IMPACT OF SMALL PRODUCERS ON POWER QUALITY IN DISTRIBUTION GRIDS
BASED ON ELEKTRILEVI OÜ GRID

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ABSTRACT
The amount of distributed generation (DG) units in distribution grids has been increasing. DG has a potential for energy savings but can also have an effect on power quality, both positive and negative. This paper gives an overview of the connection procedure for DG units to Elektrilevi OÜ grid, the possible effects of DG units on power quality and present the results of practical measurements carried out at 11 DG units in Elektrilevi OÜ distribution grid.

INTRODUCTION
Elektrilevi OÜ is a distribution grid operator in Estonia, covering about 90% of the country. The growing interest in distributed generation has led to an increased number of DG units in the Elektrilevi OÜ grid. Since 2010 there have been 33 new distributed generation units connected and there are almost as many in construction or being connected [1].

One of the aspects of distributed generation connections is the effect on local power quality. Some research has been carried out in Estonia regarding this topic: analysis of power quality problems in low voltage networks [2], measurements at wind turbines [3] and solar panel installations [4]. The aim of this paper is to use measurement data from practical measurements at 11 producers to analyze the current situation of power quality and the effects of the DG units to see if they have an effect on local power quality and if the current connection procedure is adequate.

CONNECTING SMALL PRODUCERS TO THE DISTRIBUTION GRID
In Estonia DG units are usually divided into four groups based on their production capacity:
- Micro producers with a production capacity up to 11 kW
- Very small producers with a production capacity of 11 kW up to 200 kW
- Small producers with a production capacity of 200 kW up to 5 MW
- Large producers with a production capacity over 5 MW

This paper focuses on small producers with a production capacity of 200 kW up to 5 MW. The connection process for distributed generation units to Elektrilevi OÜ distribution grid consists of four steps [5]:
- Application to connect and network analysis
- Signing the connection contract
- Commissioning the electricity production equipment
- Signing the network services contract

During the first step of the process the client provides an application to connect, that has the main information about the generation unit. Based on this information a network analysis of the following aspects is conducted [6]:
- Rapid voltage changes
- Supply voltage variations
- Flicker levels
- Current harmonics
- Short-circuit currents
- Transmission capacity

Rapid voltage changes ($\Delta u$) that are caused by the switching of the DG unit cannot exceed 4% at the connection point. This is assessed based on the DG unit’s apparent power ($S_n$), power factor angular shift at startup ($\varphi$), starting current multiplier ($k$), the grid’s short-circuit power ($S_{kv}$) and fault impedance angle ($\psi$).

\[
\Delta u = k \cdot \frac{S_n}{S_{kv}} \cdot \cos(\varphi + \psi)
\]

For wind turbines the following formula is used:

\[
\Delta u = k_u(\psi) \cdot \frac{S_n}{S_{kv}}
\]

Supply voltage variations ($\Delta u_L$) caused by the DG unit cannot exceed 4%. The variations are calculated separately for reactive power consumption and production based on the DG unit’s apparent power and power factor angular shift at startup and the grid’s short-circuit impedance active ($R_{kv}$) and reactive parts ($X_{kv}$) and nominal voltage ($U_n$).

\[
\Delta u_L = \frac{S_n(R_{kv} \cos(\varphi) \pm X_{kv} \sin(\varphi))}{U_n^2}
\]

The long-term flicker levels emitted by the DG unit cannot exceed 0.5 in low voltage and 0.25 in medium voltage grid. This is calculated based on the flicker coefficient ($c_{fär}$).

\[
P_{lt} = c_{fär} \cdot \frac{S_n}{S_{kv}}
\]

Current harmonic levels are assessed based on the DG unit’s type testing results and compared to allowed levels.
Table 1 Current harmonic limits A/MVA

<table>
<thead>
<tr>
<th>Nr</th>
<th>Uc [kV]</th>
<th>Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0,4</td>
<td>Wind, IGBT inverter</td>
</tr>
<tr>
<td>2</td>
<td>6,3</td>
<td>Wind, IGBT inverter</td>
</tr>
<tr>
<td>3</td>
<td>10,5</td>
<td>Cogeneration, async. generator</td>
</tr>
<tr>
<td>4</td>
<td>10,5</td>
<td>Cogeneration, sync. generator</td>
</tr>
<tr>
<td>5</td>
<td>10,5</td>
<td>Cogeneration, async. generator</td>
</tr>
<tr>
<td>6</td>
<td>0,23</td>
<td>Diesel and wind, sync. and async.</td>
</tr>
<tr>
<td>7</td>
<td>10,5</td>
<td>Wind, async. generator</td>
</tr>
<tr>
<td>8</td>
<td>10,5</td>
<td>Wind, async. generator</td>
</tr>
<tr>
<td>9</td>
<td>10,5</td>
<td>Cogeneration, sync. generator</td>
</tr>
<tr>
<td>10</td>
<td>15,7</td>
<td>Biogas, sync. generator</td>
</tr>
<tr>
<td>11</td>
<td>10,5</td>
<td>Biogas, sync. generator</td>
</tr>
</tbody>
</table>

Sort-circuit current analysis compares the dynamic and thermal ability of the grid elements to the combined short-circuit currents of the system and the DG unit. Transmission capacity analysis compares the maximum allowed loading of the grid elements to the DG unit’s maximum production.

