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Supply voltage quality in low voltage industrial networks of Estonia

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Abstract. This paper is focused on the measurement and analysis of supply voltage quality in low voltage industrial power systems in Estonia. A practical method for analysis of supply voltage quality parameters, implementing stochastic theory, is discussed. Measurement results of supply voltage quality parameters – voltage magnitude, voltage events, harmonics, flicker and unbalance in industrial 0.4 kV power systems of Estonia – are shown.

Key words: supply voltage quality, voltage magnitude, voltage level, harmonics, flicker, unbalance.

1. INTRODUCTION

Supply voltage quality is a complex term concerning deviations of the voltage from its ideal characteristics. Supply voltage quality problems are often discussed regarding disturbances and failures (voltage disturbances, harmonic resonances) [1–5]. Still, some voltage quality parameters like the supply voltage magnitude, harmonic voltages and voltage unbalance affect directly active and reactive power consumption and power losses in power systems, particularly in induction motors, transformers and capacitors. As most of the electrical energy in Estonia (about 90%) is produced from oil shale, efficiency of power consumption directly affects the use of oil shale deposits and emission of carbon dioxide. The problems of analysing and optimizing voltage quality in industrial networks are actual and have been discussed in several publications [6–13]. Voltage quality measurement results in different countries are described in [7,14–20]. Several papers discuss means and methods to improve power quality and advanced power quality monitoring systems [11,21–23].

Standards that define the quality of supply voltage in low voltage (LV) networks exist in most countries for some time already [24–26]. The latest version of the European standard EN 50160 has been released in 2007 and is adopted also in Estonia as EVS-EN 50160:2007 [24].

The standard describes electricity as a product and gives the main voltage quality characteristics under normal operating conditions as follows:

– nominal frequency of supply voltage 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 EN 50160 states, for example, that the supply voltage has to remain in the range of ±10% of the rated operating voltage. Operating the consumer network close to the limit values of voltage magnitude will be unfavorable for the customer, causing either disturbances or additional power consumption, power losses and consequently extra costs for the customer. Therefore the problem arises – what is the optimum voltage magnitude and what is the optimum range of voltage variations for the customer?

Voltage optimization (voltage regulation) is a term commonly used to refer to the well-known energy-saving technique of reducing the voltage, supplied in order to reduce losses in equipment. The voltage, supplied to industrial companies, is quite often higher than it needs to be, leading to higher power consumption and additional losses. This is partly because of the need to compensate voltage drops at high loads across the supply network, but is also a consequence of the harmonization of supply voltages throughout Europe.

During the years from 2000 up to 2011, studies have been performed to measure and analyse the supply voltage quality parameters in LV industrial networks in Estonia. 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 affecting power consumption and losses of the customers [27–30].

2. FREQUENCY OF THE SUPPLY VOLTAGE

Frequency of the supply voltage is the frequency of fundamental harmonic voltage, measured as the mean value during a given time interval. In Estonia the rated frequency is 50 Hz. As it is stated in the standard, the network frequency has to be:

50 Hz ± 1% (49.5–50.5 Hz), 99.5% of time intervals;
50 Hz – 6%/+ 4% (47–52 Hz), 100% of time intervals.

In networks not connected to the main network, e.g., in some islands, the frequency is allowed to vary within a wider range. The frequency in the main network of Estonia is determined by the rotating speed of turbines and generators. When the load is increasing, the rotating speed of generators will decrease and is to be compensated. The frequency can be controlled only having the necessary power capacity available and controlling voltage levels as the power consumption depends on voltage levels. Frequency deviation is expressed as

$$\Delta f = \frac{f - f_{\text{rated}}}{f_{\text{rated}}} 100\%. \tag{1}$$

As an example, the frequency throughout one week period is shown in Fig. 1.

The power stations of Estonia are connected to the interconnected power system, including the NW region of Russia, Latvia and Lithuania and are running synchronously with this huge power system. Operating the power system in the interconnected network is useful for Estonia while keeping the frequency within a narrow band around the rated value is easier, since the load changes are more smooth and more predictable. The frequency of the interconnected power system has been very stable during the last decade, mainly between 49.95 and 50.05 Hz and the frequency deviation is up to ±0.1% from rated frequency 50 Hz. This is approved by numerous voltage quality measurements. So the frequency deviation is about 10 times less than the deviation stated in the standard. Such a negligible frequency deviation does not affect the consumers in any way. As the consumers do not affect the frequency and such small frequency deviations do not affect electrical appliances and power consumption, the frequency deviations are not main objectives of this research.

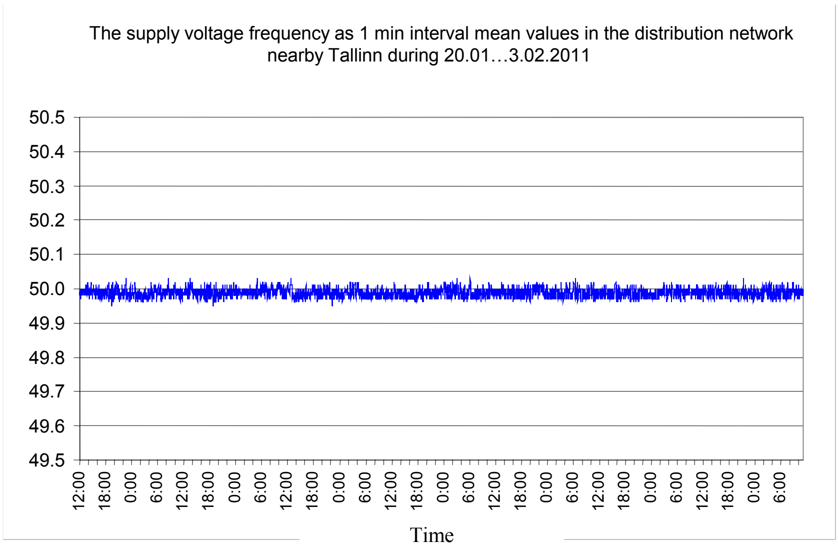

Fig. 1. The supply voltage frequency in the interconnected network of Estonia.

3. FACTORS AFFECTING SUPPLY VOLTAGE QUALITY

The supply voltage quality in LV networks is affected by the following factors:

- customers' load characteristics (active and reactive loads, load fluctuations, harmonic currents, load unbalance),
- customers' power systems characteristics, presence of shunt capacitors,
- characteristics of the supply network (short-circuit power),
- load characteristics of other consumers in the same network,
- random effects like faults in the HV network or natural phenomena.

The power system of industrial companies usually includes a substation with a transformer and the power metering point on the LV side of the transformer, which is often the point of common coupling (PCC). The supply circuit includes the main grid transformer, the MV supply line, the MV/LV transformer and the consumer network with different loads, as shown in Fig. 2. Voltage level in the MV network is controlled by on-load tap-changer of the main grid transformer. The MV/LV transformer is usually equipped with 5 taps enabling to choose the voltage level by ±5% under no-load conditions.

One of the most critical parameters for a consumer is the voltage level in the PCC. However, this is varying to some extent all the time. The voltage variations are characterized as slowly changing variations of the rms voltage. These voltage variations are usually expressed as

$$\Delta U = U - U_{\text{rated}}, \tag{2}$$

$$\delta U = \frac{U - U_{\text{rated}}}{U_{\text{rated}}} 100\%, \tag{3}$$

where U_{rated} is the rated operating voltage and U is the actual voltage value.

