Energy Saving Effect due to the Voltage Reduction in Industrial Electrical Networks

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ABSTRACT: The power consumption is depending on the voltage level at the load bus. For many enterprises, especially for the enterprises making small series of various products the production conditions and, respectively, the power consumption by different consumers can be significantly different from day to day. It is difficult to assess the real effect of optimizing the voltage level over a short-time. The method of the express-estimation of the power reduction effect caused by the reducing of the voltage level is discussed in the paper. A row of LV networks were investigated with the purpose to develop and to verify practical measures for the reduction of power consumption without affecting the production processes in the enterprises. The practical results of the carried out voltage optimization are discussed in the paper.

1. Introduction

There are a row of typical measures in electrical networks for an energy saving. One of the possible measures for energy saving is an optimization of the voltage levels in electrical distribution networks. The authors' investigations have shown that such measure can be realized in a lot of industry enterprises and can reduce of monthly and annual energy consumption (and, respectively, payments) by several percents. The practical effects of energy saving by voltage reduction are considered in the paper.

2. Theoretical Considerations

It is known that the reduction of voltage level causes a reduction of power consumption for many kinds of consumers in electrical networks [1]–[7], [15]. The dependences of load power consumption from the supplied voltage are *static load characteristics*. The power consumption, as a rule, is increasing for main load types (industrial, commercial, residential) with the increasing of the actual supply voltage and can be approximately represented as follows:

$$P(U) = P_0 \cdot \left(\frac{U}{U_0}\right)^{k_P}; \quad Q(U) = Q_0 \cdot \left(\frac{U}{U_0}\right)^{k_Q} \tag{1}$$

where P, Q – active and reactive power consumption by actual voltage U,
P_0, Q_0 – active and reactive power consumption by the voltage U_0,
k_P, k_Q – factors characterizing the voltage dependences

For an idealized RL-load the factors are $k_P = 2$, $k_Q = 2$. It means that the voltage reduction by 1% causes the reduction of power consumption of the ideal RL-load by 2%.

According to [5] the typical values corresponding to real loads in electrical networks for k_P, k_Q are:

$$0.6 < k_P < 1.8$$
$$1.8 < k_Q < 4.0 \tag{2}$$

The static load characteristics for a row of concrete types of consumers are given in [7].

The Fig. 1 illustrates schematically the supplying of a consumer from the power utility. From the conventional formula for the determination of power losses in a network element

$$\Delta P + j \cdot \Delta Q = \frac{P^2 + Q^2}{U_C^2}(R + j \cdot X) \tag{3}$$

can be concluded that by the reduction of the voltage at the consumer bus $\underline{U}_C$ and $k_P > 1$, $k_Q > 1$ the active and reactive network losses will be also reduced.

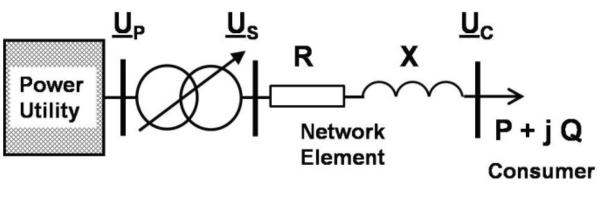

Fig. 1. Supplying of a consumer from the power utility.

In dependence on the relations P/Q and k_P/k_Q in some cases distribution network losses can be decreased by voltage reduction despite of $k_P < 1$ or $k_Q < 1$.

Decreased power consumption by consumer loads reduces the power consumption from the power utility and, respectively, leads to the reduction of power losses in the power utility network.

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Example of a numerical estimate of the changes of power consumption and power losses in the network due the voltage reduction is given in [2]. In [2] was shown that the power consumption was decreased by 3.6% and the active power losses in the modeled consumer network were reduced by 7.1% due the voltage reduction.

The idea to use the voltage reduction for energy saving is not new. A lot of investigation results were published in 80th, for example [15]. Nowadays are many technical devices for energy saving by voltage reduction present in the market [16], [17].

The offered paper is concerned with problems of express-estimation of the power reduction effect caused by the reducing of the voltage level in industrial enterprises.

3. Practical Realization

3.1 Voltage reduction due the tap changing.

For the decision about the permissibility of the tap changing the estimation of the RMS voltage values distribution at the busbar under study is required.

