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 Δf,
- nominal voltage and voltage variations U_n and ΔU,
- voltage events (voltage sags and swells) $U_{\min}$ and $U_{\max}$,
- individual harmonic voltages U_h and total harmonic voltage distortions THD_u,
- flicker P_{lt},
- unbalance in a three phase system K_{2U}.

The standard states for example that the supply voltage has to remain in the range of ±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.

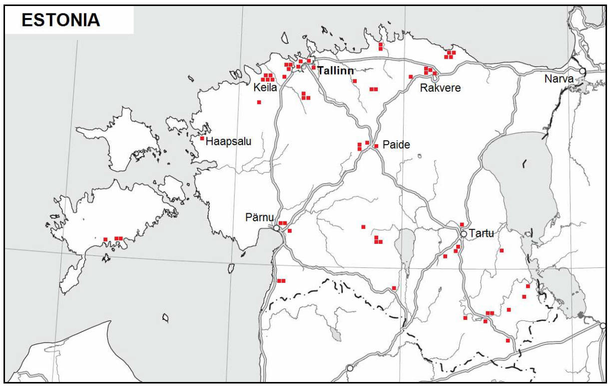

Figure 1. Location of supply voltage quality measurement sites in LV industrial networks of Estonia.

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:

$$f(U)=\frac{1}{\sigma\sqrt{2\pi}}e^{-\frac{(U-\bar{U})^2}{2\sigma^2}}, \quad (1)$$

where $\bar{U}$ – expected value of voltage magnitude;
σ − standard deviation.

Problems of optimizing voltage levels have been discussed in [8]–[13]. In case the optimum voltage level is 230 V ±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.

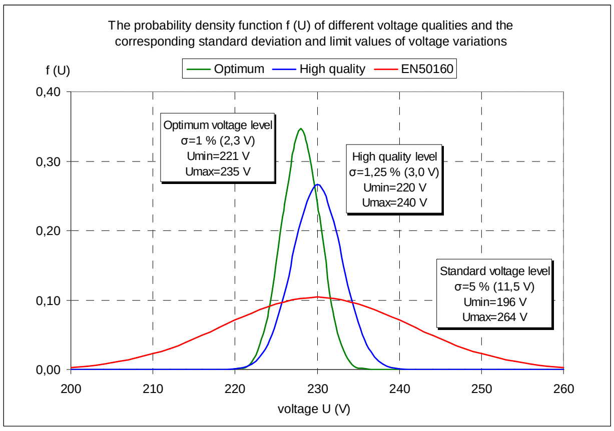

Figure 2. The probability density functions f(U) of different voltage level qualities.

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

Parameter	U_{min}	$U_{5\%}$	$U_{50\%}$	$U_{95\%}$	U_{max}
Dispersion D	6.57	5.12	4.78	5.32	6.00
Standard deviation σ, (V)	2.56	2.26	2.19	2.31	2.45
Absolute deviation K(V)	5.06	4.13	4.00	4.32	4.49
Mean value U_{mean} (V)	221.6	226.5	231.7	236.3	239.0
Minimum value U_{min} (V)	204.0	213.0	220.5	223.0	224.0
Maximum value U_{max} (V)	236.0	239.0	242.0	250.0	254.0

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.

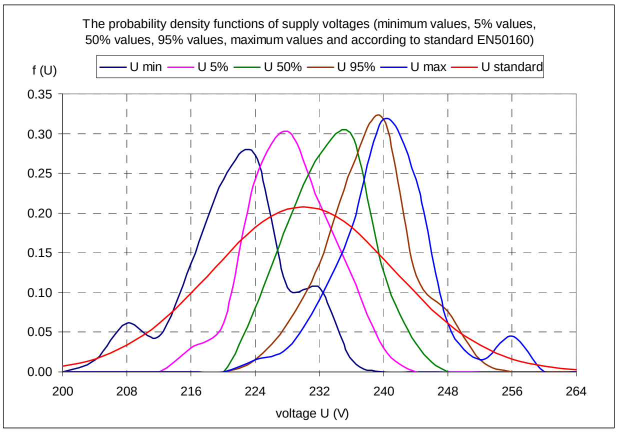

Figure 3. The probability density functions of voltage level measurement results in LV industrial networks of Estonia.

LV networks often include shunt capacitors to improve the power factor and to reduce the load current. Still, using capacitors has despite of well-known benefits also features that affect active power consumption in the whole LV system, [11], and [13]. One of the features is the increased voltage level. As an example the density curves of supply voltage with capacitors on and off and according to standard are shown in Fig. 4. As appears the use of capacitors increases the voltage level, whereas the dispersion is considerably reduced. So, installation of shunt capacitors into the LV system should be followed by voltage level adjustment to achieve the expected results in energy savings.

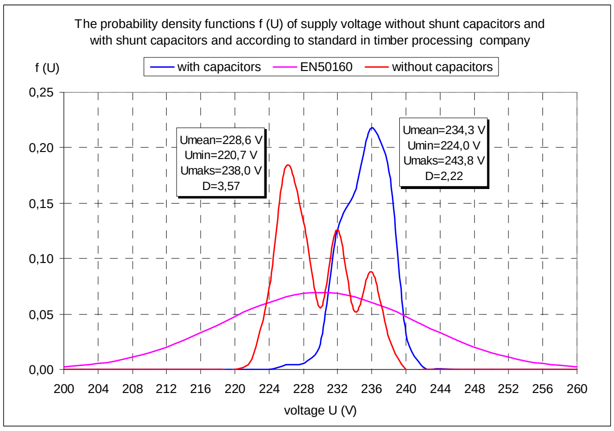

Figure 4. The probability density of supply voltage level values when using shunt capacitors.