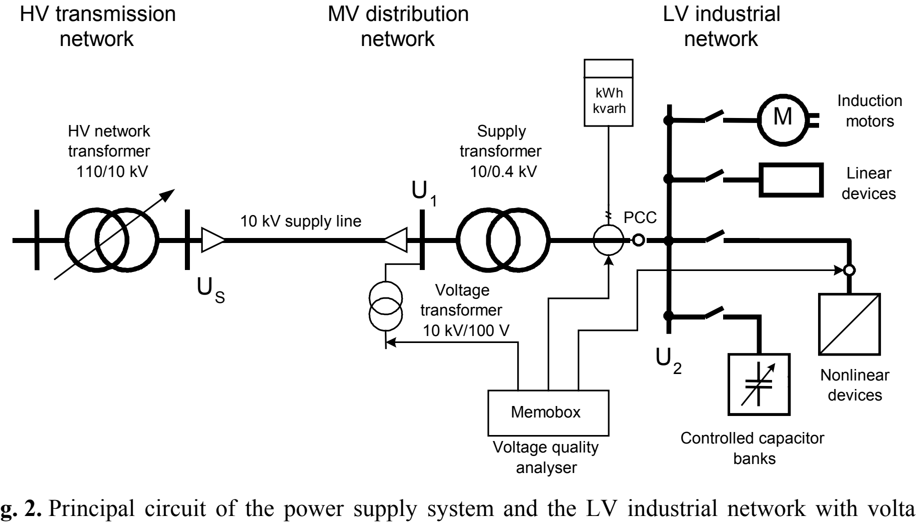

Fig. 2. Principal circuit of the power supply system and the LV industrial network with voltage quality measurement equipment.

The main problem for customers is often supposed to be too low voltage in the feeder. As network impedance is constant most of the time, the voltage deviation is mainly caused by load current variations. Therefore, the voltage on the transformer secondary side is often stepped up to ensure the rated voltage level during peak loads. This is also done to handle the voltage drops during the start of powerful induction motors. However, this in turn means that most of the time the actual voltage is higher than rated voltage. Consequently, supply voltages are often higher than rated and the deviation from rated voltage is mostly above the rated value. This situation leads to extra power consumption, which will also contribute to extra costs [6–8,27–29].

4. MEASUREMENT SITES OF SUPPLY VOLTAGE MAGNITUDE

The supply voltage magnitude as well as other voltage quality parameters have been measured in industrial companies during the years 2000–2011. The total number of measurement sites was 66 and the location of them in Estonia is shown in Fig. 3. The measurement points were the PCC or the LV busbars of the substation.

In the following an example of supply voltage measurement results is shown. Figure 4 shows the phase voltages 10 min interval mean values throughout one week period and Fig. 5 the probability density distribution of measured values, the optimum distribution and distribution according to the standard EN 50160.

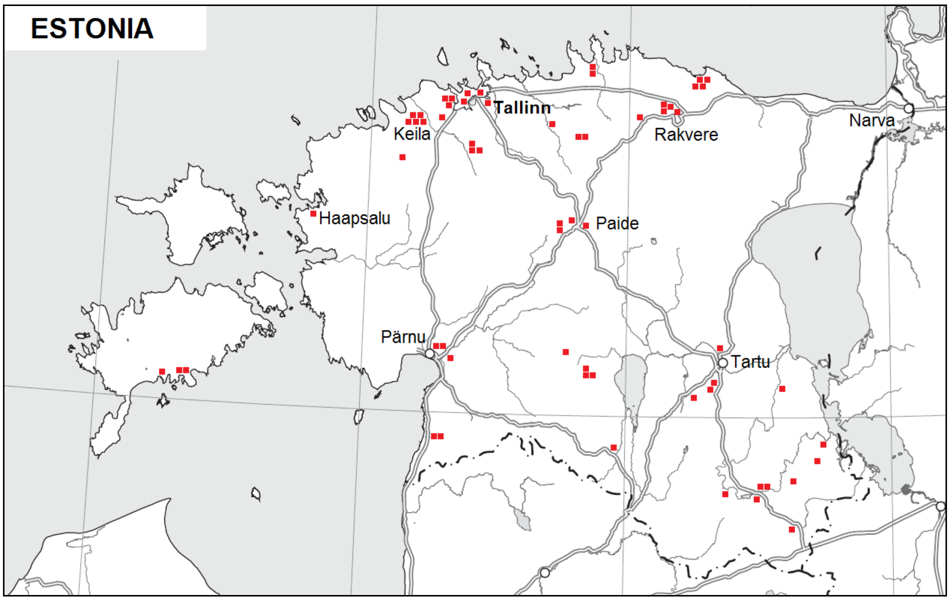

Fig. 3. Location of supply voltage quality measurement sites in LV industrial networks of Estonia.

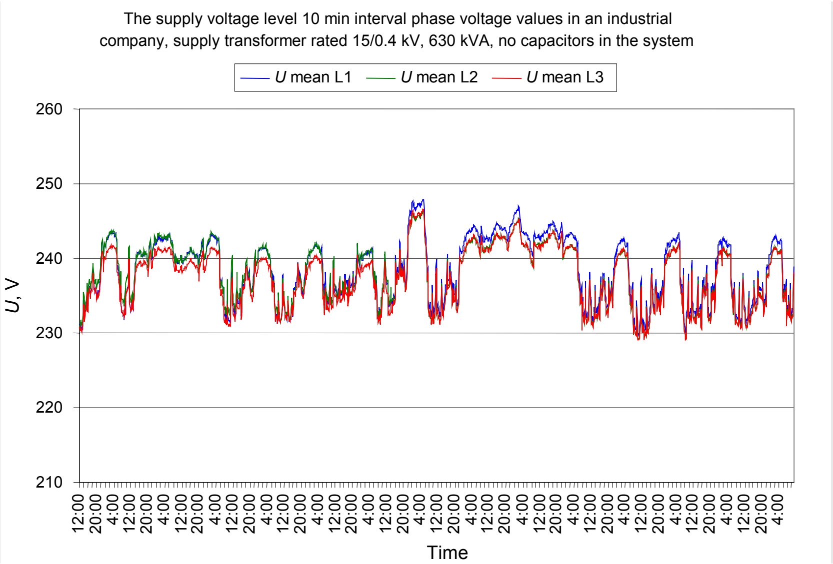

Fig. 4. The supply voltage 10 min interval mean values in industrial network, two weeks period.

