GENERALIZED CALCULATION METHODOLOGY OF TECHNICAL ELECTRIC POWER LOSSES IN DISTRIBUTION NETWORK

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Abstract – Electric power is one of production types, which uses its own production for its transportation. So one of the most important tasks is to determine and achieve the optimal level of electric power losses. Power system losses may be defined as the difference between energy or power that is required to be delivered to a system to supply the customers' energy or power needs. Energy losses can be classified to technical – associated with the passage of current through the system; and non-technical losses associated with unidentified and uncollected revenue. Knowing exact amount of technical electric power losses in developing countries distribution network is an important task of distribution system operators. Accurate estimation of actual and technical electric power losses let for distribution system operators evaluate and minimize the range of commercial energy losses (energy theft) that is very common for post-soviet and developing countries. The main problems and methodology of calculation of technical power losses in power lines, transformers and auxiliary equipment together with estimation of measurements' errors is presented in this report.

Keywords: electric power, distribution network, technical losses, commercial losses.

1 INTRODUCTION

Technical electric power losses are inevitable in the processes of generation, transmission and distribution of electric power and they occur in power generators, transformers, power lines and other devices. Technical electric power losses are calculated for the past period, analyzing operation of electric power network. The main task is to determine technical electric power losses and its components, which should let:

- Evaluate the economy of electric power network in different situations;
- Plan the means of economy improvement in electric power network;
- Evaluate the rate of commercial electric power losses and improve the customers' payments.

The percentage of total network losses in different countries varies significantly. In Luxembourg, the level achieved is 1,72%, compared to the levels in Hungary and Romania of 12,74% and 12,80% respectively. The average level of network is losses in European countries are around 6-7% [1].

Knowing exact amount of technical electric power losses in developing countries distribution network is an important task of distribution system operators. Accurate estimation of actual and technical electric power losses let for distribution system operators evaluate and minimize the range of commercial energy losses (energy theft) that is very common for post-soviet and developing countries. As the example is taken Lithuanian distribution network where calculation methodology is applied and results are presented.

2 THE STRUCTURE OF LITHUANIAN DISTRIBUTION SYSTEM

The structure of Lithuanian distribution system is presented in the Figure 1.

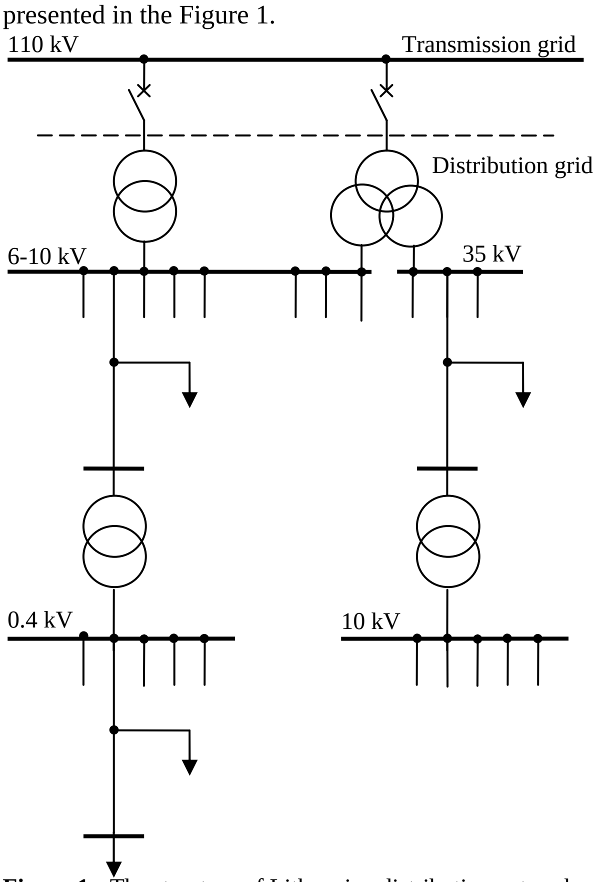

Figure 1: The structure of Lithuanian distribution network

3 TECHNICAL AND COMMERCIAL ELECTRIC POWER LOSSES

Technical energy losses for distribution can be computed as follow:

$$W_{tech.loss} = W_{Din} - (W_{Dout} + W_{aux}); \quad (1)$$

where W_{Din} – delivered energy to the distribution network (from transmission network, directly from electrical power plants, etc.); W_{Dout} – energy delivered from distribution network; W_{aux} – energy consumed in auxiliary equipment including own needs.