The limits of the permissible changes of voltage levels for LV networks are given in [8]–[10] 95% of the values measured during one week must be between (90 – 110) % of the network rated voltage. For a LV network with a rated voltage 230 V it means that the 95% of the measured values must be between 207 V and 253 V.

The Fig. 2 shows the voltage levels at the LV busbar of an enterprise before and after the tap changing for reduction of the voltage level.

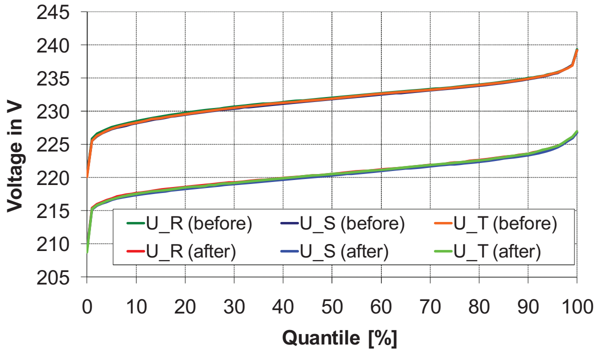

Fig. 2. Voltage levels at the LV busbar before and after the tap changing.

It can be seen from Fig. 2 that all measured voltage values are within the limits mentioned above. It means that the carried out tap changing did not violate the power quality requirements.

Figure 3 shows the active power consumption in the enterprise mentioned above for the week before the tap changing and for the week after the tap changing. These weeks can be considered as reference weeks for the fast-analysis of the effect of the voltage level reducing.

It is important for the estimation of the effect caused by the reducing of the voltage level considered over a relative short time (for instance one week) and has to be made sure that the same consumers are in operation under comparable condition during both reference time periods.

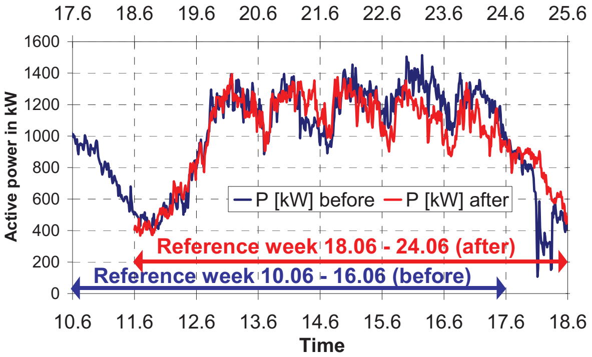

Fig. 3. Active power consumption (15-min average values) before and after the tap changing.

For many enterprises, especially for the enterprises making small series of various products the production conditions and, respectively, the power consumption by different consumers can be significantly different from day to day. Using the correlation analysis the estimation of the power reduction effect caused by the reducing of the voltage level can be carried out more correctly.

Table 1 characterizes the measured energy consumption in the enterprise under consideration for each day of both reference weeks. On the base of the analysis of the active power consumption (30-min values) the correlation coefficients r_{AB} for each day of the week were determined and represented in Table 1. From Table 1 can be seen that the total energy consumption was reduced by 4.07% after the tap changing.

Table 1. Active energy consumption before and after tap changing

Before		After				
Date	W_P [kWh]	Date	W_P [kWh]	ΔW_P [%]	r_{AB}	Day
10.6	19041.0	24.6	18407.1	3.33	0.95	Sa.
11.6	13215.3	18.6	13209.0	0.05	0.90	Su.
12.6	30934.8	19.6	27270.6	1.25	0.93	Mo.
13.6	28729.5	20.6	25309.5	–3.94	0.60	Tu.
14.6	28939.2	21.6	28736.7	0.70	0.70	We.
15.6	27719.4	22.6	28811.4	11.84	0.71	Th.
16.6	27877.8	23.6	27528.6	11.90	0.62	Fr.
	Total 176457.0		**Total 169272.9**	**Total 4.07**		

The correlation between two data rows can be characterized as follows:

$$\begin{aligned} &0.2 < r_{AB} \le 0.5 - \text{weak correlation} \\ &0.5 < r_{AB} \le 0.7 - \text{medium correlation} \\ &0.7 < r_{AB} \le 0.9 - \text{strong correlation} \\ &0.9 < r_{AB} \le 1.0 - \text{very strong correlation} \end{aligned} \qquad (4)$$

For the pairs of days characterized by correlation coefficients $r_{AB} > 0.7$ (strong and very strong correlation – marked by grey in the Table 1) can be concluded that the consumers operation at these days was similar. It can be seen from Table 1 that the reduction of the energy consumption were registered for all these days.