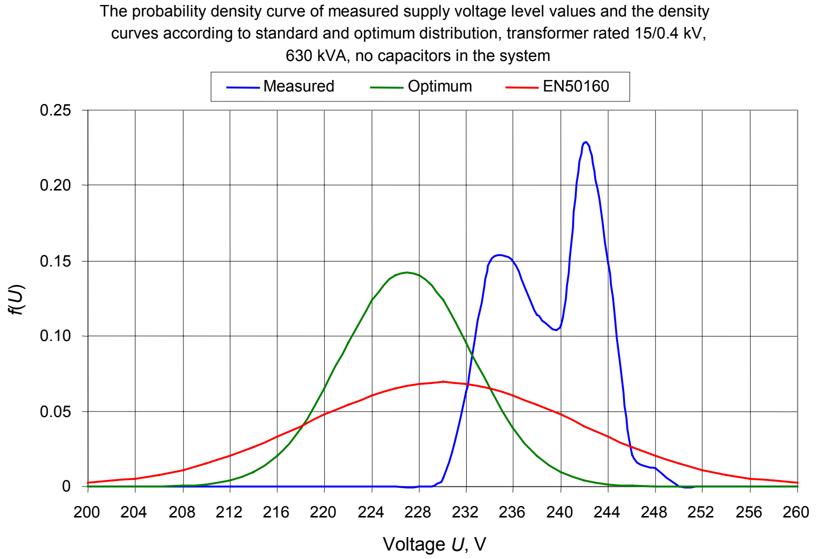

Fig. 5. The measured probability density $f(U)$, the distribution according to requirements of the standard EN 50160 and according to optimum criteria.

The probability density functions calculated from measurement results have different expected values and dispersion. Most probably the voltage is higher during low loads and lower during high loads. In general, the following cases of density distribution functions could be described:

- narrow distribution, optimum expected (average) value,
- narrow distribution, but shifted either towards higher or lower voltages,
- broad distribution, optimum expected value,
- broad distribution, but shifted either towards higher or lower voltages.

The method of voltage level optimization is based on statistical analysis of measurement results. Calculating the probability density function and comparing it with the optimum density function enables one to draw conclusions about necessary measures to adjust the voltage level – adjustment of transformer taps or reinforcing the supply circuit (transformer and lines) or improving reactive power compensation.

5. ANALYSIS OF VOLTAGE VARIATIONS BASED UPON STOCHASTIC THEORY

Voltage variations are relatively small deviations of the voltage magnitude. The standard [24] gives limits for voltage variations. The length of the measurement window is 10 min, thus very short time scales are not considered in the standard. As for voltage magnitude 95% of the 10 min mean values, U_i during one week period have to be within ±10% of the rated voltage

$$P(U_{i\min} \le U_i \le U_{i\max}) \le 0.95. \tag{4}$$

The voltage magnitude is recorded every 10 min – that gives a total of 1008 samples per week. On average, voltage magnitude is close to its rated value. Figure 6 shows the variation of the voltage magnitude as a function of time.

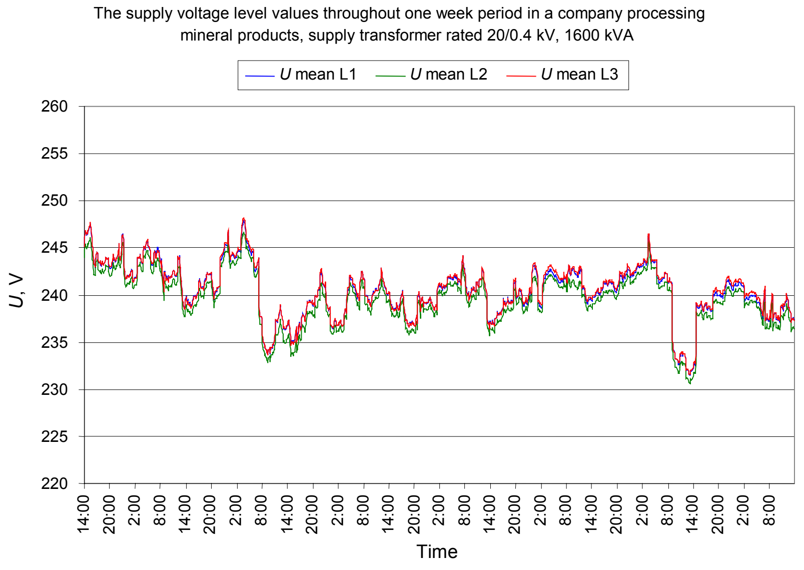

Fig. 6. Voltage level variations as mean values of 10 min intervals through one week period.

It would be extremely complicated to present the distribution functions of various stochastic variables like voltage quality parameters in an analytical form. To describe voltage quality deviations in a statistical way the probability density and probability distribution functions should be used. According to density functions one can easily assess the measurement results comparing these with the rated values or with the optimum voltage distribution.

The probability density and probability distribution functions of the voltage magnitude for the case in Fig. 6 are shown in Fig. 7. The probability density function gives the probability that the voltage magnitude is within a certain range. Of interest is mainly the probability that the voltage magnitude is below or above a certain value. The probability distribution function (the integral of the density function) gives that information directly.

In case of the supply voltage value U, the distribution function looks as follows:

$$F(U) = P(U < U_i). \tag{5}$$

This function shows the probability of the voltage value U being lower than U_i. For example, as it can be seen in Fig. 7, the voltage is higher than 240.5 V with a probability of 50%.

As it is known from stochastic theory, the diversity of a stochastic variable is called dispersion D. The diversity is often expressed as a square root of

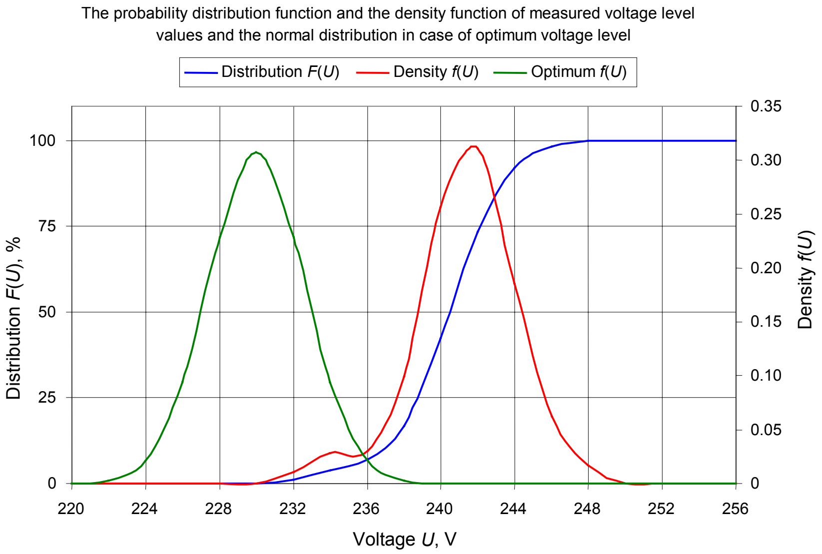

Fig. 7. The distribution and density functions of measured voltage values as shown in Fig. 6.

dispersion and is called standard deviation σ. As for sampled data of voltage level, the dispersion and the standard deviation can be calculated as

$$D = \sigma^2 = \frac{\sum_{i=1}^{n} (U_i - \bar{U})^2}{n}, \tag{6}$$

where n is the number of samples over the time period T and $\bar{U}$ is the expected value of voltage magnitude.

In normal operation, the voltage at the customer is determined by a series of voltage drops in the system. All of those are of a stochastic character and can be described by a normal distribution, where the probability density function is

$$f(U) = \frac{1}{\sigma\sqrt{2\pi}} - \frac{(U - \overline{U})^2}{2\sigma^2}, \tag{7}$$

where U is the voltage magnitude as a stochastic variable.