Electrical energy accounting losses can be calculated:

$$W_{acc.loss} = W_{Din} - (W_{settled} + W_{aux}); \quad (2)$$

where $W_{settled}$ – settled electrical energy.

Knowing technical losses, factual commercial losses could be determined as the difference between accounted and technical losses:

$$W_{com.loss} = W_{acc.loss} - W_{tech.loss}; \quad (3)$$

Optimal technical electric power losses are not constant quantity and can show minimal level of economically based technical losses. Optimal level of accounted losses should be in a range:

$$W_{acc.opt} = W_{tech.loss,opt} \pm W_{com.loss,pr}; \quad (4)$$

where $W_{tech.loss,\ opt}$ – economically based (optimal) technical power losses; $W_{com.loss,pr}$ – permissible commercial losses, determined according to accuracy classes of measuring circuits.

Taking into account computation and permissible measuring errors, electrical energy accounting losses, defined according to equation (2), for the given period should be in the range:

$$W_{tech.\min} - W^{+}_{com.loss,pr} \le W_{acc.loss} \le W_{tech.\max} + W^{-}_{com.loss,pr}; \quad (5)$$

where $W_{tech.min}$, $W_{tech.max}$ – minimum and maximum values of calculated technical electric power losses; $W^{+}_{p.meter}$, $W^{-}_{p.meter}$ – permissible commercial electric power losses due to measuring errors.

4 IDENTIFIED COMPONENTS OF TECHNICAL POWER LOSSES

Technical losses can be classified according to their origin and power network elements:

- Variable technical losses in transformer windings, which depend on transmitted power, and otherwise are called copper losses;
- Fixed technical losses in transformers, which depend on electrical network voltage, and otherwise are called core or iron losses;
- Variable technical losses in power line active resistance, which depend on power flow in the line;
- Losses in the reactive power compensation devices;
- Technical losses in the measurement transformers, secondary circuits and energy metering devices;
- Losses due to errors in measurement transformers and energy metering devices;
- Technical losses in the substations, switchyards, distribution boards and etc.

5 CALCULATION PROBLEMS AND METHODOLOGY OF TECHNICAL POWER LOSSES

Calculation of technical electric power losses according to classical equations is complicated due to information shortage: lack of accurate technical data about 0,4-35 kV Lithuanian distribution network components, lack of accurate energy data and etc. In such situation to compute technical electric energy losses for the past period is very complicated, therefore alternative methods should be found. Methodology of computation technical losses using average network component and energy quantities has developed and presented here.

5.1 Technical data

Due to a large number of separate divisions of distribution companies there is a large amount of not accurate technical data (lines' number and length, transformer data, measuring and auxiliary devices).

The solution found is to operate with summarized data of every separate division of the distribution company:

- Power lines' length, number, resistance;
- Power transformers' number, type;
- Number of measuring equipment.

5.2 Energy data

Lack of accurate energy data at the different levels of distribution network is another problem in the process of computation of technical losses.

The solution is to operate with summarized energy data at different voltage levels for the period for every separate division of the distribution company:

- Energy supplied to the distribution company;
- Energy supplied to the medium voltage consumers.

Energy flows at the low voltage side are commutated knowing injected amount of energy into medium voltage network and power losses in medium voltage power lines and power transformers.

5.3 Load pattern

Beside the problems with technical and energy data, calculation of duration time τ of the highest load flow losses or load curve shape coefficient is complicated and not exact, because there is no sufficient load pattern data of every division of distribution companies.

