and 50% linear, 50% non-linear of Industrial loads; Case 1.1. 70 SNSP with 50% linear, 50% non-linear of DN and 50% linear, 50% non-linear of Industrial loads; Case 1.2. with 80% linear, 20% non-linear of DN and 80% linear, 20% non-linear of Industrial loads; Case 1.3 with 80% linear, 20% non-linear of DN and 50% linear, 50% non-linear of Industrial loads)

For the purpose of analysis of the PDFs given in Figure 6-21, Table 6-5 gives the parameters of the PDFs of buses with the highest 95th THD values.

Table 6-5: PDFs parameters of buses with the highest 95th THD values

<table>
<thead>
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<th>Case</th>
<th>Mean</th>
<th>Variance</th>
<th>Standard deviation</th>
<th>Bus</th>
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</thead>
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<tr>
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<td>0.25</td>
<td>0.50</td>
<td>B46</td>
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<td>0.96</td>
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<tr>
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<td>0.70</td>
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<tr>
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</tr>
<tr>
<td>Case 2</td>
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<td>1.93</td>
<td>B317</td>
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<tr>
<td>Case 3</td>
<td>5.63</td>
<td>6.29</td>
<td>2.51</td>
<td>B317</td>
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</table>

For the purpose of analysis of the PDFs given in Figure 6-18, Table 6-6 gives the parameters of the PDFs of buses with the highest 95th HD values.
Figure 6-18: Individual PDFs of buses with the highest 95th THD values, dominant harmonics (Reference case, Case 1, Case 2 and Case 3 correspond to 60, 70, 80 and 90 SNSP with 80% linear, 20% non-linear of DN and 50% linear, 50% non-linear of Industrial loads; Case 1.1. 70 SNSP with 50% linear, 50% non-linear of DN and 50% linear, 50% non-linear of Industrial loads; Case 1.2. with 80% linear, 20% non-linear of DN and 80% linear, 20% non-linear of Industrial loads; Case 1.3 with 80% linear, 20% non-linear of DN and 50% linear, 50% non-linear of Industrial loads)

Table 6-6: PDFs parameters of buses with the highest 95th THD values, dominant harmonics

<table>
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<tr>
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<th>Mean</th>
<th>Variance</th>
<th>Standard deviation</th>
<th>Bus</th>
<th>Dominant harmonic</th>
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Maintenance scenario

The maintenance scenario, as explained in the chapter 4.1.1, represents the cases where the impedance of the network changes due to disconnection of some 220 kV lines and harmonic filters at 110 kV. Changes in network topology are important for the planning purposes since the network impedance changes and causes the impact on the harmonic performance of the network. The study case (M case) is based on the Reference study case (Ref case), therefore the comparison of results is shown for the Ref and M case.

Apart from the line and filter disconnection, i.e., topology change, the other settings in the M case correspond to the Reference case (Ref case). Harmonic performance is observed based on the 95th THD and average THD values calculated at each bus.

As it can be seen from Figure 6-19, Figure 6-20 and Figure 6-21, the changes in network structure and the absence of harmonic filter have significant impact on the harmonic performance of the network (220 kV and 110 kV buses, where the changes in network topology occurs), i.e., harmonic levels are significantly increased (up to 6 times). However, that increase over the threshold value is only present on 110 kV network for the selected simulation case. It is therefore essential to consider real actual network topology and presence of harmonic filters in the network when the assessment of harmonics in actual power networks is conducted.

Figure 6-19: Comparison of THD performance of 400 kV buses in test network a) 95th THD values, b) average THD values – reference case and maintenance case
Figure 6-20: Comparison of THD performance of 220 kV buses in test network a) 95th THD values, b) average THD values – reference case and maintenance case
Figure 6-21: Comparison of THD performance of 110 kV buses in test network a) 95th THD values, b) average THD values – reference case and maintenance case
6.2 Conclusions and Recommendations

With respect to analysis of the impact of high proliferation of PE devices in terms of harmonic propagation in power systems, a future scenario for 2040 for a large power system was implemented and probabilistic harmonic propagation methodology is applied. In accordance with MIGRATE WP1, the amount of PE in the system was defined in terms of system non-synchronous penetration (SNSP) levels and ranges from 60 % to 90 %. A representative model of the Irish transmission network is prepared and provided by transmission system operator EIRGRID in PowerFactory DlgsILENT software. It is important to emphasize that the results provided in this report are for the illustrative purposes of the potential impact of different PE penetration levels on harmonic propagation only and they do not reflect in any way actual, measured or expected harmonic performance of the Irish transmission network. The Irish grid network model is used only to illustrate the application of the developed methodology in a realistic transmission network topology and to demonstrate the potential for the application of such methodology for the TSOs in terms of understanding the harmonic propagation in the transmission network.

Based on the results obtained on the simulated test power system, it can be seen and confirmed that the harmonic propagation through the power system is highly influenced by power system topology. According to simulation results it is confirmed that the increase of PE devices causes the increase of harmonic distortions and have significant impact on harmonic propagation in the network. Additionally, the importance of having as more accurate and realistic data for the analysed power system is extremely high since the results are highly dependent on the assumed values i.e. exact load structure for each network load or exact harmonic injections would be favourable input data for such analysis.

The power electronic interfaced loads and generators involve high level of uncertainties in both general performance and harmonic emission. The analysis performed using different simulation cases to illustrate the methodology highlighted that the harmonic performance of a power system is an individual characteristic influenced by different uncertainties. It seems though that there are busses in the network that are typically more sensitive to harmonics than the others irrespectively of the level of harmonic injection and operating condition of the network.

For the purpose of analysis of the behaviour of the power systems in terms of harmonic occurrence it could be said that planning system level requires also as accurate as possible input data in terms of potential harmonic sources and network data topology. The probabilistic harmonic methodology as presented could be used for the purpose of identification of potentially highly influenced nodes. Additionally, further improvements of the methodology could be made in terms of performing the sensitivity analysis within the methodology itself and inclusion of additional uncertainties in more detail manner.
7 Influence of PQ on PE devices

Simulations that are performed and presented within previous chapters of this document describe the influence of the massive penetration of PE based devices on the power quality of the transmission grid. The power electronics that are utilised within modern generation units or FACTS devices have been characterised as one of the culprit for the negative impacts on the power quality at different network levels of electrical grids. The PQ phenomenon that is influenced by the PE devices the most is the harmonic distortion, which occurs due to the nature of the switching devices, technically being the characterized as harmonic sources in the electrical circuit. Power electronics, as a part of the modern distributed generation devices of renewable energy sources (wind, solar power etc.), are prone to power fluctuations due to fluctuating character of the primary energy source. This causes influence also on other PQ indices, voltage amplitude and frequency variations.

The interaction between the PE devices and PQ occurs in both directions. While the PQ of the grid is affected by the PE devices' disturbances, also the other PE devices can be adversely affected by the low PQ levels which cause effects on the connected PE devices. To prevent the extensive influence on the operation of PE devices, these are designed to operate under range of different operating conditions, defined by the voltage quality conditions at the point of connection (POC).

Each device is designed to be immune to different kinds of disturbances below certain level. The term immunity level therefore indicates the maximum value of disturbance present in the network that does not degrade the behaviour of particular device [3]. Often, the reality shows that higher is the level of immunity of particular device, higher is the price of the equipment and therefore an economic trade-off between installation costs and price of unavailability of equipment drives the reason for reductions of the immunity of devices.

For some influences, operation under increased disturbances within immunity levels does not necessarily means that the device will not be degraded in the long-term. Such example is the constant loading of power transformers with harmonics. Although they are in the range of normal loading, presence of harmonics causes additional heating of transformer, which eventually reduces the lifetime expectancy.

Therefore, each power electronic or passive device must be designed to withstand certain distortion levels that occur at the point of connection to the grid. Still, one might find some phenomena that are in some cases not considered at the design stage of the device as for example extreme deviations of individual power quality parameters that are not covered within the grid’s compatibility levels, or impedance characteristics that could cause resonances between the device and grid or other devices connected to the grid.

Analyses of the PQ disturbances on the PE devices are therefore an important topic as the share of power electronic devices increases.
7.1 General effects of the poor PQ on PE devices

The influence of the PQ on PE devices cannot be generalized in a way as it can be for the individual passive devices (e.g. transformer, passive compensation, others) which will always respond to disturbances in the similar way. Power electronics of modern devices operate based on the combination of passive and active controlled elements, which can be both together for the steady-state analyses treated as a controlled impedance. Their response to disturbances is mostly dependent on the control algorithm of the active power converter, while in the uncontrollable frequency regions it keeps the characteristics of the passive elements. For the dynamic analyses, each device or its control algorithms can be tuned differently thus causing different responses to the PQ disturbances.

The response of PE device to different disturbances can be reflected internally within device or externally, which can be observed at the connection terminals of the device. With the shunt-connected devices, the external response is indicated by the current that is injected from the PE device into the grid while internally, the grid PQ influences the PE device in different aspects (internal circulating or DC currents distortions, dc voltage distortions, influence on controls etc.).