For the pairs of days characterized by medium correlation the changes of the energy consumption have different signs.

Both an increase and a decrease of the energy consumption were registered for these days. It can be explained by different consumer operation states at the days mentioned above.

A complete estimation of an energy saving effect after the tap changing can be carried out only after a long time of operation under changed conditions.

The Fig. 4 shows cumulative frequency distributions of 15-min values of the active power consumption during one month (April) which was chosen as a case in point. The distributions are shown for three years (2006, 2007 and 2008). The values measured in the year 2006 characterize the power consumption in the enterprise before the tap changing was made. The values for the years 2007 and 2008 represent the power consumption by operation under changed conditions.

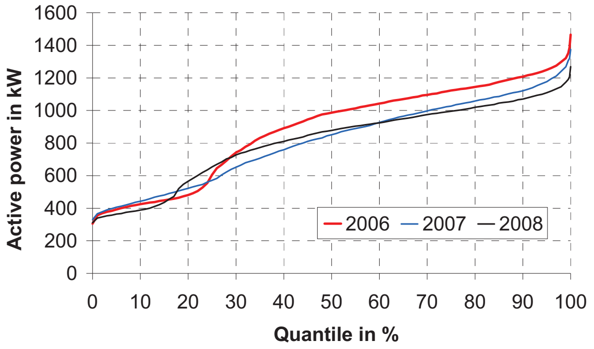

Fig. 4. Monthly (April) active power consumption (15-min average values) before (year 2006) and after (years 2007, 2008) the tap changing.

It can be clearly seen from Fig. 4 that the power consumption was decreased after the tap changing.

The achieved reduction of the monthly power consumption for the choosen month is up to 11 percents.

These results correspond with the power consumption reduction of 10 percent achieved due to the voltage optimization mentioned in [4].

Figure 5 explains the changes of the power consumption.

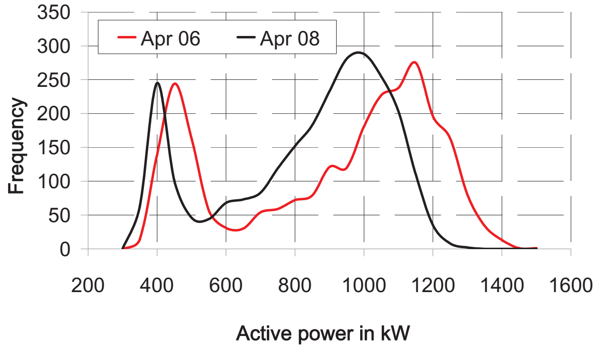

Fig. 5. Distribution of monthly active power consumption values (15-min average values) before (year 2006) and after (year 2008) the tap changing.

It can be seen from Fig. 5 that the monthly frequency distribution can be characterized by two typical peaks. The left peak in Fig. 5 corresponds to a low-load period, i.e. loads at weekends and at the nights, the right peak in Fig. 5 corresponds to the load at work days.

It can be seen from Fig. 5 that both load peaks mentioned above are shifted in direction of smaller loads after the tap changing.

It can be seen from Fig. 5 that the reduction of power consumption is more significant for the workdays in comparison with the low-load period.

This reduction is about 15% for the workdays peak in comparison with the reduction by 11% for the low-load time.

3.2 Voltage reduction due the optimization of parameter of reactive power compensation devices

Reactive power compensation devices are widely used in industrial electrical networks. But actual changes in production program of enterprises and respectively the changes of power consumption in the network are not always accompanied by correction of operation mode of reactive power compensation devices.

In some cases a non-optimized operation of reactive power compensation units can cause increased active power consumption in the enterprise and respectively additional payments for consumed energy.

Figure 6 shows cumulative frequency distributions of voltage r.m.s. values at the LV busbar of the step-down substation in an enterprise over reference weeks before and after the carrying out of the optimization of reactive power units operation states. Reactive power compensation devices in the enterprise consist of regulated and unregulated capacitor banks. The unregulated capacitor banks were permanent connected to the LV busbar before the carrying out of the optimization measures. It can be seen in Fig. 5 that the voltage level at the LV busbar due the carrying out of the optimization was reduced.