For normal distribution the following relationship between standard deviation and probability holds: the probability of a stochastic variable to stay in the range of four times standard deviation 4σ is 95%. The lower and upper limits for this range are:

$$U_{\min} = \overline{U} - 2\sigma; \quad U_{\max} = \overline{U} + 2\sigma. \tag{8}$$

Knowing the expected value $\bar{U}$ and standard deviation σ of the normal distribution, the whole distribution is known. Thus calculating the probability that the voltage deviates are more than 10% from its rated value, is no longer difficult. The results of this calculation are given in Table 1. The first column gives the probability that the voltage is within the voltage range. The voltage range is given in standard deviations, in volts and as percentage of the nominal voltage.

When high quality voltage level is expected, it is suggested that the measured voltage rms mean values of all 10 min intervals will be in the range of 220–240 V and the average value of all mean values will be between 225 and 235 V as shown in Table 2 [31].

Table 1. Probability of voltage exceeding a certain range, according to EN 50160 limits, where $\bar{U} = 230\,\text{V}$ and $\sigma = 11.5\,\text{V}$ (5%)

Probability	Voltage range		
		V	%
0.683	$\bar{U} \pm \sigma$	218–242	±5
0.954	$\bar{U} \pm 2\sigma$	207–253	±10
0.997	$\bar{U} \pm 3\sigma$	195–265	±15

Table 2. Probability of voltage exceeding a certain range, according to the high quality voltage level, where $\bar{U} = 230\ \text{V}$ and $\sigma = 2.3\ \text{V}$, 1%

Probability	Voltage range		
		V	%
0.683	$\bar{U} \pm \sigma$	228–232	±1
0.954	$\bar{U} \pm 2\sigma$	225–235	±2
0.997	$\bar{U} \pm 3\sigma$	223–237	±3

Long-term experience of power systems shows that if no voltage control is used in distribution networks, the voltage deviation would exceed 10%. In practice, the voltage regulation measures (capacitor banks, transformer tap-changers) exist, which become active when the voltage deviates too much from its nominal value. The main assumption used is that voltage variations are caused due to the sum of numbers of small voltage drops. For voltage events, sags or swells, this assumption holds no longer. This makes the principal difference between “events” and “variations”. For voltage variations the normal distribution can be used, for voltage events it is the time between events and the duration of events, which is of main importance [8].

Therefore the problem exists – which are the characteristics of optimum voltage level? What is the optimum range for voltage variations? As we could take for the optimum voltage level the rated value in the network or the rated value of electrical devices used (e.g., shown on the nameplate), we get the range for variations ±10% or 207–253 V. Such a range would satisfy the customer regarding service failures due to voltage variations, but cannot serve as optimum voltage level for power consumption, power losses and lifetime of devices. The following approach for optimum voltage level has been suggested in [27]. The optimum voltage level average value should be equal to the rated voltage, or somewhat lower. The dispersion of voltage variations should be much more narrow than in the standard, e.g., the range for variations should be about ±25% up to ±5%. Thus we could specify the optimum voltage level parameters as, e.g., 230 V ±2.5% or 230 V +2%/–4%.

6. MEASUREMENT RESULTS OF VOLTAGE LEVELS

The objective of voltage level measurements in industrial companies 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 analyser LEM-Memobox. The instrument measures and stores phase voltages as mean values of 10-min time intervals throughout one week period; also, the minimum and maximum voltage values in each 10-min interval. The measurement sites are located all around Estonia and permit to assess the voltage level in LV industrial networks. Measurement results are stored in a database. Statistical measurement results of voltage level parameters are given in Table 3.

The cumulative probability distribution curves of voltage levels show, what is the probability of a voltage level to reach a certain value. For example, in Fig. 8 one can see that with 50% probability the minimum voltage level is 220 V, the average level is 232 V and the maximum voltage level is 240 V. Also one can see that 10% of LV networks have the minimum voltage level below 210 V and 37% of LV networks have the maximum voltage level more than 240 V. The probability density curves of voltage levels in Fig. 9 show the voltage values with the highest probability and distribution of voltage variations.

In addition, the correlation with normal distribution can easily be assessed. For example, from Fig. 9 one can see that the highest probability of maximum

Table 3. 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
Mean value of absolute deviation K, V	5.06	4.13	4.00	4.32	4.49
Voltage mean value U_{mean}, V	221.6	226.5	231.7	236.3	239.0
Voltage minimum value $U_{\min}$, V	204.0	213.0	220.5	223.0	224.0
Voltage maximum value $U_{\max}$, V	236.0	239.0	242.0	250.0	254.0

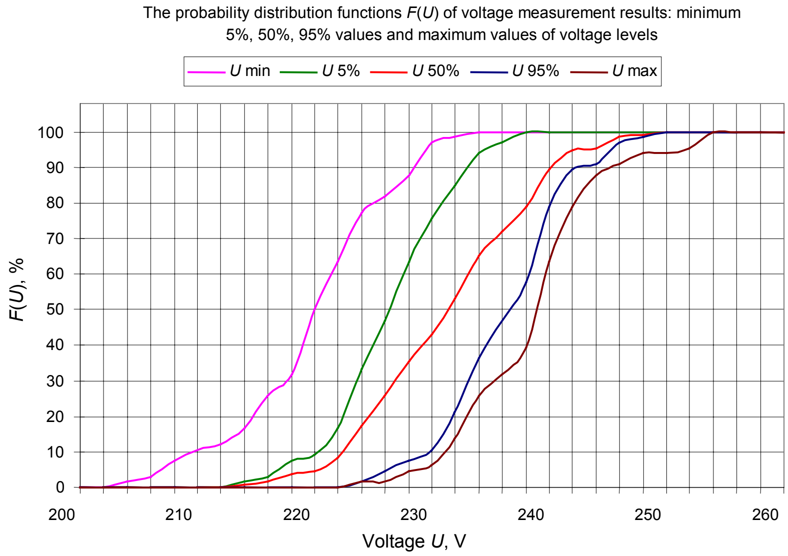

Fig. 8. The probability distribution functions of voltage level measurement results in LV industrial networks of Estonia.

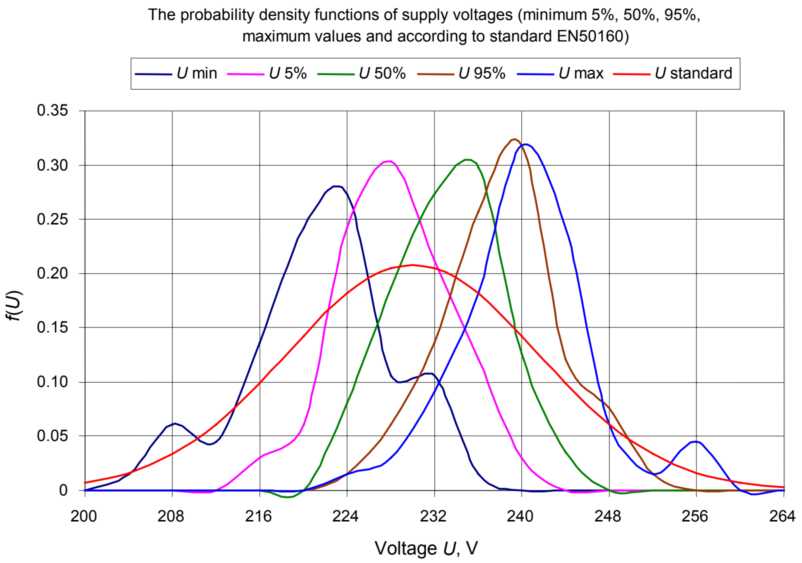

Fig. 9. The probability density functions of voltage level measurement results in LV industrial networks of Estonia.

voltage levels is 240 V, but the distribution is in the range of 220–260 V. Also, one can 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.

