POWER QUALITY PROBLEMS IN LOW VOLTAGE NETWORKS OF ESTONIA

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ABSTRACT
This paper is focused on supply voltage quality in low voltage (LV) networks of Estonia. Measurement results and analysis methods of supply voltage quality characteristics implementing stochastic theory are presented. Problems of supply voltage quality – voltage magnitude, voltage level, voltage sags, harmonic distortions of voltage and unbalance are discussed.

INTRODUCTION
The subject is power quality, particularly supply voltage quality. Supply voltage quality problems are often discussed regarding disturbances and failures. Still, voltage quality parameters like the supply voltage level, harmonic voltages and voltage unbalance affect directly active and reactive power consumption and power losses in LV power systems, particularly in induction motors, transformers, cable lines and capacitors. The problems of monitoring and optimizing voltage quality in LV networks are actual and have been discussed in several publications, [1]–[6].

PROBLEMS OF VOLTAGE QUALITY
Standards that define the quality of supply voltage in low voltage (LV) networks have been present in most countries for some time already. The latest version of the European standard EN 50160 has been released in 2007 and adopted also in Estonia as EVS-EN 50160:2007, [7]. The standard describes electricity as a product and gives the main voltage quality characteristics under normal operating conditions as follows:
- nominal frequency \( f \) and frequency variations \( \Delta f \),
- nominal voltage and voltage variations \( U_n \) and \( U_{\text{var}} \),
- voltage events (voltage sags and swells) \( U_{\text{min}} \) and \( U_{\text{max}} \),
- individual harmonic voltages \( U_h \) and total harmonic voltage distortions \( THD_U \),
- flicker \( P_f \),
- unbalance in a three phase system \( K_{ug} \).

The standard states for example that the supply voltage has to remain in the range of \( \pm 10\% \) of the rated operating voltage. Also it is stated that total harmonic distortions have to remain below 8% and limit values for each individual harmonic voltages are given. Operating the LV network close to these limit values will be unfavourable for the customer causing either disturbances or additional power consumption, power losses and consequently extra costs. Therefore the problems arise – what are the characteristics of voltage quality in LV networks? What are the optimum voltage level characteristics and the range for voltage level variations? What are the optimum limit values of harmonic distortions and unbalance?

VOLTAGE QUALITY MEASUREMENTS
During the years from 2000 up to 2011 numerous studies have been performed to measure and analyze the supply voltage quality parameters in LV networks of Estonia, Fig. 1. The objectives of these studies have been, on the one hand to estimate the current situation about supply voltage quality and on the other hand to find the optimum voltage quality parameters regarding power consumption and power losses of the customers. The voltage quality analyzer was connected to the PCC or LV busbars of the local substation.

The method of voltage quality data analyses is based upon stochastic theory. Calculating the probability density function and probability distribution function enables to draw conclusions about necessary measures to adjust the voltage quality – adjustment of transformer taps, reinforcing the supply circuit, improving reactive power compensation, installing passive filters.

In normal operation voltage at the customer is determined by a series of voltage drops in the supply system. These voltage drops are of a stochastic character and therefore could be described by a normal distribution, where the probability density function is:

\[
f(U) = \frac{1}{\sigma\sqrt{2\pi}} \cdot \frac{(U - \bar{U})^2}{2\sigma^2},
\]

(1)

where \( \bar{U} \) – expected value of voltage magnitude;
\( \sigma \) – standard deviation.

Problems of optimizing voltage levels have been discussed in [8]–[13]. In case the optimum voltage level is 230 V \( \pm 10\% \) we get the whole range as 207–253 V. Such a range would satisfy the customer regarding service failures, but could not serve as optimum voltage level regarding power consumption, power losses and the service time of equipment. The following approach for optimum voltage level has been suggested in [8], [9].
The optimum voltage level average value should be equal to rated voltage, or somewhat lower. The dispersion of voltage values should be much narrower than in the standard, e.g., the range for variations should be ±2.5% up to ±3%. Thus we could specify the optimum voltage level or high quality voltage level parameters as, e.g., 230 V ±2.5% or 230V +2% and –4%, Fig. 2.

**MEASUREMENT RESULTS OF VOLTAGE LEVELS IN LV NETWORKS**

The objective of voltage level measurements was to study the actual voltage levels and optimization of voltages when installing shunt capacitors for reactive power compensations. The supply voltages have been recorded with the voltage quality analyzer LEM-Memobox. The instrument measures and stores phase voltages as mean values of 10-minutes time intervals throughout one week period; also, the minimum and maximum voltage values in each 10-minutes interval. Statistical data of measurement results of voltage level parameters are given in Table 1.

Table 1. Statistical measurement results of voltage levels in industrial LV networks of Estonia

<table>
<thead>
<tr>
<th>Parameter</th>
<th>$U_{\text{min}}$ (V)</th>
<th>$U_{5%}$ (V)</th>
<th>$U_{95%}$ (V)</th>
<th>$U_{\text{max}}$ (V)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dispersion $D$</td>
<td>6.27</td>
<td>5.12</td>
<td>4.78</td>
<td>5.32</td>
</tr>
<tr>
<td>Standard deviation $\sigma$ (V)</td>
<td>2.56</td>
<td>2.26</td>
<td>2.19</td>
<td>2.31</td>
</tr>
<tr>
<td>Absolute deviation $K$ (V)</td>
<td>5.06</td>
<td>4.13</td>
<td>4.00</td>
<td>4.32</td>
</tr>
<tr>
<td>Mean value $U_{\text{mean}}$ (V)</td>
<td>221.6</td>
<td>226.5</td>
<td>231.7</td>
<td>236.3</td>
</tr>
<tr>
<td>Minimum value $U_{\text{min}}$ (V)</td>
<td>204.0</td>
<td>213.0</td>
<td>220.5</td>
<td>223.0</td>
</tr>
<tr>
<td>Maximum value $U_{\text{max}}$ (V)</td>
<td>236.0</td>
<td>239.0</td>
<td>242.0</td>
<td>250.0</td>
</tr>
</tbody>
</table>