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.

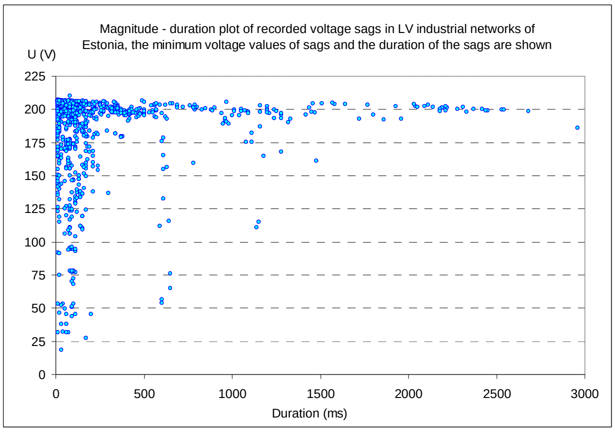

Figure 5. Scattered diagram of voltage sags in LV networks.

What is done to overcome voltage sags? Increasing the voltage level is by no means a good solution to overcome voltage sags, although it might help to overcome sags caused by induction motor starting. Well-known means to damp the inrush current of motors should be used instead. As for disturbances caused by voltage sags from HV network failures the increased voltage level does not help to cope with this type of sags in any way. Reconfiguring or rebuilding and improving the distribution network are required to reduce network failures.

HARMONIC DISTORTIONS OF SUPPLY VOLTAGE

Harmonic distortions of supply voltage cause additional losses in the consumer network. These losses include operating costs and aging costs. The studies described in [16]–[19] show clearly that operating losses caused by harmonic distortions are not negligible.
Harmonic distortions in the supply voltage are characterized by harmonic voltages at a specific harmonic frequency U_h in relation to the fundamental voltage U_1 and by total harmonic distortion factor THD_u:

$$THD_u = \frac{\sqrt{\sum_{h=2}^{\infty} (U_h)^2}}{U_1} . \qquad (2)$$

Statistical data of measurement results of total harmonic distortions of voltage are given in Table 2.

Table 2. The measurement results of total harmonic distortion THD_u statistical values

Parameter	THD_u min	THD_u 5%	THD_u 50%	THD_u 95%	THD_u max
Dispersion *D*	0.73	0.90	2.11	2.31	2.79
Absolute deviation *K*, %	0.49	0.62	1.56	1.86	2.20
THD_u mean value, %	1.26	1.60	2.70	3.80	4.80
THD_u minimum value, %	0.39	0.53	0.72	1.05	1.39
THD_u maximum value, %	4.96	5.46	7.81	9.81	13.85

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.

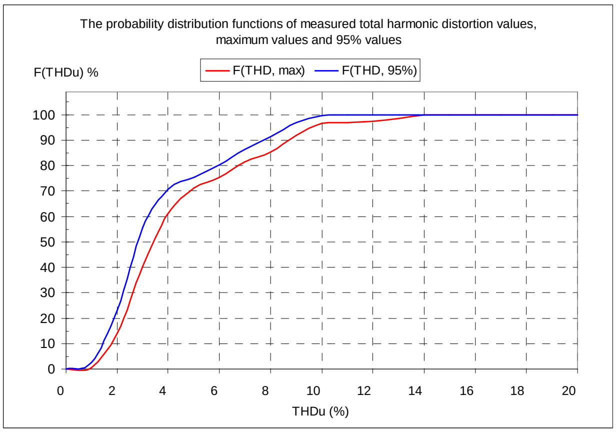

Figure 6. The probability distribution functions of total harmonic distortions THD_u in LV industrial networks of Estonia.

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:

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

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.

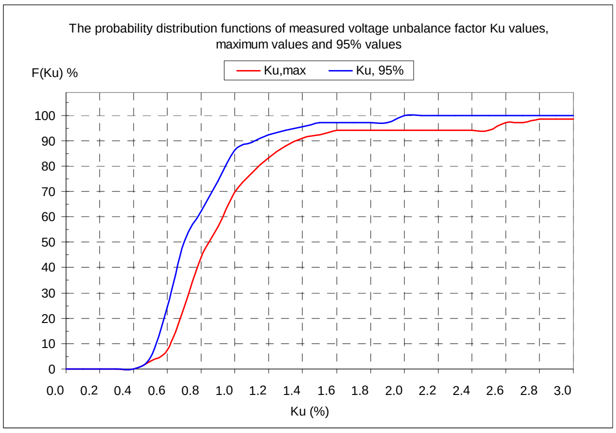

Figure 7. The probability distribution function of negative-sequence voltage unbalance factor K_{2U} in LV industrial networks of Estonia.

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 analyses 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 THD_u 8% is exceeded by 15% of measurement sites. The recommended value of THD_u 5% is exceeded by 30% of measurement sites. The dominating harmonics in the spectrum are *h*5, *h*7, *h*3, *h*11, *h*13 and *h*17.
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 THD_u should be up to 5%.
9. Regarding unbalance factor K_{2U} 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.

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