7. VOLTAGE EVENTS – VOLTAGE SAGS AND SWELLS

Voltage events are phenomena which only happen occasionally, but may cause considerable economic damage to customers [1,4,8,9,15,16]. In this study voltage events were recorded as fundamental frequency voltage magnitude disturbances due to an increase or decrease in voltage magnitude.

Voltage sag (dip) is a sudden decrease of the supply voltage to a value below 90% of the rated voltage followed by recovery after a short period. Usually, the duration of a voltage sag is between 10 ms and 1 min. In industrial networks, the threshold for voltage sags is 85% of the rated voltage.

In Fig. 10, an example of measured voltage sags are shown in an industrial LV network in one week period.

When recording voltage events, the rms value of each half period was measured. If the actual rms value was outgoing from the preset voltage range, the maximum or minimum voltage value during this event and the duration of the event were recorded. The measurement results are given in Table 4 according to

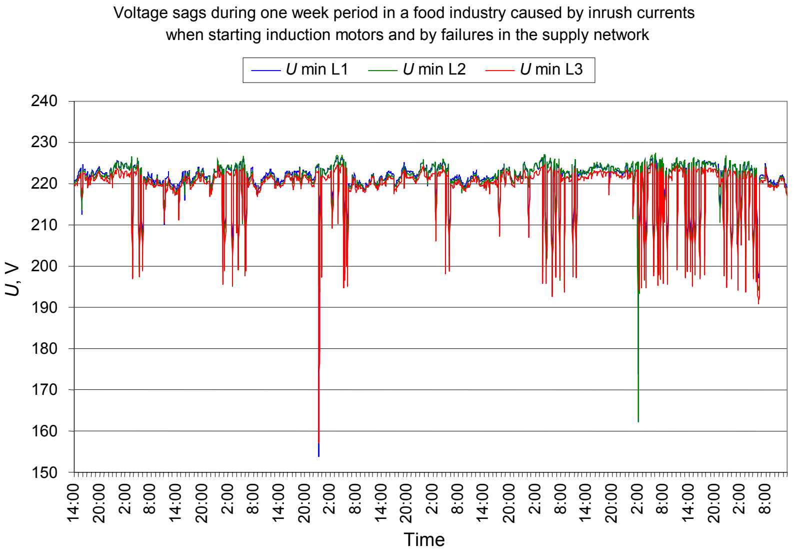

Fig. 10. Voltage sags in industrial LV network during one week period.

Table 4. Measurement results of voltage events according to the IEC classification form in LV industrial networks in Estonia

Duration of events	Up to 20 ms	20–100 ms	100–500 ms	0.5–1 s	1–3 s	3–60 s	Over 60 s
Voltage swells	453	31	1 648	83	77	43	2
Voltage sags							
10%–15%	33 262	14 788	8 416	364	393	227	22
15%–30%	167	73	52	13	48		3
30%–60%	10	30	23	6	4		
60%–99%	2	28	10	4	1	15	4
Interruptions		3		1	6	27	54

the IEC form, where the events are sorted by magnitude and duration. Also the results are shown in a scattered diagram as magnitude–duration plots. In Fig. 11 the voltage sags and in Fig. 12 the voltage swells are shown.

Most often the voltage sags are caused by induction motor starting and do not cause any disturbances. The depth of these sags is up to 85% from the rated voltage and the duration is between 0.2 and 20 s. The sags in all three phases are equal, the voltage drops rapidly and recovers smoothly [[8,9]].

Activation of transformers also causes voltage sags. These are caused by the inrush current when magnetizing the transformer. These sags are asymmetrical. They are of different depth in each phase. Voltage recovery takes place smoothly. The depth of these sags is up to 80% and duration between 0.06 and 0.2 s.

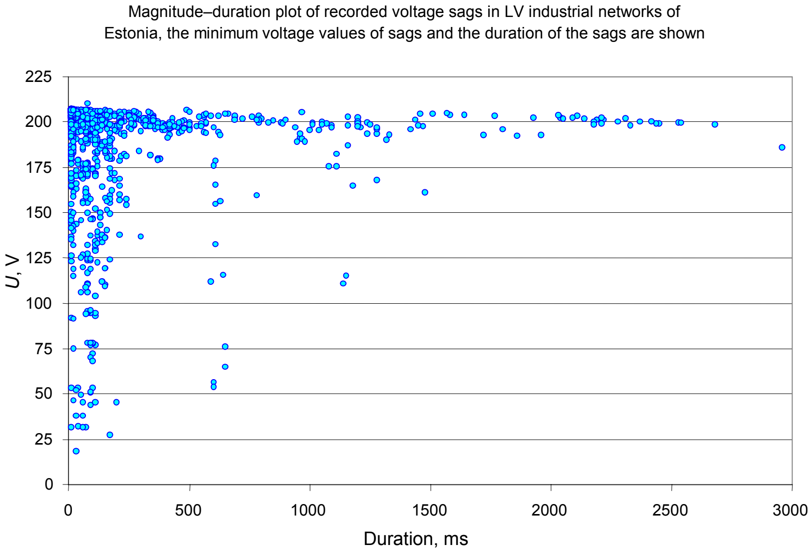

Fig. 11. The recorded voltage sags in LV industrial networks of Estonia.

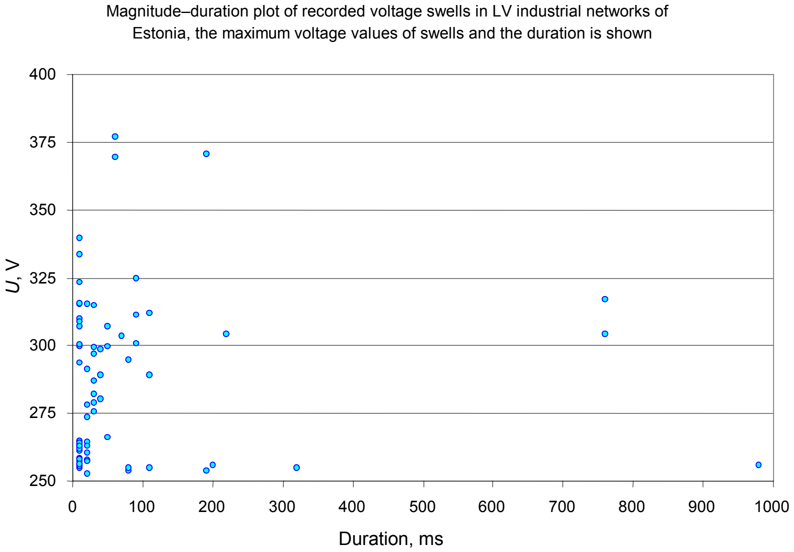

Fig. 12. The recorded voltage swells in LV industrial networks of Estonia.

Voltage sags are also caused by short circuits and failures in the distribution or transmission HV network. The transmission network failures are usually of short duration between 50 and 100 ms and the depth is up to 60% of the rated voltage. Failures in remote transmission networks cause sags up to 80% of rated voltage and the duration is between 20 ms and 3 s. Failures in local distribution networks cause sags between 40% and 80% of rated voltage [8,9].