The best solution could be found is to use hourly measured energy flow data from transmission to distribution network, because these data are available in the trading process.

Hence duration time of the highest load flow losses is calculated like this:

$$\tau = \frac{\sum_{i=1}^{n} W_i^2\, t_i}{W_{i,\max}^2}; \quad (6)$$

where n – number of time intervals; t_i – time interval (in this case is one hour); W_i - hourly energy of the load pattern; $W_{i,max}$ – maximum hourly energy of the load pattern for the specified period.

In other expressions load curve shape coefficient, k_s is used and calculated according to the following equation [2]:

$$k_s^2 = \left(\frac{1090}{T_{\max}} + 0{,}876\right)^2 = \left(\frac{0{,}124}{k_{fill}} + 0{,}876\right)^2; \quad (7)$$

where T_{max} – maximum power duration time:

$$T_{\max} = \frac{W_P}{P_{\max}};\quad (8)$$

k_{fill} – filling coefficient of the load curve:

$$k_{fill} = \frac{W_P}{P_{\max} \cdot T};\quad (9)$$

where W_P – summarized active energy supplied to the network; P_{max} – maximum load power; T – time duration of the specified period in hours.

5.4 Technical power losses in 0,4 and 10 kV power lines

Complicated and not exact calculation of technical power losses in 0,4 and 10 kV power lines is big issue during the process of calculation.

The generalized methodology using summarized data of every division of the distribution companies is presented here. The main features of this methodology are these:

- Use of coefficient (k_A=0,51), which estimates dispersal of loads, line filiation and current density inequality;
- k_A should be calculated for every division;
- Power losses should be computed in overhead power lines and power cables separately;
- Power losses could be computed for every subdivision (industrial, domestic, agricultural and etc.) separately;

Calculation of technical electric power losses according to classical equations is complicated due to information shortage, because in distribution networks only energy is being measured. Therefore technical electric power losses for all medium voltage 35, 10 and 6 kV power lines of one transformer substation is calculated as follow:

$$W_{L,L\,6\text{-}35} = \frac{W_P^2 + W_Q^2}{10^3 \cdot N^2 \cdot V_{eq}^2 \cdot T} k_s^2 \cdot R_{eq};\quad (10)$$

where W_P, W_Q – active and reactive energy flowing through the transformer substation; T – countable period in hours; V_{eq} – equivalent voltage of the feeder; R_{eq} – equivalent resistance of the feeders; N – number of feeders of transformer substation; k_s – load curve shape coefficient.

Total technical electric power losses in medium voltage 6, 10 or 35 kV power lines are calculated according to the given sample of 10 kV power lines [3]:

$$W_{L,L10} = \frac{W_{P,10}^2 + W_{Q,10}^2}{V_{10}^2 \cdot T_{\max}^2 \cdot N_{10}^2} \cdot k_A \cdot r_{av10} \cdot L_{\Sigma 10} \cdot \tau_{10} \cdot 10^{-3};\quad (11)$$

where k_A – coefficient, which estimates dispersal of loads, line filiation and current density inequality. Recommended value is 0,51 [4,5]; r_{av10} – average resistance of 10 kV one kilometer power line; $L_{\Sigma 10}$ – total length of 10 kV power lines; τ_{10} - duration time of the highest load flow losses.

Technical electric power losses for 0,4 kV power lines of one transformer substation can be calculated as follow:

$$W_{L,L\,0,4} = \frac{W_P^2 + W_Q^2}{10^3 \cdot N^2 \cdot V_{av}^2 \cdot T} k_s^2 k_{as} k_A L\, r_o;\quad (12)$$

where k_{as} – load phase current asymmetry evaluating coefficient. In practice it is hard to determine exact value of this coefficient. It varies from 1,05 to 1,55. Recommended value is 1,2 [5].