Fig. 3 shows the probability density distribution of measured voltage level values (10 min interval values) and the distribution according to standard EN 50160. For example, one could see that the highest probability of maximum voltage levels is 240 V, but the distribution is in the range of 220 V – 260 V. Also, one could see that the voltage level average values are distributed very close to normal distribution, while the voltage level minimum and maximum values have a higher deviation from normal distribution. In addition, one can also see that nearly all voltage level values correspond to the requirements of the standard EN 50160. So the standard does not help to specify the optimum voltage level values.

**VOLTAGE SAGS**

The majority of voltage events that occur in LV networks are voltage sags (voltage dips). Problems related to voltage sags are thoroughly discussed in [14], [15]. Usually the duration of voltage sag is between 10 ms and 3 s. The majority of voltage sags are caused by induction motor starting. Depth of these sags is up to 85% from rated voltage and the duration is between 0.2 s up to 2 s. Voltage sags are also caused by short-circuits and failures in the distribution or transmission network. Duration and depth of these sags is depending upon the location of the fault and means to correct the fault. Transmission network failures are usually of short duration between 50 and 100 ms and the depth is up...
to 60% of rated voltage. Failures in distribution networks cause sags between 40% and 80% of rated voltage with duration between 0.1 and 1 s, [14]. The duration and depth of voltage sags in LV industrial network are shown in Fig. 5.

The cumulative distribution curves of total harmonic distortion values are shown in Fig. 6. As could be seen the average value for $THD_u$ is quite low, only 2.7%. Fig. 6 shows, that about 30% of measured networks exceed the recommended $THD_u$ value of 5% and about 15% of networks exceed the 8% level.

The probability distribution functions of total harmonic distortions $THD_u$ in LV industrial networks of Estonia.

VOLTAGE UNBALANCE

Unbalanced state of voltages is calculated using the method of symmetrical components. A three phase system could be described as a sum of three phasor systems – positive, negative and zero sequence phasors $U_1$, $U_2$ and $U_0$. Voltage unbalance is expressed by unbalance factors, where the negative-sequence factor $K_{2U}$ is the ratio between negative-sequence and positive-sequence voltage components and the zero sequence factor $K_{0U}$ is the ratio between zero-sequence and positive-sequence components:

$$K_{2U} = \frac{U_2}{U_1} \times 100\% \quad ; \quad K_{0U} = \frac{U_0}{U_1} \times 100\% \quad (3)$$

The average value of the unbalance factor $K_{2U}$ is 0.8 as for the 95% values and 1.0 as for the maximum values. From Fig. 7 one could see that nearly all measurement results comply with the standard [7], but about 30% of networks exceed the recommended 1% unbalance level as for maximum values.

The probability distribution function of negative-sequence voltage unbalance factor $K_{2U}$ in LV industrial networks of Estonia.
CONCLUSIONS

1. Frequency of the supply voltage has been very stable in Estonia as well as in other Baltic states, the frequency deviations are up to ±0.1% from rated frequency 50 Hz.
2. The supply voltage level, harmonic voltages and voltage unbalance are the basic factors affecting power consumption and power losses in LV networks. A practical analysis method is introduced, where the probability density and probability distribution functions are used.
3. The optimum voltage level average value should be equal to rated voltage, or somewhat lower but not higher. The dispersion of voltage level values should be much narrower than in the standard. Thus we could specify the optimum voltage level as for example 230 V ± 2.5% or 230V ± 2% and – 4%.
4. The average voltage level in LV networks of Estonia is often too high. About 30% of measurement sites have it higher than 235 V. The dispersion of voltage level is too high as well. The reasons are improper position of the tap-changer of transformers, insufficient power rating of power supply, missing shunt-capacitors, missing filters for harmonic currents and in some cases high impedance of neutral conductor and asymmetric loads.
5. Installation of power-factor correction shunt capacitors in a LV network will result in increased voltage level and reduced dispersion of voltage values. Therefore the supply transformer tap-changer should be adjusted to avoid an increase in active power consumption.
6. Most of the voltage events in LV networks are voltage sags in the range of 0.85 – 0.9 from rated voltage. These sags do not cause problems mostly. The sags causing problems are deeper than 85% of rated voltage and caused by failures in HV and MV networks. The average frequency of such sags has been 2 – 3 times per week.
7. Harmonic distortions of voltage have been increasing in Estonia. The limit value of THDv, 8% is exceeded by 15% of measurement sites. The recommended value of THDv, 5% is exceeded by 30% of measurement sites. The dominating harmonics in the spectrum are h5, h7, h3, h11, h13 and h17.
8. The limit values of harmonic voltages in the standard EN 50160 are rather too high regarding additional harmonic losses in LV networks and could not serve as guidelines for optimizing the system performance. The optimum limit value for THDv should be up to 5%.
9. Regarding unbalance factor K30, almost all measurement results comply with the standard as for 95% of time intervals. As for 100% of time intervals 7% of sites exceed the 2% limit value and 30% of sites exceed the recommended 1% value.

REFERENCES