Power frequency overvoltages – voltage swells – occurred much more rarely than voltage sags. Voltage swells are caused by switching, single-phase faults, transformer energizing, high impedance of a neutral conductor or high capacitive load. The duration of power frequency overvoltages is of 10 ms up to several minutes. Transient overvoltages that are of high frequency but short duration are not considered in this study.

8. HARMONIC DISTORTIONS OF THE SUPPLY VOLTAGE

Harmonic distortions of the supply voltage cause additional losses and costs in the consumer network. These losses include operating costs and aging costs. The numerous studies described in [1,3,18,19,23,32–35] show clearly that the operating costs 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 often in relation to the fundamental voltage U_1 and by total harmonic distortion factor THD_u:

$$THD_u = \frac{\sqrt{\sum_{h=2}^{\infty} (U_h)^2}}{U_1}. \tag{9}$$

The rms value of the voltage can be calculated from individual harmonic values or from the fundamental value and total harmonic factors as follows:

$$U = \sqrt{\sum_{h=1}^{\infty} U_h^2} = U_1 \sqrt{1 + THD_u^2}. \tag{10}$$

The rate of harmonic distortions of industrial and commercial LV networks in Estonia has been steadily increasing from the middle of the 90-ies caused by intensive installation of adjustable speed drives, welding rectifiers, converters, electronic luminaries and other electronic non-linear equipment. Measurement results of voltage harmonic distortions in industrial networks show that often the limit value 8% for THD_u has been reached, while the total harmonic distortion in the supply current THD_i is 20%–60%. Some examples of harmonic distortions of supply voltage in industrial networks are presented in Figs 13, 14 and 15.

The measurements in industrial networks show that harmonic distortions vary in time, extent of harmonics and harmonic spectrum. Also, the level of voltage harmonic distortions depends on shunt capacitors in the network. If no filtering reactors are used, the level of distortions is increasing when capacitors are switched on.

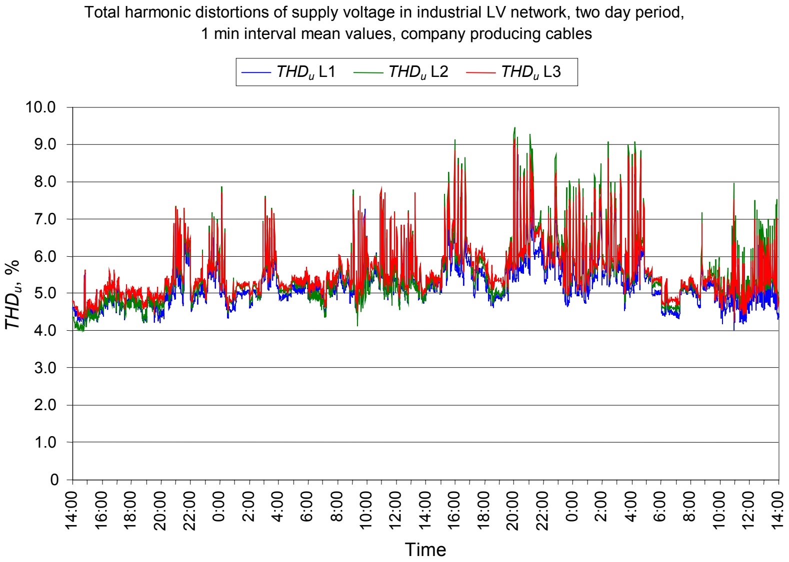

Fig. 13. Harmonic distortions of supply voltage caused by DC and ASD drives, two day period.

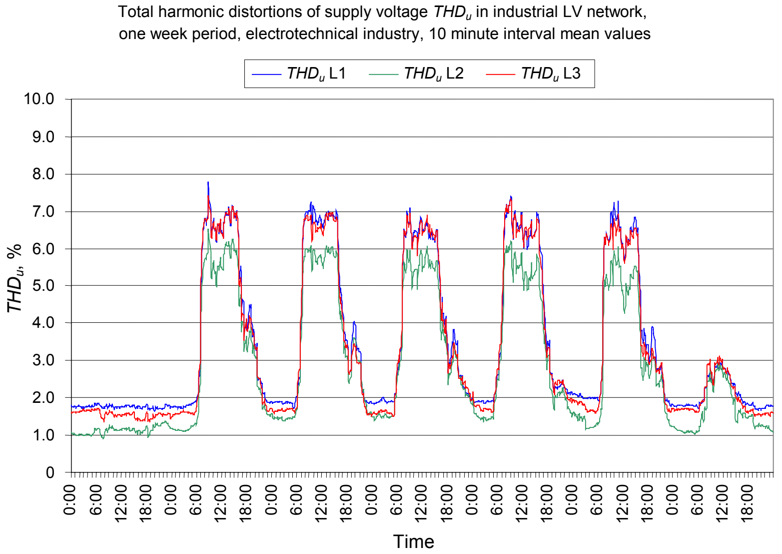

Fig. 14. Harmonic distortions of supply voltage in industrial network, one week period.

In the present voltage quality studies the total harmonic distortion THD_u and individual harmonic voltages U_h were measured throughout one week periods as the mean values of 10-min time intervals. Individual harmonic voltages up to $h25$ were included. The objective of measurements was to study harmonic distortions

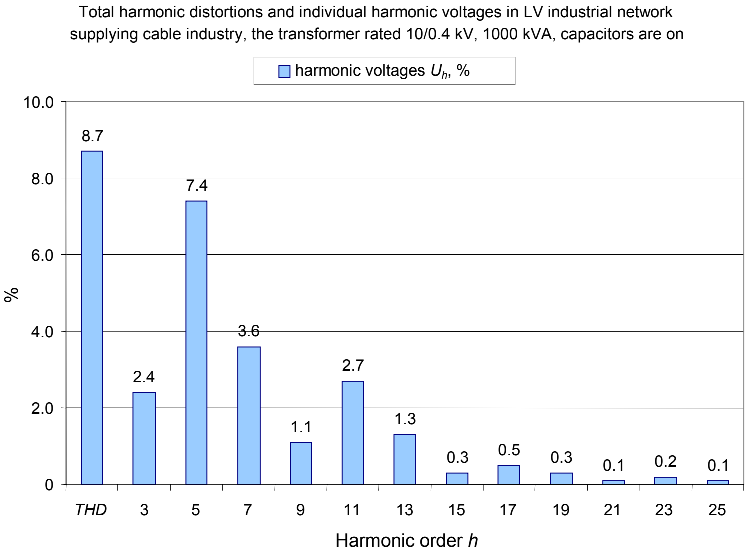

Fig. 15. Harmonic spectrum of the supply voltage in the PCC of an industrial consumer, shunt capacitors are switched on.

and resonant conditions of LV networks when installing shunt capacitors for reactive power compensation.

The measurement results of 66 measurement sites are stored in a database. The statistical parameters of measurements are given in Table 5, the probability distribution of THD_u is shown in Fig. 16 and the probabilty density in Fig. 17. As can be seen from Figs 16 and 17, the 95% rate of total harmonic distortions exceeds the limit value 8% in 9% of measured sites and the recommended value 5% in 25% of measured sites. As for the rate of 100% of measured time intervals, the rate of harmonics exceeds the recommended value in 30% of sites. The conclusion is that the level of total harmonic distortions is higher than recommended in several cases and mitigation measures have to be discussed to reduce the harmonic level.