The voltage reduction was resulted from the switching off the unregulated capacitor banks during low-load periods (weekends, evenings, nights). It was possible

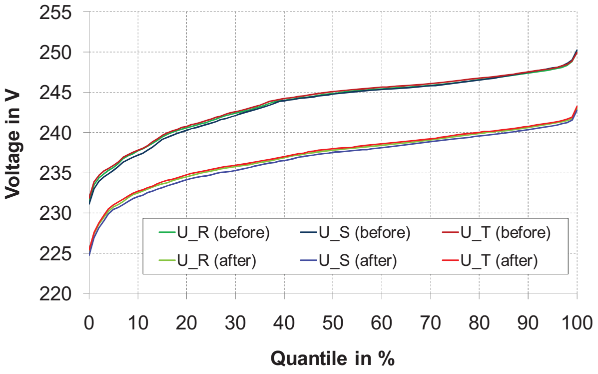

Fig. 6. Voltage levels at the LV busbar before and after the optimization of operation states of reactive power compensation units.

because reactive power compensation devices were overdimensioned for the actual power consumption in the enterprise.

Figure 7 shows the active energy consumption of the enterprise under study on the weekends (calendar weeks from 1 till 35) for two years. It can be seen from Fig. 7 the significant reduction of power consumption on weekends after the full switching off of the unregulated capacitor banks on 25 calendar week 2009.

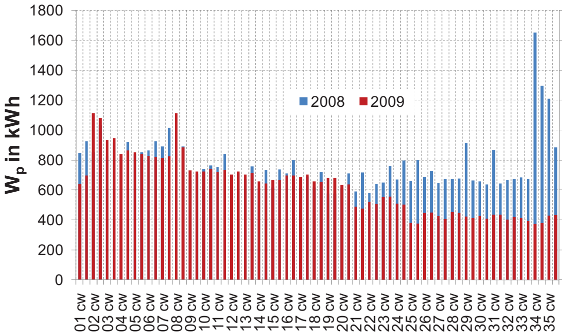

Fig. 7. Active energy consumption (15-min values) on Saturdays and Sundays before and after the switching off of capacitor batteries.

The comparison of active energy consumption on the working days can be done on the base of Table 2 containing the values for two reference weeks – before and after the realization of the optimization measures named above.

It can be seen from Table 2 the significant reduction of the active power consumption for all days under consideration. All correlation factors r_{AB} are higher than 0.9. It characterizes the very strong correlation between both corresponding day series and, obviously, similar production processes.

Table 2. Active energy consumption before and after the optimization of the operation of reactive power compensation units

Before		After				
Date	W_P [kWh]	Date	W_P [kWh]	ΔW_P [%]	r_{AB}	Day
8.6	6433.35	22.6	4163.55	35.28	0.91	Mo.
9.6	5392.5	16.6	4517.4	16.23	0.98	Tu.
10.6	4130.93	17.6	4126.5	0.11	0.94	We.
11.6	4489.73	18.6	4092.83	8.84	0.96	Th.
12.6	1333.2	19.6	1016,25	23.77	0.93	Fr.
	Total 21779.7		**Total 17916.53**	**Total - 17.74**		

3. Possible Constraints

It must be noted that the reduction of the voltage level at the busbar leads to an increase of the depth of short-term voltage drops (dips) caused by transients, for example, during the start of a motor load connected to the busbar. Sometimes it can cause non-permissible voltage dips in the electrical network.

Figure 8 shows the measured voltage dips at the LV busbar of the enterprise considered above before and after the tap changing. The measured minimal voltage RMS values during the time in which voltage dips occurred and their durations are presented in Fig. 8. The limiting curve for permissible voltage dips levels is the ITIC-curve presented in Fig. 8 [10]. The measurements were carried out during the reference weeks.

It can be seen from the Fig. 8 that more significant voltage dips occurred after the tap changing in comparison with the voltage dips quantity before the tap changing was made. It can be seen from the Fig. 8 also that the limiting values are not violated.