Total technical electric power losses in 0,4 kV power lines are calculated according to this equation [3]:

$$W_{L,L0.4} = \frac{W_{P,0.4}^2 + W_{Q,0.4}^2}{V_{0.4}^2 \cdot T_{\max}^2 \cdot N_{0.4}^2} k_A k_{as} r_{av0.4} L_{\Sigma 0.4} \tau_{0.4} 10^{-3};\quad (13)$$

5.5 Technical power losses in power transformers

There are no big problems for calculation of technical losses in 110/10 kV, 110/35/10 kV, 35/10 kV power transformers, because the technical data are known and energy metering systems are installed. On the other hand technical power losses in 6-10/0,4 kV transformers, which are the most vital of all distribution network power losses, are more complicated to compute.

Losses that occur in transformers are being divided into two main components: no-load losses, which depend on core material, lamination type, isolation (paper, oil), voltage, and frequency. The most predominant no-load losses are the core losses, which consist of hysteresis and eddy current losses. The second group – copper losses are the I^2R losses which are inherent in all conductors because of the finite resistance of conductors.

Depending on the available data about distribution network loads, for technical loss computation in every 110, 35, 10, 6 kV power transformer can be used various methodologies.

The most exact but also hardest to implement in reforming Lithuanian distribution networks, especially in low voltage network due to the large quantity of transformers, lack of measure points, transformer parameter database, automated data collection, is “classical” method:

$$W_{T,L} = \frac{P_{Cu}}{S_N^2} \sum_{i=1}^{n} S_i^2\, t_i + P_0\, t_0;\quad (14)$$

where P_{Cu} – rated copper losses; S_N – transformer rating; n – load curve number of steps; t_i – load curve step i duration time; S_i – load curve step i transformer rating; P_0 – rated no-load transformer losses; t_0 – transformer’s connection the to the power system time.

To simplify transformer loss estimation maximum losses duration time method can be used. To compute technical losses there is a need of the maximum loading S_{max} and load duration curve of the computational period.

$$W_{T,L} = P_{Cu} \frac{S_{\max}^2}{S_N^2} \tau + P_0\, t_0;\quad (15)$$

where S_{max} – transformer maximum loading during measuring period (day, month, year); τ - duration time of the highest load flow losses (8).

If active and reactive energy delivered through the transformers is known, technical losses can be evaluated by this equation:

$$W_{T,L} = W_v + W_0 ; \quad (16)$$

where W_v – variable transformer losses; W_0 – fixed transformer losses.

Variable transformer technical losses during period T are being calculated:

$$W_v = \frac{(W_p^2 + W_Q^2) \cdot P_{Cu}}{S_N^2 \cdot T} k_s^2 ; \quad (17)$$

where W_P and W_Q – active and reactive energy injected from the network according measuring instrument readouts during period T; k_s – load curve shape coefficient (6); T – loaded transformer's operation time or average loading time per month in hours.

Fixed or no-load losses are being calculated:

$$W_0 = P_0 \cdot t_0 ; \quad (18)$$

where P_0 - rated no-load losses; t_0 – duration of specified period in hours.

Technical loss computation in 6-10/0,4 kV power transformers is difficult and redundant process, because of several reasons:

- The lack of data about transformer rated copper and core losses due to huge variety of transformers models and age;
- Not implemented energy metering nor on high, or low side of the 6-10/0,4 kV transformers. For computation estimated energy is used instead of metered transformer loading;
- Impossible to determine load curve due to the shortage of energy data.

Therefore in maximum losses duration time computations empirical formulas are used very often, but the practical calculations have shown that they cannot be used for the loss estimation during shorter period than a year (day, month). To overcome that problem for technical loss calculation in the 6-10/0,4 kV power transformers, average transformer model can be used, which is made by aggregating a lot of transformers data and which is characterized by an average estimated electrical load $\overline{P}_D$ and average variable technical losses $\overline{P}_v$. This model enables to compute losses in transformers without having data about transformer's loading coefficients. Despite calculating transformers parameters in average values it is desirable to have a database of the transformers rated no-load losses.