Power quality defines different aspects of the voltage waveform at the observed point in the network. In this document, the main aspects observed in respect to the influence on the PE devices are the variation of fundamental frequency voltage amplitude, variation of the fundamental frequency and the presence of the higher frequency voltage components.

7.1.1 Influence of the increased harmonic distortion

As the number of nonlinear devices increases, the harmonic injections into transmission system and consequently the harmonic distortion of the network voltage increases as well. New operating conditions cause the adverse influence on all the grid-connected devices which respond with new harmonic contributions.

The level of the new or the additional level of injections can differ among different nonlinear PE devices and is defined by the susceptibility of individual PE device. Distortion of the voltage at the POC causes higher harmonic current flow to the poorly damped low impedance frequency regions of the passive elements, while the influence on active controlled converters varies based on the topology, modulation strategies and control algorithms. The harmonic voltages at the POC reduce the efficiency of the generation and transmission of the electrical energy due to lower voltages at which lower power can be transmitted, or due to additional thermal stress on components, which is causing accelerated component ageing, malfunctioning of protection systems.[4]
**PFC capacitors, Filters and other capacitors in the circuits**

Capacitors are the electrical elements that are indispensable elements of the PE devices. They are utilized within different circuit topologies and are used for different functions at the AC or DC side of the power converters. The capacitors are the main components of the filters and are very susceptible to higher order harmonics. When exposed to harmonic voltages, the capacitor will draw harmonic current. Due to its lower impedance at higher frequencies, it could easily be overloaded when sufficient harmonic voltage source is present in the network. If not protected from the harmonics stress, capacitor may fail soon [5]. Capacitors that suffer from the too high harmonic current loadings can cause tripping of the fuses or overload internal connections which could cause local overheating within the element itself.

On the other hand, the capacitors are sensitive also to the excessive voltage amplitudes which increase the dielectric losses and reduce the reliability, eventually causing failure of the capacitor.

The capacitors that are installed in different topologies or within different devices could create parallel and series resonances also with the grid impedances which could lead to high harmonic current or voltage distortions when a particular frequency harmonic source is present in the grid [6]. Resonances could lead to extreme harmonic conditions which could also cause failures of elements that are in the particular resonance loop.

**Transformers**

The transformers are built for relatively long lifetime cycle but the ageing can be, among other factors, accelerated by higher operational temperatures of materials and higher dielectric stresses [8]. Transformers exposed to harmonic voltages may be affected by the temporary over voltages caused by the superposed harmonics. Higher voltage peaks and gradients lead to higher dielectric stress on the transformer insulation, higher magnetic flux and magnetization losses (eddy losses and hysteresis losses). These losses can be characterized as the no-load losses [9].

The harmonic current that flows through a transformer increases the load losses, the copper losses and the stray-flux losses in a transformer (eddy losses in winding and transformer steelwork). The load losses increase with the second power of the current and increase even faster with higher frequency components. Similarly, the magnetization losses due to the conducted current may be present in the iron core reactors.
With the new types of PE loads, the transformer that have been operating reliably in the past are now more often exposed to severe failures caused by the effect of harmonics. The harmful effect of harmonics therefore often go unnoticed until the actual failure occurs [7].

Higher expected harmonic loading of transformers of PE devices is the reason for new requirements of improved designs of transformers that must properly include all possible harmonic components and their influences. The capacity of a transformer can be increased by the K-factor rating, where the K-factor is equal to sum of square of harmonic currents multiplied with the square of harmonic number [7]. The K factor presents the heavy nonlinear dependency of the harmonic frequency which is due to the effect of eddy current losses.

**Generators**

Generators of all types represent the main electrical element of wind turbine generators. They are connected directly to the electrical grid (DFIG with WTG T3) or through a full AC/DC/AC converter (WTG T4) therefore may be exposed to the grid harmonics or to the harmonics produced by the supplying converters. The major impact of the harmonic distortion on generators is the increase of the generator losses, i.e. additional coper losses and iron losses in the stator winding, rotor circuit and rotor laminations [17]. Since the losses are frequency-dependent, they increase with increased harmonics. The skin effect increases this effect even more. Heating of generator results in excessive degrading of bearing lubrication causing bearing failures, consequently, the overheating reduces the lifetime of an induction generator significantly. The generator windings could also suffer insulation damage due to high rate of rise of voltage which occurs with high harmonics or especially due to line notching.

The heating effect due to harmonics can be reduced by proper de-rating of the generators supplying nonlinear loads.

**Converters & controls**

With the active components it can be expected that based on different designs of PE devices, multiple influences of harmonics can occur:

- Active components can be influenced by harmonics at POC and could cause additional harmonic injections.
- Active components can internally compensate external harmonic distortions at POC, therefore, no harmonic additional harmonic current is injected by the device.
- Active components can compensate the additional harmonic injections of the passive components (e.g. filters).

The voltage source converters act as voltage sources with the ability to control the voltage components up to the range of switching frequencies. In this controllable frequency bandwidth, the
VSC could eventually compensate much of the output harmonic currents of the device when properly
designed and tuned. If not, the harmonics at the POC could give rise to controller’s poor performance
which is expressed by harmonic amplification [10], [11], excessive dc-voltage variations, transfer of
harmonics through back-to-back converter etc.

Operation under harmonically distorted ac-side voltages could lead to higher distortions also at the
dc-side of the voltage source converter. The harmonic currents that flow from the AC-side to the DC
side cause harmonics, modulated by the fundamental frequency. Harmonic currents of the frequency
f could cause $f \pm f_0$ voltage components at the dc side ($f_0$ is the fundamental frequency) [12]. The
harmonics at the DC-side must therefore be taken into consideration when designing and tuning the
controllers and topology of the converter. Low capacitances of the DC-side capacitors of the
converters could be overloaded by voltage harmonics in case of higher harmonic currents of the
converter [13]. Also, based on individual converter concept, the harmonic currents could be induced
within the phase-legs of the converter causing circulating currents [14]. These effects could be
minimized by utilizing the appropriate control strategy.

The voltage source converters are due to internal capacitances sensitive to voltage excesses,
especially in case when no voltage reserve is considered within the design. Increase of the voltage
rating of the high power PE device could cause high investment costs, but must be considered when
the maximum reached voltage is increased due to harmonic components.

The harmonic currents, that flow through the semiconductor switches causes additional losses. The
semiconductor switches are therefore exposed to extensive heating, which demands proper design
including use of parallel switching stacks, improved cooling system or other measures.

Since the converters are usually protected against high harmonics (voltage or current), the tripping
could occur whenever excessive harmonics would appear. The cases with tripping of HVDC converters
are described in [15] and [16].

**Effect on protection**

The fuses and circuit breaker that operate based on the bi-metallic trip mechanisms can suffer from
presence of harmonic currents, which can cause additional heating of the tripping mechanism and
consequently premature tripping of the device. Similarly, the harmonic currents that load fuses
could cause additional heat effect and non-uniform current distribution across the fuse due to skin
effect. [17]

Some circuit breakers are designed to interrupt current at zero crossing. Highly distorted load
currents could cause premature interruption of the circuit breaker leading to non-optimal loading of
interrupters during the switch-off transition [17].

Harmonics can cause negative effects also on the protection devices which include the frequency
measuring units. Algorithms for frequency measurements are often very sensitive to harmonics or
noise in the measured signals and can consequently cause premature or undesired protection tripping.
**Effect on cables**

The main effect of harmonic voltages on the cables is the increased voltage stress on the insulation layers caused by higher voltage peaks due to harmonics. The harmonic current loading causes additional cable losses which are higher at higher frequencies due to the effect of frequency dependent resistance of the cable. Resistance of the cable is defined by the DC resistance, skin effect and proximity effect. Due to the skin effect, the currents flow near the surface of conductor while the proximity effect reduces the conducting cross-section due to mutual inductance of parallel cables. Both effects are frequency-dependent and therefore with higher harmonics the losses increase much faster [17].

7.1.2 Voltage amplitude variation

Voltage amplitude variation is a phenomenon expected during normal or off-normal operation conditions of the electrical grid. In networks with high penetration of renewable energy sources, as are the wind generators or the photovoltaic systems, the voltage can vary due to power fluctuations of the primary energy source (wind speed of solar radiation).

Under normal conditions, the grid codes define the ranges of the expected voltage levels where the generators should be able to operate undisturbed (e.g. allowed variation of the network voltage +10% / - 12,5% from the nominal voltage). The grid codes define also the voltage ranges for the low voltage disturbances that the generators must withstand (LVRT – low voltage ride through capability of generators).

Normally it can be expected that when the voltage levels are out of the normal operation range or out of the range of the LVRT requirements, the PE device will be tripped or will operate with reduced functionalities. Tripping a generator results in increased costs on both sides, transmission system’s and generator’s due to malfunctions, defects of equipment, undelivered energy etc.

Under normal operating conditions, when the voltage remains within the normal operating range, the voltage variation, described by the power quality parameters, could indicate the influence on operation of individual devices, as follows.