Table 5. 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
Mean value of 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

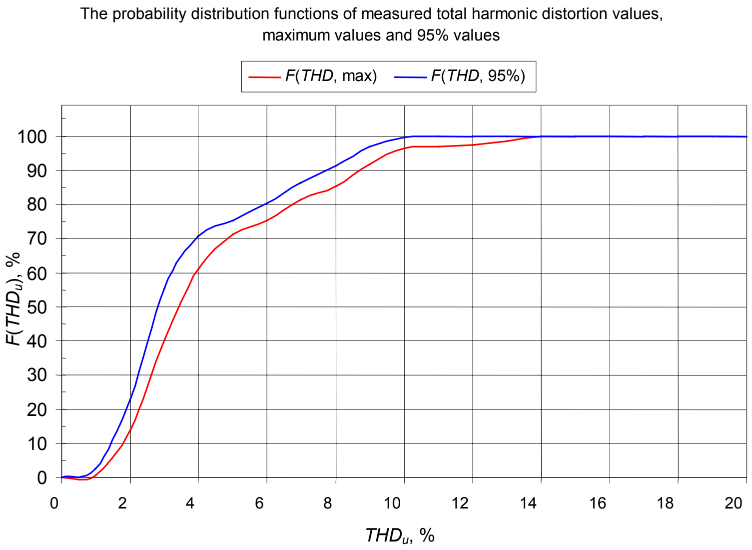

Fig. 16. The probability distribution functions of total harmonic distortions THD_u in LV industrial networks of Estonia.

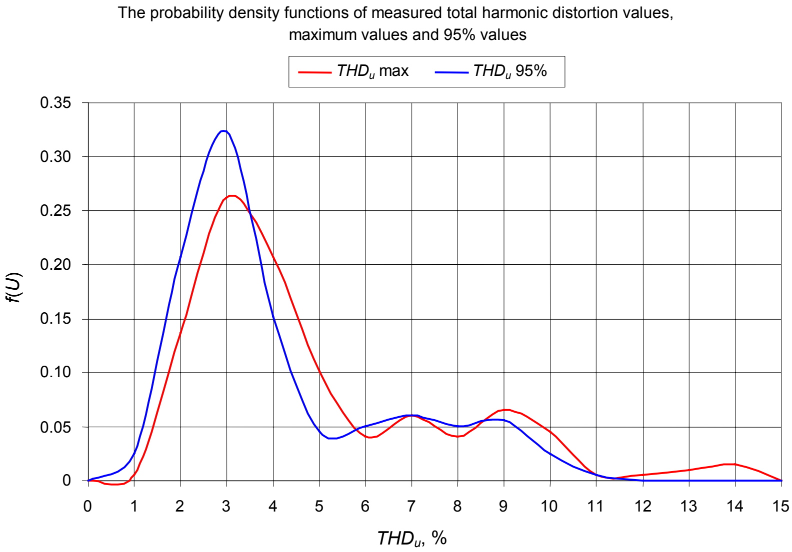

Fig. 17. The probability density functions of total harmonic distortions THD_u in LV industrial networks of Estonia.

9. FLICKER CAUSED BY VOLTAGE FLUCTUATIONS

Flicker is a phenomenon caused by supply voltage fluctuations, where the voltage variations are of relatively low frequency, usually below 30 Hz. The most disturbing fluctuations have frequency between 1–10 Hz.

Flicker severity is calculated as the ratio between voltage fluctuations and rated voltage at different frequencies. According to the standard [15], the flicker severity should not exceed the value $P_{lt} = 1.0$ in 95% of time intervals in a week. Method for flicker measurement is described in standard IEC 868. Studies of flicker related problems have been published in [16–18].

The measurement results of P_{lt} statistical values are given in Table 6. The probability distribution function of P_{lt} is shown in Fig. 18. The measurement results show that the average value for P_{lt} complies with the standard, but sometimes the P_{lt} value is much higher (up to 10 times), than the limit value in

Table 6. The measurement results of flicker P_{lt} statistical values

Parameter	P_{lt} max	P_{lt} 95%
Dispersion *D*	1.23	1.20
Mean value of absolute deviation *K*	0.68	0.64
P_{lt} mean value	1.4	1.0
P_{lt} minimum value	0.2	0.2
P_{lt} maximum value	10.9	10.5

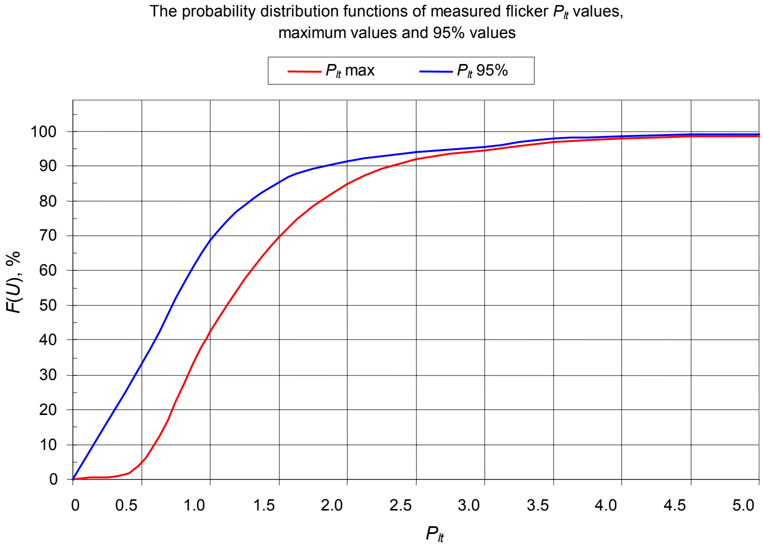

Fig. 18. The probability distribution function of flicker P_{lt} in LV industrial networks of Estonia.

the standard, and visually disturbing. Such cases were recorded in metal processing production factories, were spot-welding devices were used, and in sawmills, where the load of induction motors is fluctuating all the time. The difference between these two flicker types is that when caused by spot-welders, flicker occurs mostly only in two phases, while in sawmills the flicker is equally affecting all three phases.

10. VOLTAGE UNBALANCE

In ideal case, the rms voltage values in the three phases are equal in magnitude and the phase angles between consecutive phases are equal also. Voltage unbalance is the state of a three-phase system, where the voltages or angles are not equal.

Unbalanced state of voltages can be calculated using the method of symmetrical components. According to this, any three-phase system of voltage phases could be described as a sum of three phasor systems – positive, negative and zero sequence phasors $\underline{U}_1$, $\underline{U}_2$ and $\underline{U}_0$.

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:

$$K_{2U} = \frac{U_2}{U_1} 100\%, \quad K_{0U} = \frac{U_0}{U_1} 100\%. \tag{11}$$

The standard states that under normal conditions the negative sequence unbalance factor K_{2U} shall not exceed 2%, measured in 10-min time intervals during one week. Still, a lower value of the factor, $K_{2U} \leq 1\%$, is often recommended, because of additional losses in induction motors if the unbalance factor exceeds 1% [6,31,36].