Technical losses in the average transformer are being calculated:

$$W_{T,L,10/0,4} = (\overline{P}_{v,10/0,4} \cdot \tau_{10/0,4} + W_0) N_{10/0,4} ; \quad (19)$$

where $N_{10/0,4}$ – number of 10/0,4 kV transformers; $\overline{P}_{v,10/0,4}$ – calculated average variable technical losses; W_0 – the sum of no-load losses, which simply can be calculated by summing all transformers rated no-load losses and then multiplying them by the specified period hours t_0.

Assuming that transformers are loaded by the average estimated electrical load, variable technical losses can be computed according to this equation [3]:

$$\overline{P}_{v,10/0,4} = 0{,}05544 \cdot \overline{P}_{D,10/0,4}^{0,7644} ; \quad (20)$$

where $\overline{P}_{D,10/0,4}$ – average estimated electrical load of the 6-10/0, 4 kV transformers during period t_0 and is being calculated:

$$\overline{P}_{D,10/0,4} = \frac{W_{0,4}}{t_0 \cdot N_{10/0,4}} ; \quad (21)$$

where $W_{0,4}$ – the active energy delivered to the 0,4 kV voltage network.

Energy used by auxiliary equipment should also be estimated. Technical losses of the auxiliary equipment are being defined as additional power for supplying energy to the transformer cooling equipment (fanners, pumps), electrical machinery, lightning, etc. This additional power flow through the transformers entails additional losses.

5.6 Calculation of technical electric power losses in electric energy measuring circuits and other equipment

Electric power losses in distribution network occur not only in power lines and transformers, but also in some other equipment: measuring devices, contacts of power lines and switchyards, network of domestic customers, losses occurring during short circuit faults and earthings and etc. These losses usually are not vital, but they are important in order to define the range of possible additional losses.

Electric power losses in energy measuring circuits consist of losses in measuring transformers and energy meters. Electric power losses in energy meters should not be taken into account if they are connected to the measuring transformers, because those losses are already included into losses of measuring transformers due to the loading of secondary windings.

Electric power losses in energy measuring circuits during the period T can beg computed as follow:

$$W_{MC,s} = (\sum_{i=1}^{N_{TV}} P_{TV} + \sum_{i=1}^{N_{TA}} P_{TA} + \sum_{i=1}^{N_{ME}} P_{ME}) \cdot T ; \quad (22)$$

where P_{TV}, P_{TA}, P_{ME} – power demand of voltage and current transformers together with power demand of energy meters; N_{TV}, N_{TA}, N_{ME} – number of voltage and current transformers together with the number of energy meters.

Additionally electric power losses should be estimated in electric contacts. Those power losses could be calculated by estimating the resistance of the contacts and the number of switching substations, underground cables substations and other equipment in the system:

$$W_{i,s} = \frac{W_P^2 + W_Q^2}{10^3 \cdot N_i^2 \cdot V_N^2 \cdot T} k_s^2 R_i ; \quad (23)$$

where i – group of equipment; R_i – resistance of switching substation, underground cables substation or other equipment; W_P, W_Q – active and reactive power transmitted to the lower voltage network during the period T; N_i, – the number of switching substations, underground cables substations or other equipment in the system.

Electric power losses in the network of domestic customers can be calculated knowing the distribution of domestic customers according to consumption, house type and etc. In general the equation shown below could be used [5]:

$$W_{b.s} = \sum_{i=1}^{n}\left(\frac{W_{Pi}^2 \cdot R_{eq}}{N_i^{\ 2}}\right)\cdot\frac{k_s^2 k_{as} k_A}{10^3 \cdot V_N^2 \cdot T}; \tag{24}$$

where W_{Pi} – energy supplied to defined consumers group; R_{eq} – equivalent resistance of consumers group power supply line; N_i – the number of consumers group power supply lines; n – the number of consumers groups.