**Transformers**

Transformers exposed to slow voltage variations should not express any exaggerated side effects unless the saturation knee of the magnetization curve is low. In such case, the magnetization current could draw significant amount of nonlinear, harmonically distorted magnetization current. Higher voltage levels could lead to higher dielectric stress on the winding insulation while during lower voltage levels, the current could increase when constant power is generated by the generator, thus causing higher copper losses which also influences to additional heating of the transformer.
Induction generators, DFIG generators

Generators, similarly as transformers, respond to voltage variation by increasing the output current to deliver the constant power. In case, when operating at maximum current limit, other controls must take care of reducing the mechanical power delivered to the generator (e.g. control of pitch shift, brake). Eventually, voltage that differs from the rated voltage may in extended periods accelerate the deterioration of the insulation system.

With modern generators of renewable sources, as are the WTG T3 and T4, which are capable of active control of output power and fast adaptation to the system disturbances, is the dynamic response to slow voltage variations neglected. An important topic which has gain a lot of research activities is the low voltage ride through of WTG, especially with the DFIG generators which are susceptible to voltage dips. To meet the grid codes that define the conditions under which the generators need to stay connected several topology and control improvements have been proposed and utilized [18],[19],[20],[21].

Converters

Voltage source converters exposed to slow voltage variations easily operate undisturbed. The control algorithm adapts the output voltage of the converter to transmit the required active or reactive power to the grid. Nevertheless, since the converters or their elements (semiconductor switches) are sensitive to the overvoltages the temporary levels of the voltages must not increase above the maximum allowed value in order to protect them from failures.

During periods with lower voltages, the converter elements might be loaded with higher current to transmit the same amount of power. This results in the increased conducting losses of the converter. In order to transmit the maximum generated power during low voltage levels, the current short-term overloading capacities of the converter might be beneficial to optimize the efficiency of the WTG. Short-term overloading capacities are available with some manufacturers which utilize the heat accumulation mechanisms to mitigate the effect of the short-term overloading.

To mitigate the influence of the grid-side voltage variation, the ac voltage generated by the VSC varies as well. Since the AC voltage of the VSC is produced by the modulation of the DC voltage(s), the altering of the fundamental ac voltage amplitude might influence also the harmonic spectrum of the produced ac voltage, consequently also the spectrum of the emitted currents.

Controller tuning and influence on the flicker

When the susceptibility to the voltage variation is analysed within normal operation voltage range, the main concern focuses on the dynamic performance of the control to different dynamics of the variations.
It is well known from the control theory that the performance and the stability of the controlled system, which we can find in most of PE devices, is highly dependent on the time constants and gains of controllers in different stages of the control system. Therefore, tuning of the controllers for different system changes becomes inevitable action to satisfy the performance/stability criteria and to reduce the influence of the variations in the network voltage on the operation of PE device.

The slower controller dynamics can follow the steady-state conditions that occur after transients while during the transients the control might not perform optimally in view of PQ influence. A case with flicker in the network is highlighted as follows.

**Flicker**

Flicker is classified as an impression of visual sensation induced by a light stimulus, whose luminance fluctuates with time \[22\]. The main reason for the flicker is the voltage variation phenomenon, where the frequencies of the amplitude variation are closer to the frequencies that are the most sensitive to the light perception of the human eye. The voltage variations that cause annoying effect with the incandescent lights are in the range of 1% or less.

The passive elements like transformers or capacitors do respond to voltage fluctuations but there is no severe reason for equipment failures. However, the power electronic devices, especially those that require constant power supply could be affected if not adequately designed and the flickering effect could be transmitted further on to the elements connected to the PE device. In case of light emitting loads, the flicker could be increased even more. \[23\]

The influence of the flicker could increase also when the flickering signal is introduced in the signals of the control algorithms of the PE device. If not properly tuned, different control algorithms (voltage control, active or reactive power control etc.) could be affected by the flickering frequency in the voltage thus the resultant output current of the PE device could show excessive fluctuations.

Although the flicker in the network might be increased when a particular PE device is connected to it this does not necessarily means that the PE device will be anyhow critically affected.

**Capacitors and filters**

PFC capacitors and different topologies of capacitor based filters respond to voltage variation by variation of the reactive power generated during high and low voltage states. During high voltages, the capacitors might be exposed to higher dielectric voltage stress at the capacitor insulation layers.
7.1.3 Frequency variation

Frequency variation of the system voltage occurs due to different reasons. The one that has been analysed within this document is caused by variation of the power injections from renewable energy source generators, mostly the wind turbines. The frequency variation depends on the share of fluctuating sources and share of stiffer conventional synchronously connected machines with higher amount of mechanical inertia.

The varying frequency influences the operation of PE based devices from several points and could be divided into the impact on the passive elements and impact on the active, controlled converters.

With the passive elements, the varying frequency is evaluated for transformers, capacitors or filter circuits and grid connected generators, especially the DFIG with the active elements, where the influence is assessed from the controller’s and converter’s perspective.

**Transformers**

Transformers exposed to the frequencies that are above the rated frequency suffer from higher losses under load or no-load conditions. During conduction, also the voltage drop across the transformer may be higher than expected. Losses of the transformer are caused by the eddy currents in the copper wires as well as eddy and hysteresis losses in the iron core and all are frequency dependent [24].

**Capacitors, Filters, etc.**

In the same manner as with other passive reactive impedances, the frequency variations cause variation of impedance of the capacitors and filters at varying fundamental frequency.

With PE devices, the capacitive elements are often used as compensators of reactive power of PE devices or as harmonic filters. Variation of the grid frequency does not change the resonance frequency of the filter but it does changes the harmonic number relatively to the fundamental frequency. Variation of the fundamental frequency in range of ± 0,5 Hz will cause the 5th harmonic component to vary in range ±2,5 Hz, and higher for other harmonics. Due to frequency dependent impedance of the harmonic filters it could be expected that the damping of individual characteristic harmonic component could vary when the fundamental frequency varies, therefore variation of the filtered current amplitude could be expected.

**Induction generators, DFIG**

The generators of wind turbines that may be affected by the frequency variations are the WTG of the type 1, 2 and 3. The type 1 and 2, the obsolete constant speed turbines, have been replaced by the
variable speed type 3 (DFIG) and type 4 (full converter) wind turbines. Since the type 4 WTG is fully driven by the AC-AC converter, the system frequency does not propagate through the converter. The influence could be therefore introduced to the other models, especially the type 3, based on the DFIG generator.

In [25] the simulation results of the research work indicate that the fixed-speed generators show higher sensitivity of the torque and output power to the frequency variation as a DFIG generator. The fixed-speed asynchronous and synchronous generators release the kinetic energy from their rotating masses during the changes of the system frequency. With the variable-speed DFIG generators, the kinetic energy of the rotating masses that is converted to the electrical energy can be controlled, thus the influence of the variable frequency can be compensated as well as different inertia responses of the device can be achieved.

**Converters and controls**

Active components of PE devices show different dependencies from the fundamental frequency. The two main modules that can be affected are the modulator of the converter and control algorithms.

Due to diversity of modulation techniques voltage source converter can respond differently to the frequency variations. Some techniques are synchronized with the fundamental frequency (e.g. nearest level modulation of MMC converter, PLL based PWM switching) or are totally independent and synchronized to other clock sources (PWM or other modulation techniques with 2- or 3- level voltage source converters). The modulation during fundamental frequency variation causes variation of particular harmonic components by amplitude and by frequency or harmonic order.

The frequency variation could influence also the control algorithms of PE devices. Normally, all PE devices are designed to meet the requirements to operate under predefined frequency range and frequency dynamics (ROCOF – Rate Of Change Of Frequency). Any frequency variation within the predefined normal operation range should not cause any influence on the power generation/consumption of the PE device. However, the control algorithms could show some other secondary influences that could consequently cause the influence on the harmonic spectrum of emissions, dc voltage levels or other quantities. The dynamic ability to adapt to the new system frequency is mostly based on the performance of the synchronization control (phase locked loop) driven by different algorithms. Failing to track the fundamental frequency could cause high control errors and misoperation of the device.
7.2 Expected sensitivity threshold of PE devices in future networks

As it has been shown with the results of the simulations of the PQ disturbances in the future network, the expected levels of harmonics, voltage and frequency variations will increase due to new installed PE based renewable energy generators. The existing devices will be exposed to new disturbance levels that could lead to the unplanned operation conditions at the point of connection of devices connected to the transmission or distribution systems (PE devices, transformers, generators and others). On the other hand, the impedance of the transmission system will also be influenced by new equipment (lines, transformers, compensators, etc.) and will cause reallocation of sensitive network impedance resonances that cause high network voltage distortions.

The current sensitivity level of the existing devices in the network to PQ disturbances is not exactly defined. The individual device’s design is based on the technical recommendations, standards or the customer’s specifications to fulfil the expected compatibility levels. However, there are technical limitations of the performance of these devices for the operation conditions that are outside the prescribed levels. Keeping the PQ levels within the normal limits should offer the PE devices to operate normally while in other case, massive interactions could occur which will lead to tripping or failures of individual devices in the network.

The main concern tackles the existing compatibility levels, which indirectly represent the expected sensitivity levels of the new or existing devices and will potentially be exceeded by the increasing PQ disturbances of future networks. This will demand to redesign the existing devices (the ones exposed to higher disturbances) and new devices or to utilize the PQ disturbance mitigation measures that could be taken by the operator of the grid to prevent the system to reach the unplanned levels of all PQ disturbances.