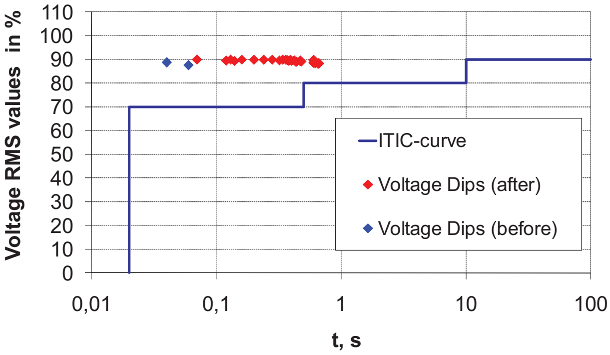

Fig. 8. Voltage dips before and after the tap changing during the reference weeks.

It must be taken into consideration that the change of the operation states of reactive power compensation devices can lead to the change of the payment for the consumed reactive energy.

Figure 9 shows reactive power consumption during a weekend in the enterprise under study by switched off reactive power compensation devices.

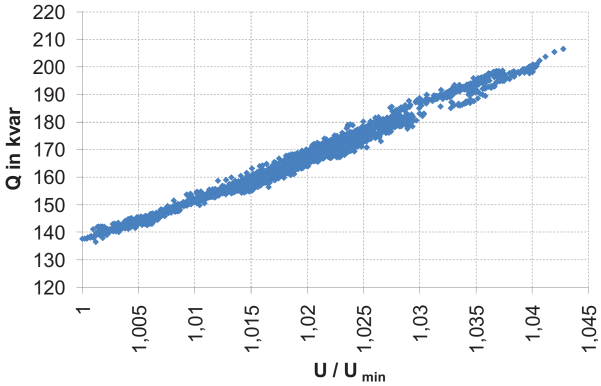

Fig. 9. Reactive power consumption during a weekend by switched off LV reactive power compensation devices in the enterprise under study.

Figure 10 shows corresponding active power consumption curves for the weekend under consideration.

It can be seen from Figs. 9 and 10 that the reactive power consumption during the weekend is much higher than the active power consumption. According to rules of German distribution network operators the enterprise must pay for the consumed reactive energy in case of exceeding of predetermined limiting value. In case of significant reactive energy consumption during the low-load periods which is added to the reactive energy consumption during the full-load operation states limiting values can be exceeded. It means that reactive power consumption must be analyzed and controlled continuously.

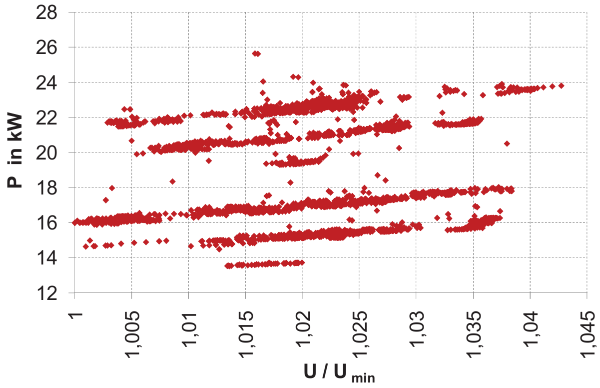

Fig. 10. Active power consumption during a weekend by switched off LV reactive power compensation devices in the enterprise under study.

In the case under consideration a high reactive power consumption during the low-load periods was determined by the presence of four old step-down transformers 30/0.4 kV with rated power values of 3×500 kVA and 1×800 kVA.

Figure 11 shows the experimental determined equivalent no-load characteristic of four transformers connected simultaneously to the MV busbar and the theoretical curve recommended in [13] for the representation of the linear part of the no-load characteristic of a power transformer.

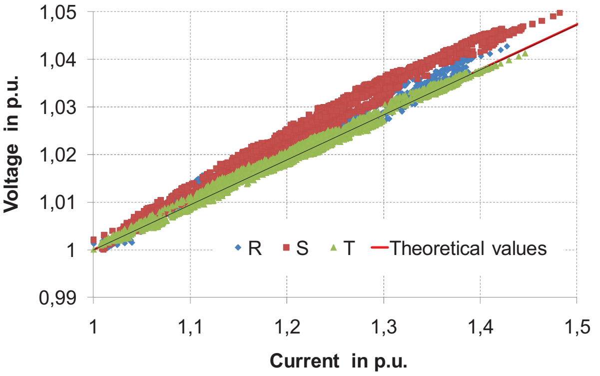

Fig. 11. Measured equivalent no-load characteristic of four step-down transformers connected to the MV busbar and the theoretical no-load characteristic of a power transformer (linear part).