**SMALL PRODUCERS’ POSSIBLE EFFECTS ON POWER QUALITY**

Small producers can have an effect on all aspects of power quality. They can be both positive and negative. The possible effects of a producer depend mostly on the size of the producer compared to the grid’s short-circuit capacity. Also DG units have more effect on local phenomena such as supply voltage variation, events, flicker etc. DG units are usually not large enough to have significant effect on system frequency and in Estonia islanding is not allowed, but with larger units and a higher ratio of DG units there can be problems [7].

DG units can cause problems with supply voltages due to complications in voltage regulation [8] or due to producing only active power, which can cause overvoltages in nearby substations [7]. The problems get more difficult if the DG unit is very large and/or very deep in the grid [9]. There can also be a positive effect, especially if DG units are allowed to produce reactive power to stabilize the voltage levels [10].

Flicker can be caused by different reasons, for example small changes in the output of the DG unit can cause voltage regulators to constantly switch levels which increases flicker levels [11]. Wind turbines can cause flicker due to wind and tower turbulence [12].

Harmonic problems were serious with earlier thyristor based inverters, but modern inverters with IGBT-transistors and pulse width modulation have reduced these problems [11]. Generators can also produce different harmonics, depending on their construction either 3rd or 5th and 7th. With the wider usage of power electronics there are also higher levels of even- and interharmonics, especially of higher orders [13].

Synchronous generator usually have a positive effect on voltage event duration and depth, especially if they are allowed to produce reactive power [14]. Asynchronous generator on the other hand usually have a negative effect, due to their need for reactive power that either is taken from the grid or has to be generated locally. This can lead to increased reactive power consumption from the grid during a voltage dip, thus making the dip longer and deeper.

**MEASUREMENT LOCATIONS AND METHODS**

The measurements were carried out at 11 different measurement points in 9 substations. The main information of the measurement points is presented in table 1.

The measurements were carried out using stationary power quality analyzers that comply with IEC 61000-4-30 class A requirements and using voltage and current transformers with 0,5 accuracy class.

The measurement data was collected from 2013 week 24 to 2014 week 14, that is during 44 weeks. For some measurement points the DG units were connected later and thus the measurement data is not available for the whole period. MP1 and MP2 measurements start from 05.02.2014, MP3 measurements start from 02.08.2014. MP7 data is missing between 2013 weeks 34 and 39 due to equipment malfunction.
Measurement results for continuous phenomena are presented using the Power Quality Index (PQI) method. The PQI method has been chosen because measurement results from different voltage levels and systems need to be shown on the same graphs and compared. Also the PQI method gives a simpler overview.

The PQI method uses a relative value that indicates the real value relative to the EN 50160 limit for the value. For example THD<sub>U</sub> values of 3.8% and 10% correspond to PQI values of 47.5% and 125%.

For all continuous parameters a summary PQI value is also calculated according to the following rules:
- If no parameter exceeds the limits, then the maximum individual PQI value is chosen
- If one or more parameters exceed the limits, then the summary PQI value is equal to one plus the sum of the exceedances

For example if the PQI values for flicker and harmonics are 1.25 and 1.3 then the summary PQI value would be 1.55 (1 plus the sum of 0.25 and 0.3).

**MEASUREMENT RESULTS**

According to the measurement results the overall level of power quality is good with the average PQI value of 44%. The summary results for all continuous parameters are presented in table 2.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Avg PQI</th>
<th>Max PQI</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency&lt;sup&gt;1&lt;/sup&gt;</td>
<td>4.5%</td>
<td>(0.5%&lt;sup&gt;2&lt;/sup&gt;)</td>
</tr>
<tr>
<td>Frequency&lt;sup&gt;2&lt;/sup&gt;</td>
<td>2.6%</td>
<td>(1.0%&lt;sup&gt;3&lt;/sup&gt;)</td>
</tr>
<tr>
<td>Supply voltage variations&lt;sup&gt;1&lt;/sup&gt;</td>
<td>18.5%</td>
<td>66.7%</td>
</tr>
<tr>
<td>Supply voltage variations&lt;sup&gt;2&lt;/sup&gt;</td>
<td>20.1%</td>
<td>35.5%</td>
</tr>
<tr>
<td>Flicker</td>
<td>43.6%</td>
<td>150.0%</td>
</tr>
<tr>
<td>Asymmetry</td>
<td>22.2%</td>
<td>50.5%</td>
</tr>
<tr>
<td>THD&lt;sub&gt;U&lt;/sub&gt;</td>
<td>17.4%</td>
<td>46.2%</td>
</tr>
<tr>
<td>Harmonics</td>
<td>5.4%</td>
<td>57.0%</td>
</tr>
</tbody>
</table>