The mitigation measures can include different acts which includes use of FACTS devices, improvements of transmission system capacity, stricter requirements for new PE devices or some other actions. These and many other measures are considered more in details in the following task of the MIGRATE project, which is the Task 5.5 of the Work package 5.
8 Review of existing grid codes on PQ phenomena

8.1 Trends in power system development

The European Union has set a long-term goal of reducing greenhouse gas emission by 80-95% by 2050 (compared to 1992 levels). For these goals investments in new low-carbon technologies, renewable energy, energy efficiency, and grid infrastructure has to be made. European Commission has therefore concluded that increasing the share of renewable energy and using newer technologies for more efficient energy usage are crucial [45]. The Renewable Energy Directive states that by 2020 at least 20% of EUs total energy needs are to be from renewables. Furthermore, the Commission has published a proposal to ensure that the target of at least 27% renewables in the final energy consumption is met by 2030.

From the last decades it can be seen that electricity generation from fossil fuels (coal etc.) is decreasing over time and this generation deficit is more and more covered from renewable sources (wind generation, PV generation, biofuels etc.). To illustrate, Figure 8-1 shows the renewables versus coal electricity generation in the years 2010-2017 [46]. European transmission system operators have been already planning their transmission systems from these objectives and other global utilities are recognizing these trends and showing their plans for the future, for example more can be read in [47]-[51].

![Figure 8-1: Renewables versus coal electricity generation in Europe in 2010-2017.](image)

Taking into consideration all the above, the increase of power electronic devices in transmission systems would therefore also be steep. Moreover, new technologies in power electronics are being developed and implemented.
Devices with complicated construction, higher voltage levels and more sophisticated control algorithms are being studied and assessed for use in future power systems. Besides PE devices that are used for WTG or PV connections or for stability in transmission systems (FACTS devices etc.), the usage of HVDC in transmission systems is also increasing, which makes future power systems more complex. Studies are made to investigate the possibilities to interconnect synchronous areas and to transfer more power over long distances. For example, there are ultra-HVDC transmission solutions already offered on the market for transferring bulk power (up to 10 GW) over very large distances (reaching even above 3000 km) [52],[53].

All these trends in power systems bring up a question how the power quality should be covered in the future and what regulation and in what extent is needed to be placed to guarantee reliable and coordinated operation of different power system components. For the purpose of proposing future approaches, it is important to understand how this item is currently covered in Europe by different TSOs.

8.2 Existing grid codes on PQ

8.2.1 Europe

In Europe, the grid connection and system operation is in general regulated by European Commission regulations such as Demand Connection Code (DCC) [54], Requirements for Generators (RfG) [55], High Voltage Direct Current Connections (HVDC) [56] and System Operations Guidelines (SOGL) [57]. The main drawback of these regulation is that the PQ is covered in quite general way or not covered at all. This means that a significant amount of work to define the framework for PQ is left to the country level. What has been regulated are the frequency and voltage levels, but specifics for other PQ parameters have been omitted.

For example, DCC [54] defines that transmission-connected demand facility owners and transmission-connected distribution system operators shall ensure that their connection to the network does not result in a determined level of distortion or fluctuation of the supply voltage on the network, at the connection point. The level of distortion shall not exceed that allocated to them by the relevant TSO. TSOs shall coordinate their power quality requirements with the requirements of adjacent TSOs. RfG [55] defines the connection requirements for generators in Continental Europe, Great Britain, Nordic, Ireland and Northern Ireland, and Baltic synchronous areas, but is silent on PQ requirements. HVDC [56] defines the requirements for grid connection of high voltage direct current systems and direct current-connected power park modules. HVDC system, DC-connected power park modules and/or remote-end HVDC converter station owners shall ensure that their connection to the network does not result in a level of distortion or fluctuation of the supply voltage on the network, at the connection point, exceeding the level allocated to them by the relevant system operator, in coordination with the relevant TSO. SOGL [57] defines only the limits for voltage and frequency for Continental Europe, Great Britain, Nordic, Ireland and Northern Ireland, and Baltic synchronous areas (see Table 8-1 for voltage ranges and Table 8-2 for frequency ranges).
Table 8-1: Voltage ranges at the connection point between 110 and 400 kV[57]

<table>
<thead>
<tr>
<th>Synchronous area</th>
<th>Limit (110 – 300 kV) [p.u]</th>
<th>Limit (300 – 400 kV) [p.u]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Continental Europe</td>
<td>0.90 – 1.118</td>
<td>0.90 – 1.05</td>
</tr>
<tr>
<td>Nordic</td>
<td>0.90 – 1.05</td>
<td>0.90 – 1.05</td>
</tr>
<tr>
<td>Great Britain</td>
<td>0.90 – 1.10</td>
<td>0.90 – 1.05</td>
</tr>
<tr>
<td>Ireland and Northern Ireland</td>
<td>0.90 – 1.118</td>
<td>0.90 – 1.05</td>
</tr>
<tr>
<td>Baltic</td>
<td>0.90 – 1.118</td>
<td>0.90 – 1.097</td>
</tr>
</tbody>
</table>

Table 8-2: Frequency ranges and deviations of the synchronous areas [57]

<table>
<thead>
<tr>
<th></th>
<th>CE</th>
<th>GB</th>
<th>IE/NI</th>
<th>Nordic</th>
</tr>
</thead>
<tbody>
<tr>
<td>Standard frequency range</td>
<td>± 50 mHz</td>
<td>± 200 mHz</td>
<td>± 200 mHz</td>
<td>± 100 mHz</td>
</tr>
<tr>
<td>Maximum instantaneous frequency deviation</td>
<td>800 mHz</td>
<td>800 mHz</td>
<td>1000 mHz</td>
<td>1000 mHz</td>
</tr>
<tr>
<td>Maximum steady-state frequency deviation</td>
<td>200 mHz</td>
<td>500 mHz</td>
<td>500 mHz</td>
<td>500 mHz</td>
</tr>
</tbody>
</table>

8.2.2 International standards for harmonic distortion

Harmonic distortion means either current or voltage harmonics, which are multiples of nominal frequency. Usually the upper limit considered in Europe for transmission voltages is 50th harmonic order or if the risk of resonance for higher harmonics is low the upper limit can also be 25th harmonic order [72]. Documents that are usually followed when implementing regulation for harmonic distortion are IEEE 519 [75], EN 50160 [72], ER G5/4 and IEC TR 61000-3-6 [76].

Voltage harmonic distortion planning levels for HV and EHV are defined in standard IEC TR 61000-3-6. Indicative values of individual harmonic voltages at supply terminals up to 150 kV are given in standard EN 50160. In IEEE standard 519 voltage and current distortion levels are defined as recommended limits at the PCC. In general, the IEC standards are commonly used in Europe by different TSOs whereas the IEEE standards have been referred less. The limits given in IEC standards for HV and EHV are planning levels, which are equal or lower than compatibility levels.

It should be noted that IEC 61000-3-6 and EN 50160 do not consider compatibility levels at HV and EHV. The precise relationship between specified compatibility levels and planning levels depends on the disturbance phenomenon being considered and whether or not they are load related. Planning levels control the emissions of large loads and are lower than or equal to compatibility levels. The margins between planning levels and compatibility levels depend on the electrical characteristics of the supply network, the background levels of distortion, the nature of the disturbance (continuous or random), load profiles, and load density of the supply system area. [64]
As an example, the harmonic distortion limits from above mentioned standards are shown in Table 8-3 to Table 8-6.

**Table 8-3: Voltage distortion limits (IEEE 519) [75]**

<table>
<thead>
<tr>
<th>Bus voltage V at PCC</th>
<th>Individual harmonic (%)</th>
<th>THD (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>69 kV&lt;V≤161 kV</td>
<td>1.5</td>
<td>2.5</td>
</tr>
<tr>
<td>161 kV&lt;V</td>
<td>1.0</td>
<td>1.5*</td>
</tr>
</tbody>
</table>

*High-voltage systems can have up to 2.0% THD where the cause is an HVDC terminal whose effects will have attenuated at points in the network where future users may be connected.

**Table 8-4: Current distortion limits for systems rated > 161 kV (IEEE 519) [75]**

<table>
<thead>
<tr>
<th>Individual harmonic order (odd harmonics)*</th>
<th>Isc/IL</th>
<th>3≤h&lt;11</th>
<th>11≤h&lt;17</th>
<th>17≤h&lt;23</th>
<th>23≤h&lt;35</th>
<th>35≤h≤50</th>
<th>TDD</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt;25</td>
<td>1.0</td>
<td>0.5</td>
<td>0.38</td>
<td>0.15</td>
<td>0.1</td>
<td>1.5</td>
<td></td>
</tr>
<tr>
<td>25&lt;50</td>
<td>2.0</td>
<td>1.0</td>
<td>0.75</td>
<td>0.3</td>
<td>0.15</td>
<td>2.5</td>
<td></td>
</tr>
<tr>
<td>≥50</td>
<td>3.0</td>
<td>1.5</td>
<td>1.15</td>
<td>0.45</td>
<td>0.22</td>
<td>3.75</td>
<td></td>
</tr>
</tbody>
</table>

*Even harmonics are limited to 25% of the odd harmonic limits above.