Electric power losses due to under voltage broken power line conductor in the low voltage network could be estimated:

$$W_{br,l} = I_{br,l} V_{br,l} t_{br,l} N_{br,l}; \tag{25}$$

where $I_{br,l}$ – current in the broken conductor; $V_{br,l}$ – voltage of the broken line; $t_{br,l}$– average duration of the broken line disconnection; $N_{br,l}$ – the number of disconnections during the specified period.

Electric power losses due to under voltage earthing of medium voltage power line conductor could be estimated:

$$W_{\mathrm{earth,l}} = I_{earth,l} V_{earth,l} t_{earth,l} N_{earth,l}; \tag{26}$$

where $I_{earth,l}$ – earthing current; $V_{earth,l}$ – voltage during the earthing; $t_{earth,l}$ – average duration of the earthing; $N_{earth,l}$ – the number of earthings during the specified period.

5.7 *Errors of commercial energy meters*

One of the biggest and tricky issues are the errors and uncounted energy in commercial energy meters, because of high number of old energy meters. In reality energy is not lost, but it is uncounted, and distribution companies are loosing money in this process.

The best solution is to replace old energy meters with new ones, but this requires a lot of investments. The process is going on and in the mean time errors of commercial energy meters can be evaluated by the level of permissible commercial losses (-0,6 ÷ 3,5%).

Permissible electric power losses due to inaccuracies of commercial accounting and measuring errors are determined according to accuracy classes of energy meters and measuring transformers and also by evaluating voltage drops in the secondary winding of voltage measuring transformer, which should not exceed the half of accuracy class of voltage measuring transformer [2].

Permissible measuring errors of voltage measuring transformers coincide with their accuracy class, because network voltage is close to the rated value. Accuracy classes of energy meters and current measuring transformers depend on their loading. During the time of low loading the change of secondary current angle in the current measuring transformers should also be evaluated.

If the number of energy meters and measuring transformers is high in the system, it is recommended to divide measuring circuits into measuring incoming and outgoing energy.

Permissible commercial electric power losses in percents due to measuring errors for certain object (transformer substation, power network and etc.) can be computed according to the following equations:

$$W_s^+ = \sqrt{\sum_{i=1}^{k_{in}} \delta_{+i}^2 \frac{d_{in,i}^2}{n_{in,i}}(1+\gamma_{in,i}^2) + \sum_{i=1}^{k_{out}} \delta_{+i}^2 \frac{d_{out,i}^2}{n_{out,i}}(1+\gamma_{out,i}^2)}; \tag{27}$$

$$W_s^- = -W_s^{\ +} + 0{,}5\cdot\left(\sum_{i=1}^{n_{in}} \delta_{TV,i}\cdot d_i - \sum_{i=1}^{n_{out}} \delta_{TV,i}\cdot d_i\right); \tag{28}$$

where $d_{in,i}$, $d_{out,i}$ – total relative incoming and outgoing power flow measured by i^{th} group meters; $n_{in,i}$, $n_{out,i}$ – number of incoming and outgoing energy measuring meters; δ_+, δ_- – permissible measuring errors of the measuring circuit to the direction of increase and decrease of read-outs;

Measuring errors can be determined by the experiment taking into account the load and load duration of the measuring device. According to the experiment with the probability of 95,4 %, measuring error of one phase devices at the loading of 10 % is in the range from -2,5 % to -12,9 %, and at the loading of 100 % - from +0,5 % to -3,1 %. For three phase devices measuring errors at the loading of 10 % is in the range from +0,7 % to -3,7 %, and at the loading of 100 % - from +0,9 % to -1,1 %.

$\gamma_{in,i}$, $\gamma_{out,i}$ – incoming and outgoing energy measuring meters dispersal coefficients, calculated according to the formula:

$$\gamma_i = \frac{(W_{max} - W_{min})_i \cdot n_i}{6 \cdot W_{\Sigma i}}; \tag{29}$$

where W_{max}, W_{min} – maximum and minimum energy read-outs of one meters' group; $W_{\Sigma i}$ – total energy read-outs of one meters' group; n_i – number of energy meters in the group.