<sup>1</sup> Limit for 100% of time  
<sup>2</sup> Limit for 99.5%, 99% or 95% of time  
<sup>3</sup> Results for MP6 using limits for systems with no synchronous connection to an interconnected system

From table 2 it can be observed that flicker has the highest PQI values for both average and maximum. The EN 50160 limits have been exceeded only for flicker. During the measurement period there were 6 weeks when the flicker levels were above the allowed limits of EN 50160.

It can be also seen that all average PQI values for individual parameters are less than the resulting average summary PQI value of 44%. This shows that individual PQI values are not related and for different weeks different parameters have higher values.

**Supply voltage variations**

From the measurement results it can be concluded that the supply voltage variation is not very high – the average PQI value is 18.5% and the maximum is less than 67%. The variations are somewhat higher at measurement points with asynchronous generators (figure 1). This can be caused by asynchronous generators’ need for reactive power compensation. If the compensation is inaccurate or done in large steps the reactive power flows to and from the grid can have variations that amplify voltage variations in the grid.

![Figure 1 Supply voltage variations at measurement points with asynchronous generators](image1)

The results are in accordance with previous research and problems with voltage variations were not detected. Overall the DG units have not had a negative effect on voltage variations, but the possible effect from asynchronous generators needs further analysis and measurements.

**Voltage harmonics and flicker levels**

The average harmonic levels are low with the average PQI value of 17.4% for THD and 5.4% for individual harmonics. Maximum values were under 47% and 57% respectively. The harmonics levels are somewhat higher at MP6 with an average value of 35% (figure 2). This is likely caused by the grid at MP6 not being synchronously connected to an interconnected system and being very small.

![Figure 2 Harmonic levels at measurement points MP1, MP2 and MP6](image2)
The flicker levels are higher and there are 6 weeks when the limits of EN 50160 are exceeded in some of the measurement points (figure 3). The average value for flicker is 43.6%. The limits are exceeded at measurement points MP5, MP8 and MP9.

Figure 3 Flicker levels

Analyzing the correlation between a measurement point’s active power and flicker levels shows that higher flicker levels are not related to the DG unit’s output (figure 4). This suggest that the DG units are not causing elevated levels of flicker but rather the flicker levels are due to some other grid phenomena.

Figure 4 Flicker and active power scatter plot for measurement point MP5

Voltage dips and swells

For voltage events the measurement data shows different results for different technologies used. At measurement points with inverters there is no difference in voltage events’ durations and depths. At measurement points with an asynchronous generator there are more voltage events with a duration of 1 to 2 seconds when the generator is working (figure 5). This suggest that the generator causes a longer recovery time which could be due to the local reactive power compensation.

Figure 5 Voltage events at measurement points with asynchronous generator

At measurement points with a synchronous generator there are fewer events that are below the ITIC lower limits when the generator is working (figure 6). This suggest that the generator is having a positive effect on voltage events, helping to sustain higher voltages and making dips shorter.

Figure 6 Voltage events at measurement points with synchronous generators

Long-term effects and seasonal variations

The measurement results show no variations between different seasons but the data does show some improvement in general levels of power quality towards the end of the measurement period. During the first 26 weeks of measurements the average PQI value is 50%, but during the latter 18 weeks the average value is 38%.

Figure 7 Summery PQI values
CONCLUSIONS

The measurement results show that overall the DG units have not had a negative effect on power quality in the Elektrilevi OÜ distribution grid and the overall power quality level is good. There are possible negative effects from asynchronous generators on supply voltage variations and voltage dips, but further measurements and analysis is needed. During the measurement period only flicker levels were above the limits set by EN 50160, but there was no correlation between DG units’ operation and flicker levels.

There is also measurement data showing positive effects of synchronous generators on voltage dip duration and depth, but to analyze DG units’ positive effects the measurements have to include data from before the connection of the DG units. For future research comparative analysis for before and after should be done and measurement data should also be compared to simulation results.

REFERENCES