**Table 8-5: Indicative planning levels for HV and EHV (IEC 61000-3-6) [76]**

<table>
<thead>
<tr>
<th>Odd harmonics (non-multiples of 3)</th>
<th>Odd harmonics (multiples of 3)</th>
<th>Even harmonics</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Order h</strong></td>
<td><strong>Harmonic voltage (%)</strong></td>
<td><strong>Order h</strong></td>
</tr>
<tr>
<td>5, 7</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>11, 13</td>
<td>1.5</td>
<td>9</td>
</tr>
<tr>
<td>17 ≤ h ≤ 49</td>
<td>1.2 · 17/h</td>
<td>15</td>
</tr>
<tr>
<td>21 ≤ h ≤ 45</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Table 8-6: Indicative values of individual harmonics at the supply terminals (EN 50160) [72]**

<table>
<thead>
<tr>
<th>Odd harmonics (non-multiples of 3)</th>
<th>Odd harmonics (multiples of 3)</th>
<th>Even harmonics</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Order h</strong></td>
<td><strong>Harmonic voltage (%)</strong></td>
<td><strong>Order h</strong></td>
</tr>
<tr>
<td>5</td>
<td>5</td>
<td>3</td>
</tr>
<tr>
<td>7</td>
<td>4</td>
<td>9</td>
</tr>
<tr>
<td>11</td>
<td>3</td>
<td>15</td>
</tr>
<tr>
<td>13</td>
<td>2.5</td>
<td>21</td>
</tr>
<tr>
<td>≥17</td>
<td>u.c.</td>
<td></td>
</tr>
</tbody>
</table>

u.c. – limits are under consideration
8.2.3 National guidelines for harmonic distortion in Europe

Allocation of harmonic distortion limits to individual customer facilities differs from country to country. A transmission node is subject to planning levels and in order to maintain those levels, the TSO allocates emission limits (individual harmonic orders and THD) to facilities connecting to that node. The challenge here is that not always it is clear whether the values stated are planning levels or individual customer emission limits.

In the following some examples are given:

EirGrid [38] users must ensure that their connection to the transmission system does not result in an increase in the level of harmonic distortion of the supply voltage on the transmission system, at the connection point, exceeding that allocated to them. These limits are determined by the TSO to ensure the compliance with IEC 61000-3-6 and EN 50160. EirGrid has an explanatory document [58] describing the process for allocation of emission limits and the applicable standards.

In Denmark, technical requirements for consumption installations connected above 100 kV [59] state that harmonic disturbances are determined based on IEC 61000-3-6. That IEC standard also applies to Swiss transmission grid [66], where EN 50160 is also cited in the grid code.

National Grid grid code [63] states that electromagnetic compatibility levels for harmonic distortion of the onshore transmission system in Great Britain under both planned and fault outage conditions must comply with levels shown in Engineering Recommendation G5/4 [64]. Harmonic voltage compatibility levels for 132, 275 and 400 kV systems are given as a table. THD must be equal or less than 5% for 132 kV and 3.5% for 275 and 400 kV networks. Planning levels are also given in Engineering Recommendation G5/4 where THD level is 3% and individual harmonic orders are given as tables for 132, 275 and 400 kV systems and are applicable to all transmission nodes. The difference between planning and compatibility levels is explained in subchapter 8.2.2.

In Croatian grid code [65] harmonic distortion is defined as part of voltage waveform quality. THD limit is 3% for 110 kV and 1.5% for 220 and 400 kV networks and referred to each individual unit and customer connection. Individual limits for harmonics are not defined in the grid code.

In Czech grid code [67] limits for both THD and individual harmonics are given for 110, 220 and 400 kV networks. Individual harmonic limits are given up to 25th harmonic order, THD is calculated using up 40th harmonic order. Those limits are designed with IEC 50160 in mind. THD for 110 kV network must be equal or less than 8%, 1.5% for 220 kV and 1% for 400 kV. It is not stated whether those limits apply to transmission node or to individual connection.
In Romanian grid code [68] harmonic distortion is defined as part of quality of voltage curve with THD limit set at 3% for high voltage (110 kV and up). It is not stated whether those limits apply to transmission node or to individual connection.

In Macedonian grid code [69] limits for both THD and individual harmonics are defined for the transmission system. Individual harmonic limits are given as a table, THD must be equal or less than 3%. Those limits apply to the point of connection.

In Polish grid code [70] total harmonic distortion is defined as the voltage deformation coefficient. Individual harmonic limits and voltage deformation coefficient are given for 110, 220 and 400 kV networks and are 1.5% and 2.5% for 110 kV and 1% and 1.5% for 220 kV and 400 kV respectively. Those limits apply to the point of connection.

In Estonia power quality requirements for grid connection are defined in Elering’s Conditions for Connecting to the Grid document [71]. Individual voltage harmonics planning levels (up to 50th harmonic) are defined for 110 kV and 330 kV networks and these apply to a node in transmission system. Separately also limits for customers are defined in connection agreement.

In Italy [77] wind power plants are equalized to disturbing loads from the power quality standpoint and therefore must comply with relevant standards (e.g. IEC 61000-3-6 for harmonics, IEC 61000-3-7 for flicker and rapid voltage variations and IEC 61000-3-13 for unbalances). Under normal conditions the THD should be less than 3% and 1.5% for 132-150 kV and 220-380 kV networks. Those limits apply to the point of connection [61].

8.2.4 National guidelines for voltage variation in Europe

Voltage changes due to events such as motor starting, energization of transformers, capacitor switching, and voltage regulator switching are classified as rapid voltage changes (RVC) as the changes are sustained over several cycles [78]. Limits for RVC are defined in IEC 61000-3-7 and IEEE 1453 standards. IEEE 1453 uses the planning levels from IEC 61000-3-7, which may be used to determine emission limits for RVC for individual customers based on number of changes. Planning levels for RVC at MV, HV and EHV are given in Table 8-7.

<table>
<thead>
<tr>
<th>Number of changes, N</th>
<th>ΔV/Vr (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>MV</td>
</tr>
<tr>
<td>N≤ 4 per day</td>
<td>5-6</td>
</tr>
<tr>
<td>N≤ 2 per hour</td>
<td>4</td>
</tr>
<tr>
<td>2&lt;N≤10 per hour</td>
<td>3</td>
</tr>
</tbody>
</table>

Table 8-7: Indicative planning levels for rapid voltage changes (IEC 61000-3-7) [79]
In EirGrid grid users must ensure that the disturbance levels introduced by their plant and/or Apparatus do not promote rapid voltage changes exceeding those specified in the grid code. EirGrid has two different definitions for rapid voltage change. Temporary voltage depression is a voltage change that must recover to nominal voltage in 3 seconds. Limit for this kind of change is 5% of nominal voltage. Step change is a one cycle voltage change with a limit of 3% of nominal voltage.

In UK’s National Grid voltage changes are split into 3 categories depending on maximum number of occurrences (Table 8-8) [63].

Table 8-8: Limits for voltage changes in National Grid Onshore Transmission Grid [63]

<table>
<thead>
<tr>
<th>Category</th>
<th>Max number of occurrences</th>
<th>%(\Delta V_{\text{max}}) &amp; %(\Delta V_{\text{steadystate}})</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>No limit</td>
<td>(</td>
</tr>
<tr>
<td>2</td>
<td>(36000 / \sqrt{2.5 \times %\Delta V_{\text{max}}})</td>
<td>(1 \leq</td>
</tr>
</tbody>
</table>
| 3        | No more than 4 per day for Commissioning, Maintenance and Fault Restoration | For decreases in voltage: \(\%\Delta V_{\text{max}} \leq 12\%\)^1 \(\%\Delta V_{\text{steadystate}} \leq 5\%\)
For increases in voltage: \(\%\Delta V_{\text{max}} \leq 5\%\)^2 \(\%\Delta V_{\text{steadystate}} \leq 3\%\)

1 A decrease in voltage of up to 12% is permissible for up to 80ms, as highlighted in the shaded area in Figure 8-2, reducing to up to 10% after 80ms and to up to 3% after 2 seconds.
2 An increase in voltage of up to 5% is permissible if it is reduced to up to 3% after 0.5 seconds.

In the table above limits are calculated as follows:

\[
\%\Delta V_{\text{max}} = \left| 100 \cdot \frac{\Delta V_{\text{max}}}{V_0} \right| \quad (8.1)
\]

\[
\%\Delta V_{\text{steadystate}} = \left| 100 \cdot \frac{\Delta V_{\text{steadystate}}}{V_0} \right| \quad (8.2)
\]

Where: \(V_0\) – initial steady state system voltage;
\( V_{\text{steady-state}} \) – system voltage reached when the rate of change of system voltage over time is less than or equal to 0.5% over 1 second and \( \Delta V_{\text{steady-state}} \) is the absolute values of the difference between \( V_{\text{steady-state}} \) and \( V_0 \);

\( \Delta V_{\text{max}} \) – is the absolute value of the maximum change in the system voltage relative to the initial steady state system voltage of \( V_0 \).

Slightly modified IEC 61000-3-7 limits for RVC are used in Czech Republic (Table 8-9).