In [13] was recommended to represent the no-load characteristic of a power transformer as follows:

$$i_\mu^* = 0.0021 \cdot \Psi^* + 0.014 \cdot (\Psi^*)^{11} \tag{5}$$

for $\Psi^* < \sqrt{2}$ and

$$i_\mu^* = 4.92 \cdot \Psi^* - 6.3 \tag{6}$$

for $\Psi^* \geq \sqrt{2}$,

where i_μ^* and Ψ^* are magnetization current and magnet flux in relation to their rated values.

Taking into consideration the corresponding minimal relative values for linear part of characteristic as the reference values the characteristic (6) is transformed into the form represented in Fig. 11.

The practical conclusion from the analysis of behaviour of no-loaded transformers is the necessity to take into account possible big reactive power consumption by old transformers in no-load state.

The recommendations of Association of German Utilities VDEW for the choice of necessary rated power of capacitor banks for reactive power compensation of step-down transformers from year 1958 [14] are graphically presented in Fig. 12.

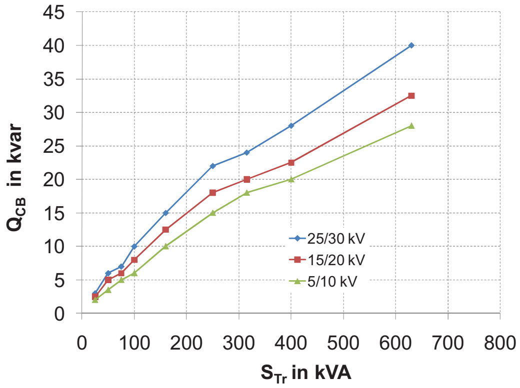

Fig. 12. Recommended rated power of capacitors banks for reactive power compensation of step-down transformers (VDEW, 1958).

The experimental determined values of required reactive power of capacitor banks for the reactive power compensation of no-loaded step-down transformers in the case under study (up to 210 kvar by total transformer rated power of 2300 kVA) has a good accordance with the recommendations of VDEW.

It must be noted that for modern transformers no-load currents are noticeably smaller.

Another problem after the realization of the voltage level reduction can be the reduction of the luminous flux from the installed lighting.

In [11] is noted that an incandescent lamp supplied by the voltage of 90% of the rated value has a luminous flux of only 75% of its rated value.

Generally the luminous flux Φ from a lamp depends on the voltage as follows [12]:

$$\Phi = U^\gamma \tag{7}$$

where γ is a factor characterizing the lamp type.

For conventional incandescent lamps is $\gamma \approx 3.6$, for fluorescent lamps is $\gamma \approx 1.5$, for modern energy-saving lamps is $\gamma \approx 0.17$ [12].

It means that the effect of the luminous flux reduction is not so important for fluorescent lamps and can be neglected for energy-saving lamps.

Taking into consideration the decision of the European Community to prohibit a production of incandescent lamps and the increase in the number of energy-saving lamps in electrical networks, it can be concluded that the reduction of the voltage level for an energy saving can be recommended for many enterprises.

Last but not least: a voltage level reduction increases significantly the lifetime of an incandescent lamp. The equation for the lifetime estimation can be written as follows:

$$\text{Lifetime} = \left(\frac{U_{\text{rated}}}{U}\right)^{13} \qquad (8)$$

where U is the actual voltage supplying an incandescent lamp.

It means that after the reducing of the supply voltage to 90% of its rated value the lifetime of the incandescent lamps is increased up to 393% or practically by 4 times.

In cases considered above the voltage reduction was about 3 – 5% (s. Figs. 2, 6). The decrease of the luminous flux of incandescent lamps is about 10 – 15%. But the increase of the lifetime for incandescent lamps in the enterprises is up to 188%.

It means that the carried out voltage reduction has mainly positive influence on the consumer operation in the enterprises under study.

4. Summary

On the base of the carried out analysis can be concluded that the reducing of voltage level in an electrical network is an efficient measure for the reduction of power consumption by consumers and, respectively, network losses by power utilities.

The authors' investigations have shown that the voltage reducing in the enterprises under study caused a reduction of the monthly energy consumption of up to 11 percents and weekly of up to 18 percents.

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