Voltage unbalance is mostly caused by uneven spread of loads in the three phases or due to a large single-phase load. Also, it is caused by failures in HV networks or by unsymmetrical characteristics of the HV supply network. This situation with unbalanced loads becomes worse in case the neutral conductor has high impedance, for example in networks with overhead LV lines in rural areas. Unbalance leads to additional heat losses in the windings of three-phase induction motors and reduces their efficiency.

The measurement results of a voltage unbalance factor statistical values are given in Table 7 and the probability distribution function is shown in Fig. 19. The measurement results show, that the average value for K_{2U} is about 1%.

Table 7. Statistical values of voltage unbalance factor K_{2U}

Parameter	K_{2U} (max)	K_{2U} (95%)
Dispersion D	0.65	0.30
Mean value of absolute deviation K	0.36	0.20
K_{2U} mean value, %	1.0	0.8
K_{2U} minimum value, %	0.5	0.4
K_{2U} maximum value, %	5.0	2.0

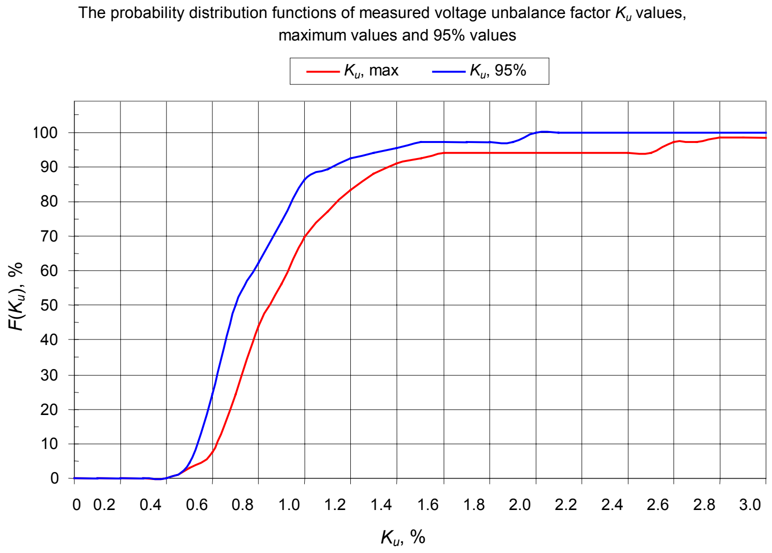

Fig. 19. The probability distribution function of voltage unbalance factor K_{2U} in LV industrial networks of Estonia.

11. CONCLUSIONS

Based on long-term studies and measurements of LV industrial networks in Estonia, the following conclusions can be drawn.

1. The frequency of the supply voltage has been very stable during the last decade; the frequency deviation is up to ±0.1% from the rated frequency 50 Hz. So the frequency deviation is about 10 times less than stated in the standard. Such a negligible frequency deviation does not affect the consumers in any way.
2. The supply voltage level is one of the basic factors affecting power consumption and losses in LV networks. A practical measurement method to analyse the voltage level is introduced, where the probability density and probability distribution functions should be used.

3. The voltage level in industrial LV networks in Estonia is often too high. About 60% of measurement sites comply with the high quality level, about 10% have the average voltage level lower than 225 V and 30% have it higher than 235 V. So the average voltage is often higher than rated voltage and the dispersion is too high in several cases as well. The reason for these phenomena is the improper position of the tap-changer of the transformer, insufficient power rating of the transformer, missing shunt-capacitors for power factor correction and sometimes high impedance of the neutral conductor.
4. Most of the power frequency voltage events are voltage sags in the range of 0.85–0.9 from rated voltage with duration up to 500 ms. Mostly these sags do not cause problems. The sags, causing problems, are deeper than 85% of rated voltage with a duration of 20–500 ms. These sags are mostly caused by failures in HV and MV networks. The average frequency of such sags has been 2–3 times per week. Voltage swells occur much more rarely than sags and they are mostly 110%–130% of the rated voltage and with duration from 100 ms up to 1 s. The maximum value of swells has been up to 180% of the rated voltage with duration up to 20 ms.
5. Harmonic distortions of the supply voltage have been increasing in Estonia. Distortions like THD_u more than 8%, and THD_i more than 40%, are not exceptions. Harmonic losses can be remarkably high in consumer LV systems and need to be estimated to make further improvements in the efficiency of the LV power system.
6. The average minimum value of a voltage harmonic factor was 1.1%, which is probably the harmonic level in MV and HV networks. The maximum value of the probability density function of THD_u maximum values is around 3%. The limit value of $THD_u = 8\%$ is exceeded by 15% of measurement sites. The most dominating harmonics in the spectrum are $h5$, $h7$, $h3$, $h11$, $h13$, $h17$, $h19$ and $h23$. Harmonic voltages with frequencies over $h23$ are below 0.1–0.3 V.
7. The limit values of harmonic voltages in the standard EVS-EN 50160 are rather too high, regarding additional harmonic losses in LV networks, and cannot serve as guidelines of optimizing the system performance.
8. The flicker severity exceeds the limit value of 1.0 in 42% of measurement sites for 100% of time and in 31% of sites for 95% of time intervals. The highest flicker values were 10–11, measured during the operation of a spot-welding device.
9. When analysing unbalance factor K_{2U}, most measurement results comply with the standard for 95% of time intervals. For 100% of time, 7% of sites exceed the 2% limit value and 30% of sites exceed the recommended 1% value. Thus the unbalance factor does comply with the standard, but in 30% of recorded cases exceeds the recommended level.
10. Supply voltage quality in industrial and commercial networks should be estimated when energy conservation is concerned. Development of practical

calculation and measurement methods is important. Such methods should be the bases for selecting optimum mitigation measures for improving power quality and reducing power consumption and power costs of customers.

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Toitepinge kvaliteet Eesti tööstuslikes madalpingevõrkudes

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Toitepinge kvaliteet tööstusettevõtete madalpingevõrkudes on väga oluline nii elektriseadmete talitlushäirete kui ka säästliku energiatarbimise seisukohalt, mõjutades otseselt nii võimsuse tarbimist kui ka võimsuskadusid ettevõtte elektrisüsteemis. Artiklis on esitatud ülevaade toitepinge kvaliteeti iseloomustavatest parameetritest, neid reguleerivatest standarditest ja mõjutavatest teguritest. Pikaajalise programmi käigus mõõdeti paljude üle Eesti paiknevate tööstusettevõtete liitumispunktide madalpinge poolel järgmisi toitepinge kvaliteedi parameetreid: pingenivoo, pingenivoo hajuvus, võrgusageduslikud pingehälbed (pingelohud ja pingemuhud), harmoonilised moonutused pinges, pinge värelus ning pingete asümmeetria kolmefaasilises süsteemis. Artiklis on esitatud toitepinge kvaliteedi parameetrite mõõtetulemused ettevõtete madalpingevõrkudes aastail 2000–2011 ja metoodika nende analüüsiks. Analüüsi tulemusena on antud hinnangud pinge kvaliteedile Eesti ettevõtete 0,4 kV elektrisüsteemides. On näidatud, et reaktiivvõimsuse kompensatsiooniks kasutatavad kondensaatorseadmed mõjutavad otseselt pingenivood ja harmooniliste moonutuste taset ettevõtte elektrisüsteemis.