<table>
<thead>
<tr>
<th>Number of changes, N</th>
<th>( \Delta V/Vr ) (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( N \leq 4 ) per day</td>
<td>3</td>
</tr>
<tr>
<td>( N \leq 2 ) per hour</td>
<td>3</td>
</tr>
<tr>
<td>( 2 &lt; N \leq 10 ) per hour</td>
<td>2.5</td>
</tr>
</tbody>
</table>

In Polish transmission grid [60] the voltage oscillation amplitudes in relation to the rated value in the network should not be higher than 1%, if the oscillations are recurring on a regular basis. The voltage oscillations not recurring on a regular basis below 3% amplitude are allowed, if it does not form a risk to the equipment. Estonian TSO Elering states in its conditions for connecting to the grid document [61] that voltage change limit at point of connection is 3%.

According to IEEE 1453 [78] flicker is defined as fluctuation in system voltage that results in observable changes in the light output of electric lamps and is mostly a problem when it is observed by the human eye. It can be an annoyance and hindrance to workplace productivity and affect visually induced worker discomfort. Flicker level evaluation can be divided into two categories, short-term and long-term. Short-term evaluation of flicker severity (\( P_{st} \)) is based upon an observation period of 10 minutes. This period is based upon assessing disturbances with a short duty-cycle or those that produce continuous fluctuations. The long-term flicker severity (\( P_{lt} \)) is calculated from 12 successive \( P_{st} \) values. The planning levels (denoted as \( L_{st} \) and \( L_{lt} \)) recommended for PCCs at HV and EHV systems are 0.8 and 0.6 respectively. The planning levels are developed to be the basis for applying emission limits for individual customers with PCC at these different voltages. The individual customer emission limits are developed using a procedure that allots each customer some portion of a planning level after allowing for flicker that propagates from other network voltage levels (or locations). Emission limits for individual loads (denoted as \( E_{st} \) and \( E_{lt} \)) are set so that their aggregate effects do not cause overall flicker at PCC to exceed an adopted planning level. A procedure for determining individual customer emission limits is provided in IEC 61000-3-7, where the flicker severity planning levels for HV and EHV are 0.8 for short term and 0.6 for long term [79]. According to IEC 61000-3-7 individual emission limits are derived from planning levels and shall be 0.35 for short term and 0.25 for long term. Standard EN 50160 [72] states that under normal operating conditions, during each period of one week the long-term flicker severity \( P_{lt} \) caused by voltage fluctuation should be less or equal to 1 for 95% of the time. In EirGrid, individual flicker emission limits are calculated on a case-by-case basis following the methodology described in IEC 61000-3-7 [58].
Voltage asymmetry or unbalance can be defined as a ratio of positive phase sequence component to negative. Voltage unbalance limits are defined in standards EN 50160 [72] and IEC 61000-3-13 [80]. Under normal operating conditions, during each period of one week, 95 % of the 10 min mean RMS values of the negative phase sequence component of the supply voltage should be within the range 0 % to 2 % of the positive phase sequence component [72]. In IEC 61000-3-13 planning levels for HV and EHV are given, which are 1.4% and 0.8% respectively. The weekly 95% values should not exceed the planning level. The greatest 99% probability values over 3 s periods should not exceed the planning level times a multiplier to be specified by the system operator or owner, depending on the characteristics of the system and the very short term capability of the equipment along with their protection devices.

8.2.5 Harmonic distortion limits allocation example from EirGrid

EirGrid has very well documented power quality requirements for connection to the transmission systems and the purpose of document [58] is to provide clarity to customers seeking connection to the transmission system about their power quality requirements prior to the energisation of the new facility. Those technical requirements are intended to ensure that the quality of supply to all transmission customers remains within the parameters described in the grid code. Other European TSOs also have similar procedures for harmonic distortion limits allocation.

This subchapter’s point is to describe how EirGrid allocates harmonic distortion limits to its customers. All the definitions and methods are from EirGrid’s document "Power Quality Requirements for Connection to the Transmission System" [58].

Harmonics related terms defined by EirGrid are following:

1. Allocated Harmonic Distortion Limit (AHDL) to a facility is the maximum Incremental Harmonic Voltage Distortion Level (IHVDL) that the facility is allowed to introduce in the transmission system voltage.

2. Harmonic Voltage Distortion Level of the $h^{th}$ order ($U_h$) is the RMS value of the steady-state sinusoidal voltage waveform at a frequency of $(50 \times h)$ Hz which is present in the voltage waveform in addition to its fundamental frequency component.

3. Incremental Harmonic Voltage Distortion Level (IHVDL) attributed to a Facility is defined as the ≤ change in magnitude of the Harmonic Voltage Distortion Level (measured at the Connection Point) which is solely caused by the connection of that Facility to the Transmission System. (An example of IHVDL is graphically depicted in Figure 8-3.)
The Incremental Harmonic Voltage Distortion Level attributed to the Facility is a combination of:

(a) New distortion caused by harmonic voltages or currents generated by the Customer's Equipment, and

(b) Amplification of the existing Harmonic Voltage Distortion Level (measured at the Connection Point) caused by an interaction between the Facility and the Transmission System harmonic impedance (for example due to resonances).

4. Transmission System Impedance Loci is a set of diagrams defining the range of possible Transmission System impedances (in the R-X plane) for the harmonic orders subject to limits and is calculated at the connection point and does not include the effect of the facility under study.

5. Total Harmonic Voltage Distortion (THD) is the RMS value of the sum of all individual Harmonic Voltage Distortion Levels \( U_h \) up to a specified order \( H \) (40\(^{th}\) order in EirGrid)

6. Harmonic Distortion Headroom \( DH_h \) at the \( h^{th} \) order is the difference between the harmonic planning level \( L_h \) and the harmonic voltage distortion level (measured or calculated) at the \( h^{th} \) order and is calculated using the IEC TR 61000-3-6 general summation law as defined below:

\[
DH_h = \sqrt[\alpha]{(L_h)^\alpha - (U_h)^\alpha}
\]

(8.3)

Where \( \alpha \) is the summation exponent as per Table 8-10.

Table 8-10: Summation exponents for different harmonic orders

<table>
<thead>
<tr>
<th>Harmonic order</th>
<th>( \alpha )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( H&lt;5 )</td>
<td>1</td>
</tr>
<tr>
<td>( 5 \leq h \leq 10 )</td>
<td>1.4</td>
</tr>
<tr>
<td>( h&gt;10 )</td>
<td>2</td>
</tr>
</tbody>
</table>
7. Harmonic Planning Levels are planning limits for harmonic voltage distortion levels and THD. These limits must be maintained in the planning and development of the transmission system and must be used for setting AHDL to user’s connections.

8. Harmonic Planning Margin is a portion of Harmonic Distortion Headroom in a transmission node that is retained by EirGrid while setting AHDL to user’s connections.

The planning levels used by EirGrid are adopted from IEC 61000-3-6 for 110, 220 and 400 kV networks. Planning levels for individual harmonics are given as a table and for THD must be equal or less than 3%. Those limits are extract form afore mentioned standard but are limited to the 40th harmonic order.

In order to guarantee that the harmonic voltage distortion levels and THD are maintained below the adopted planning levels at all transmission nodes, EirGrid must assess the impact of the connection new users and new transmission infrastructure (i.e. cables, FACTS, HVDC, etc.). The method adopted by EirGrid for calculating the AHDL for each new user’s connection is based on stage 2 of IEC TR 61000-3-6, with some enhancements aimed to distribute the emission limitation burden as equitably as possible. The main principles of the method are described below:

1. Carry-out measurements of existing background harmonic distortion levels and THD.
2. Calculate the harmonic distortion headroom.
3. Retain 25% of the harmonic distortion headroom as harmonic planning margin.
4. Allocate a portion of the remaining distortion capacity (taking into account interactions from neighbouring transmission nodes) to the user’s connection. The apportioning of distortion capacity is on a MW pro-rata basis between all users connecting at the same transmission node. This method guarantees harmonics access rights to all users in proportion to their relative size, allowing a fair distribution of the available distortion capacity.

The class A measurement method for harmonic voltage distortion level defined in IEC 61000-4-30 and IEC 61000-4-7 is used for measurements of background harmonic voltage distortion. The minimum measurement period is one week of normal business activity and the 95th percentile weekly values over 10 minute periods are considered.