The highest influence on the permissible commercial electric power losses has the measuring errors of high energy flows measuring meters. Therefore trying to decrease the permissible commercial losses, it is necessary to increase the accuracy classes of those energy meters.

6 TECHNICAL ELECTRIC POWER LOSSES IN LITHUANIAN DISTRIBUTION COMPANY

Computed technical electric power losses in one Lithuanian distribution company (there are two distribution companies in Lithuania) are presented in the Table 1 and Figure 1. Highest power losses occur in the low voltage transformers and power lines. Fixed power losses in high and low voltage power transformers dominate over variable losses because power loading of the transformers is low, especially in rural areas.

Table 1: Technical power losses in Lithuanian distribution company (2003)

Technical power losses in Lithuanian Distribution company (2003)	**%**
Fixed losses in 110/10 kV transformers	0,53
Variable losses in 110/10 kV transformers	0,09
Fixed losses in 110/35/10 kV transformers	0,40
Variable losses in 110/35/10 kV transformers	0,06
Fixed losses in 35/10 kV transformers	0,24
Variable losses in 35/10 kV transformers	0,04
Losses in auxiliary equipment	0,07
Losses in 35 kV power lines and cables	0,07
Losses in 6-10 kV power lines and cables	0,54
Losses in 6-10 kV lines due to the earthing	0,02
Losses in medium voltage network	**2,06**
Fixed losses in 6-10/0,4 kV transformers	2,58
Variable losses in 6-10/0,4 kV transformers	1,06
Losses in 0,4 kV power lines and cables	1,35
Losses in 0,4 kV contacts	0,10
Losses in the network of domestic customers	0,01
Losses in measuring equipment	0,50
Losses in 0,4 kV lines due to broken lines	0,01
Losses in low voltage network	**5,60**
Average total technical losses	**7,66**
Permissible commercial losses (-)	0,60
Permissible commercial losses (+)	3,50
Maximum permissible technical losses	**12,08**

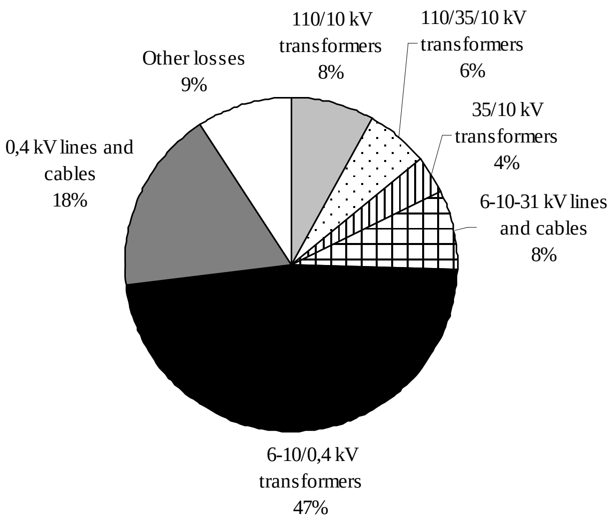

Figure 2: Distribution of power losses in Lithuanian distribution network

7 CONCLUSIONS

Calculation of technical electric power losses according to classical equations is complicated due to information shortage: lack of accurate technical data about 0,4-35 kV Lithuanian distribution network components (lines' number and length, transformer data, measuring and auxiliary devices), lack of accurate energy flows data at the different levels of distribution network. Therefore at present time exact computation of technical power losses in distribution network is impossible. So technical electric energy losses for the past period can be calculated only with the average quantities and methodology for these calculations is developed and presented in the report.

For the accurate allocation and calculation of technical losses in the distribution network should be done:

- Improvement, computerization and centralization of technical data collection;
- Automatic and remote energy data collection;
- Increase of accuracy classes of commercial energy meters replacing old energy meters with new ones;
- Computation of technical power losses in every separate element of energy distribution;
- Use of specialized technical power losses calculation programs.

Calculated technical electric power losses in Lithuanian distribution network can reach 12% of the energy supplied to the distribution system.

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