Figure 8-4 illustrates how harmonic voltage distortion levels are allocated to N users at a transmission node.
Each new customer is given AHDL table up to 40\textsuperscript{th} individual harmonic by EirGrid. Those individual harmonic limits are calculated by EirGrid on case by case bases for each new customer’s connection and are calculated in line with method described above. The customer’s facility must be designed and operated to ensure that the IHVDL at the connection point due to the new facility does not exceed the limits AHDL given by EirGrid to the customer. Background harmonic distortion levels are also presented as a table up to 40\textsuperscript{th} harmonic order. This is done for the purposes of designing the facility in accordance to the AHDL. The Transmission Impedance Loci, as seen at the Connection Point, is also provided for the customer in a R-X pane. Each locus will capture individual harmonic frequencies or bands of frequencies.
8.3 Questionnaire on existing grid codes and national standards

8.3.1 Introduction

Within this task an important aspect is to understand and establish the state of the art of the approaches regarding requirements and legislation that different network operators and countries have with respect to PQ. For that purpose, a questionnaire on range of PQ requirements and legislation in current transmission networks was developed and distributed to a number of transmission system operators (TSOs) in Europe. This section summarizes some of the key findings of that questionnaire, based on 14 responses received including responses from all MIGRATE TSO partners and responses from each synchronous zone in Europe. The aim of this section is to identify the range of existing and expected principles related to PQ requirements and legislation in transmission network and not to recommend any specific approaches or principles. The term “power quality” in this questionnaire covers the following phenomena: i) fluctuations in the rms voltage level (flicker, sags, surges); ii) imbalance between the phases (voltage or current); iii) distortions in the voltage or current waveform (harmonics, transients), and iv) frequency variations.

8.3.2 The Survey

Organization of the questionnaire

The questionnaire contained only 5 multiple choice questions, which were sent to members of various European TSOs who are involved with MIGRATE project. Questions asked were developed in a way to facilitate high response rate and provide basic, but comprehensive overview of the PQ requirements and legislation in Europe. This section analyses responses to the questions from questionnaire listed in Table 8-11.

Table 8-11: Survey questions

<table>
<thead>
<tr>
<th>No</th>
<th>Question</th>
</tr>
</thead>
<tbody>
<tr>
<td>Q1</td>
<td>Where are the requirements for Power Quality defined in your system</td>
</tr>
<tr>
<td>Q2</td>
<td>Which aspects of Power Quality are defined in relevant documents</td>
</tr>
<tr>
<td>Q3</td>
<td>Which document(s) are used for defining the Power Quality limits in your system</td>
</tr>
<tr>
<td>Q4</td>
<td>In your opinion, is there a need to define Power Quality related requirements and if yes, where should that be done</td>
</tr>
<tr>
<td>Q5</td>
<td>If Power Quality related requirements are to be defined in relevant documents, which aspects should be defined</td>
</tr>
</tbody>
</table>

Questions Q1 to Q3 are referring to situation in current transmission networks, and Q4 and Q5 ask the views in which direction the requirements for PQ should be developed.

Survey participants

Survey participants were identified by the MIGRATE WP5 members and contacted by e-mail. Objective was to receive feedback from all MIGRATE partners and other project supporting TSOs in Europe. The questionnaire was sent to the contacts by e-mail. In total, 14 responses were received,
including all MIGRATE partners and at least one response from each of the European synchronous areas.

8.3.3 The Results of the Survey

Q1: Where are the requirements for Power Quality defined in your system?
The summary of the answers to this question is shown in Figure 8-5 for all respondents. It can be seen that in all European countries the PQ requirements have been defined, mostly used option (64%) being National Grid Codes that are governmental or legislative act and somewhat less (43%) with National Grid Code that is TSO document or other TSO documents, e.g. connection agreement, separate PQ document, etc. Other options mentioned were some industry documents or directly applied standards.

Figure 8-5: Response to Q1 from all respondents – Where are the requirements for Power Quality defined in your system?

Q2: Which aspects of Power Quality are defined in relevant documents?
This question was divided into three parts for determine how different PQ aspects are defined in various countries. The questions were formed as following: i) limits for which PQ disturbances have been enclosed, ii) are there procedures available for defining/setting PQ limits for new customers, and iii) are there procedures available for compliance verification for new and existing customers.
The summary of the answers to this question is shown in Figure 8-6, in Figure 8-7 a, and in Figure 8-7 b, respectively. The analysis of the results showed that harmonics, unbalance, voltage flicker, voltage regulation and voltage dips, i.e., some of the traditionally most important PQ phenomena, remain to be of high interest (79...86%) to responding companies while voltage transients received more modest attention (57%). The other phenomena mentioned in about 14% of the responses included mostly frequency variation and interruptions The majority of TSOs (64%) have relevant...
procedures in place (defined in relevant documents and in force) for defining/setting PQ limits for new customers and for compliance verification for both new and existing customers.

![Figure 8-6: Comparison of responses to Q2 from all responses – Which aspects of Power Quality are defined in relevant documents – limits for PQ disturbances?](image)

Figure 8-6: Comparison of responses to Q2 from all responses – Which aspects of Power Quality are defined in relevant documents – limits for PQ disturbances?

![Figure 8-7: Comparison of responses to Q2 from all responses – Which aspects of Power Quality are defined in relevant documents – a) procedures for defining / setting the limits for new customers, and b) procedure for compliance verification for new and existing customers?](image)

Figure 8-7: Comparison of responses to Q2 from all responses – Which aspects of Power Quality are defined in relevant documents – a) procedures for defining / setting the limits for new customers, and b) procedure for compliance verification for new and existing customers?

**Q3: Which document(s) are used for defining the Power Quality limits in your system?**

The summary of the answers to this question is shown in Figure 8-8. The results indicate that the limits defined in transmission system documents to a large extent (43% of the respondents) correspond to the information provided in respective CENELEC or/and IEC documents. None of the answers indicate use of ENTSO-E documents or recommendations. Some TSOs (13%) indicated that CIGRE recommendations are followed while the others (17%) refer to industry guides, e.g., D-A-CH-
CZ document, or to direct contractual agreements between interested parties that are often more stringent than the standard defined limits.

Figure 8-8: Comparison of responses to Q3 from all responses – Which document(s) are used for defining the Power Quality limits in your system?

Q4: In your opinion, is there a need to define Power Quality related requirements and if yes, where should that be done?

The summary of the answers to this question is shown in Figure 8-9 and in Figure 8-10. The answers indicate that majority (86%) of respondents believe that there is a need to define Power Quality related requirements. Preferred option with respect to where these should be defined is either national Grid Codes, that are governmental act (58%), or through some form of legislation. There are also opinions (50% of the respondents) that these requirements should be defined in grid operator composed and governed grid code or other TSO internal documents (42%). Very modest number of respondents (8%) stated that following international standards is enough to define PQ requirements in their system.
Q5: If Power Quality related requirements are to be defined in relevant documents, which aspects should be defined?

The summary of the answers to this question are shown in Figure 8-11 to Figure 8-14 for all respondents. This question was separated into four parts to clarify the views on defining limits for PQ disturbances, defining procedures for setting limits for PQ phenomena, procedure for PQ monitoring, and procedure on compliance verification. The analysis of the results showed that almost all respondent stated that if the requirements related to PQ are to be defined in relevant documents then the most important PQ characteristics to be defined are harmonics (92%), unbalance (100%), voltage flicker (100%) and voltage dips (92%). Voltage regulation and voltage transients were seen
not so important receiving support of 69% and 62%, respectively. Regarding procedures for defining the limits for PQ phenomena 69% of the respondents responded that it is needed, procedure for PQ monitoring and compliance verification was supported by 62% and 85% of the respondents, respectively. Some answers also referred to setting limits and procedures for sub-synchronous oscillations and high voltage ride through.

Figure 8-11: Comparison of responses to Q5 from all responses – If Power Quality related requirements are to be defined in relevant documents, which aspects should be defined – limits for PQ disturbances?

Figure 8-12: Comparison of responses to Q5 from all responses – If Power Quality related requirements are to be defined in relevant documents, which aspects should be defined – Procedure for defining/setting the limits for different PQ phenomena for new and existing customers?
Figure 8-13: Comparison of responses to Q5 from all responses – If Power Quality related requirements are to be defined in relevant documents, which aspects should be defined – Procedure for PQ monitoring?

Figure 8-14: Comparison of responses to Q5 from all responses – If Power Quality related requirements are to be defined in relevant documents, which aspects should be defined – Procedure for compliance verification (responsibility for ensuring that the set limits are met)?
8.3.4 Conclusions

This section of the report summarises main findings of a survey on PQ requirements and legislation in transmission networks. The main conclusions arising from the analysis of the results of survey of 14 TSOs from all over Europe with all synchronous zones presented are as follows:

- Requirements for PQ in Europe are mostly defined in national legislative acts (64%) followed by TSO lead documentation (either Grid Code as a TSO document (43%) or connection agreements (43%)).
- In number of cases these documents include procedures for defining/setting limits for new customers (64%) and procedures for compliance verification (64%) for new and existing customers.
- Currently available documents include in 80% of the cases limits for harmonics, unbalance, voltage flicker, voltage regulation, and voltage dips. Limits for voltage transients are provided in less cases (57%).
- The main documents used/followed for defining PQ in respective networks are EN50160 and IEC standards (both 43%).
- With respect to defining new limits and requirements for PQ in future networks the majority of the respondents (86%) see that these should be made and preferred option is (58%) that this should be done in Grid Code as a national legislative act.
- The respondents point out that the most important PQ characteristics to be defined in future documents are harmonics (92%), unbalance (100%), voltage flicker (100%), and voltage dips (92%).
- More than two-third of the respondents point out that procedures for defining/setting limits for different PQ phenomena, procedure for monitoring, and procedure for verification should be available in these new documents. Compared to current situation procedures for compliance verification have received more support (increase from 64% to 85%).
8.4 Summary

This section included an overview of results on European approaches on PQ regulation. It included review of grid codes and relevant technical documents, that accompany the grid codes, and standards that are either power quality standards and/or have been cited in the grid codes. Furthermore, results from the feedback to a questionnaire on existing grid codes and national standards was presented.

Steady-state frequency and voltage variation, harmonic distortion, rapid voltage changes, flicker and voltage unbalance are the power quality indices that have been reviewed. Most of the grid codes available contain information about steady-state frequency and voltage variation. Allocation of harmonic distortion limits to individual customer facilities differs from country to country. A transmission node is subject to planning levels and in order to maintain those levels, the TSO allocates emission limits (individual harmonic orders and THD) to facilities connecting to that node. Challenge here is that not all grid codes specify whether the values stated are planning levels or individual customer emission limits. The limits on different voltage levels can be different but this is not the case in some of the reviewed countries. The methodology of Eirgrid’s harmonic distortion limits allocation to its users is explained thoroughly. Based on the analysis it can be concluded that harmonic distortion is the most covered PQ index other than frequency and voltage variation.

In conclusion, the requirements for power quality in national grid codes and other regulation is quite limited on one hand, but on the other hand there are some TSOs that have developed guidelines and methodology for allocating power quality limits for its customers, such as Irish TSO Eirgrid. Some of the countries do not have any limits described in their grid codes as only references to the applicable standards are given. This is the case for example in the Swiss national grid code. However, the results of the TSO questionnaire indicate that TSOs want PQ characteristics to be defined in future documents so therefore it is recommended to harmonize the PQ requirements in Europe with guidelines for TSOs. There is significant amount of work needed to be done to harmonize or set up the PQ legislation in whole European level. This requires significant cooperation and willingness to tackle this item by all parties but as a result it would be possible to have common understanding and set of requirements between networks resulting in better coordination of PQ coordination and allocation of limits between systems in future power systems. For future requirements regarding PQ more thorough recommendations are to be provided in D5.5, when mitigation methods for PQ problems are studied, and in D1.6.
9 Conclusions

This document focuses on the future characteristics of the transmission grid, where a massive penetration of the power electronic based devices will occur. The PE devices are the main components of all modern generating units of the renewable power sources (wind turbines, photovoltaics, variable speed generators etc.) as well as of devices that support the transmission network with its main function, transmission of electrical power, the FACTS devices.

The study of the impact of PE devices on the power quality (PQ) in the transmission network has been initialized with the deliverable D5.3 of the MIGRATE project, representing the present-day scenario. This document includes additional scenarios with higher share of PE-based generation units (i.e. 70%, 80% and 90%). The assessed influences are focused on the harmonic distortions of the voltage in the transmission network, voltage and frequency variations.

From the analysed simulation results it was identified that the voltage variations in the system are small. The standard deviation reaches a maximum of 0.002 p.u. for a case with 90 % SNSP. The small voltage variations are linked to the voltage control employed by the PE-interfaced generation units with a PCC at 110 kV or higher. A sensitivity analysis reveals that voltage variations increase if fewer converters of PE-interfaced generation units control the voltage. It is shown that the standard deviation for voltage reaches a maximum of 0.012 p.u. if voltage control is disabled for all PE-interfaced generation units for a case with 90 % SNSP.

Regarding system frequency variations, the following conclusions can be made. The frequency limits for normal operation are not violated in the studied use cases. However, there is a positive correlation between the level of SNSP and frequency variations. When referring to a level of 60 % SNSP as the reference case, the standard deviation of the system frequency increases by 145 % for a use case with 90 % SNSP.

One reason for these frequency variations is the fluctuating feed-in of active power by wind farms. Furthermore, PE-interfaced generation units replace synchronous generators, which contribute to primary control and system inertia. At the same time, the remaining synchronous generators are forced to vary their active power output more in order to regulate the system frequency. This is also pointed out by the simulation results showing that the amount of provided balancing energy per MVA of installed capacity of operating synchronous generators grows with a rising level of SNSP. It becomes clear that under such an operating condition also the wear and tear of synchronous generators increases.

From the study, three recommendations can be made. First, the control of system frequency in normal operation should also include further generation units in the power system. As wind farms play an increasingly important role in the power system, they should be involved in frequency support in the future.
Second, with Fourier transform it was shown that the system frequency deviations are dominated by frequency components below 50 mHz, i.e. in the time range of seconds to minutes. Therefore, the mitigation methods aiming at smoothing the system frequency should support primary control.

Third, the characteristics of eligible mitigation methods lead to different requirements for their implementation. The mitigation method can follow a global coordination scheme or a local approach, for which the method would be implemented at specific units individually. The chosen approach determines how it can be realised, e.g. if it needs to be formulated as a general grid code requirement or if it should be specified on an individual basis. Thus, the approach of how to implement the mitigation methods has to be investigated.

The power system was analysed also by means of harmonic distortion. Based on the results obtained with the simulated test power system, it can be identified and confirmed that the harmonic propagation through the power system is highly influenced by the power system topology and the structure of the loads. The values of total harmonic distortion and individual harmonic distortion are analysed for different study cases. One of the major cognitions of the studies is the high importance of having highly accurate and realistic data for the analysed power system since the results are highly dependent on the assumed values, i.e. exact load structure for each network load or exact harmonic injections would be favourable input data for such analysis.

The power electronic interfaced loads and generators involve high level of uncertainties in both general performance and harmonic emission. The analysis performed using different simulation cases to illustrate the methodology highlighted that the harmonic performance of a power system is an individual characteristic influenced by different uncertainties. It seems though that there are busses in the network that are typically more sensitive to harmonics than the others irrespectively of the level of harmonic injection and operating condition of the network. For the purpose of system planning and identification of potentially high risk areas in terms of high harmonic levels, as accurate as possible input data are required.

Beside the power quality analyses, this document includes an overview of results on European approaches on PQ regulation. It includes review of grid codes and relevant technical documents, that accompany the grid codes, and standards that are either power quality standards and/or have been cited in the grid codes. Furthermore, results from the feedback to a questionnaire on existing grid codes and national standards was presented.

In conclusion, the requirements for power quality in national grid codes and other regulation is quite limited on one hand, but on the other hand there are some TSOs that have developed guidelines and methodology for allocating power quality limits for its customers, such as Irish TSO Eirgrid. Some of the countries do not have any limits described in their grid codes as only references to the applicable standards are given. The results of the TSO questionnaire indicate that TSOs want PQ characteristics to be defined in future documents so therefore it is recommended to harmonize the PQ requirements in Europe with guidelines for TSOs. There is significant amount of work needed to be done to
harmonize or set up the PQ legislation in whole European level. This requires significant cooperation and willingness to tackle this item by all parties but as a result it would be possible to have common understanding and set of requirements between networks resulting in better coordination of PQ coordination and allocation of limits between systems in future power systems. For future requirements regarding PQ more thorough recommendations are to be provided in D5.5, when mitigation methods for PQ problems are studied, and in D1.6.
10 References


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11 Appendix

11.1 Parameters for IEEEG2 turbine governor model

Figure 11-1: IEEEG2 turbine governor model

Table 11-1: IEEEG2 generic parameters

<table>
<thead>
<tr>
<th>Speed droop $R$</th>
<th>Governor lag time $T_1$</th>
<th>Governor lead time $T_2$</th>
<th>Water starting time $T_4$</th>
<th>Gate actuator time constant $T_3$</th>
</tr>
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<tr>
<td>4.5 %</td>
<td>0.5 s</td>
<td>0.35 s</td>
<td>0.1 s</td>
<td>0.05 s</td>
</tr>
<tr>
<td>Water starting time $T_4$</td>
<td>Minimum active power $P_{\text{min}}$</td>
<td>Maximum active power $P_{\text{max}}$</td>
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<td></td>
</tr>
<tr>
<td>0.3 p.u.</td>
<td>1 p.u.</td>
<td></td>
<td></td>
<td></td>
</tr>
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</table>
11.2 Additional figures

Figure 11-2: Case 1 – Aggregated active power demand

Figure 11-3: Case 1 – Aggregated reactive power feed-in of PE-interfaced generation units
Figure 11-4: Case 1 – Aggregated reactive power feed-in of synchronous generators

Figure 11-5: Case 2 – Aggregated active power demand
Figure 11-6: Case 2 – Aggregated reactive power feed-in of PE-interfaced generation units

Figure 11-7: Case 2 – Aggregated reactive power feed-in of synchronous generators
Figure 11-8: Case 3 – Aggregated active power demand

Figure 11-9: Case 3 – Aggregated reactive power feed-in of PE-interfaced generation units
Figure 11-10: Case 3 – Aggregated reactive power feed-in of synchronous generators

Figure 11-11: Case 3.1 – Aggregated active power demand
Figure 11-12: Case 3.1 – Aggregated reactive power feed-in of PE-interfaced generation units

Figure 11-13: Case 3.1 – Aggregated reactive power feed-in of synchronous generators

Figure 11-14: Case 3.2 – Aggregated active power demand
Figure 11-15: Case 3.2 – Aggregated reactive power feed-in of PE-interfaced generation units

Figure 11-16: Case 3.2 – Aggregated reactive power feed-in of synchronous generators