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STRATEGY FOR ANALYSIS OF LOSS SITUATION AND IDENTIFICATION OF LOSS SOURCES IN ELECTRICITY DISTRIBUTION NETWORKS

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Electrical utilities must make their operation more efficient. So, reducing losses in distribution networks remains nowadays an unsolved problem of considerable importance for sound management of any utility, especially in countries with high level of losses. The first step for sound loss management and elaboration of loss reduction measures is analysis of the loss situation in the network. This paper describes a strategy for analysis of energy losses and identification of the sources of excessive losses in distribution networks with the purpose of subsequent more detailed investigations and development of action plans to solve the overall problem.

Introduction

The level of energy losses in electricity networks differs from country to country. As for the losses in distribution networks, 10% of the energy supplied to the network can be considered a technically acceptable level. A number of companies in developed countries manage to reach a level not exceeding 5%, but for utilities in many countries 10% remains an objective that is difficult to reach, and there are even countries with the loss level up to 15–30%. Main reasons of the high loss level are aged networks in bad technical state as well as shortcomings in the customer management processes. For such countries reduction of losses represent the most effective means of cutting the cost of operation of a distribution utility. The savings brought about by loss reduction do not end at the monetary value of the energy saved: the released capacity of the system can serve to delay a costly expansion and reduce ageing of the components. The worldwide experience shows that in utilities with high network loss level, 1 $ expended for loss reduction saves 10–15 $ to the utility [1].

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For further development of plans of energy loss reduction and for determination of the implementation priorities of different measures and investment projects, analysis of the nature and reasons of losses in the system and in its different parts is needed.

This paper concerns a strategy for analysis of energy losses in distribution networks and identification of loss sources, i.e. network areas with excessive losses, in condition of restricted information.

The entity of network losses and objectives of their analyses

Transport of electric energy by power networks takes place at the inevitable expense of a part of the energy, which is just the actual loss of physical energy and equal to the difference of actual amounts $W_{I\,act}$ and $W_{O\,act}$ of the incoming and outgoing energy entering and leaving the network:

$$\Delta W_P = W_{I\,act} - W_{O\,act} \,. \tag{1}$$

In reality the value of energy losses can be determined as the difference of metered and/or billed incoming and outgoing energies $W_{I\,met}$ and $W_{O\,met}$ which are not equal to the actual loss values $W_{I\,act}$ and $W_{O\,act}$ due to inaccuracy of the metering and/or accounting systems (Fig. 1). The value of losses obtained in this way is called here accounted losses ΔW_A (in practice just this value is considered to represent the total network losses):

$$\Delta W_A = W_{I\,met} - W_{O\,met} \,. \tag{2}$$

So, the accounting and physical losses are not equal due to imperfection of the accounting system.

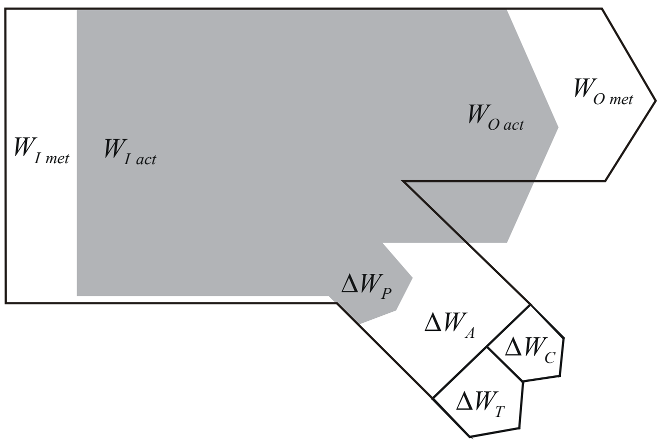

Fig. 1. Balance of losses.

In principle the physical losses are assessed by calculations. However, these calculations also cannot be accurate, and these calculated losses are called usually technical losses ΔW_T.

The imbalance of accounting and technical losses is called non-technical or commercial losses:

$$\Delta W_C = \Delta W_A - \Delta W_T \tag{3}$$

Thus, technical losses refer to the actual physical losses, while commercial losses are caused by dysfunctions in the process of metering, reading, accounting and invoicing for energy consumed by customers (errors and faults of measuring devices, inopportune or irregular payments for electricity, electricity thievery, etc.).

In more detail, physical losses can be classified as

- normal technical losses – the losses in a well-maintained network, which can be calculated by equations known from electrotechnics;
- abnormal technical losses, caused by various faults like leakage through damaged insulators, touch-sensitive conductors with branches, uninsulated short circuits due to low level of fault currents, etc., or by significant load asymmetry. Such losses are of occasional nature. In practice they cannot be calculated but assessed only by special local measurements.

As in normal well-maintained networks the share of abnormal technical losses is relatively small and their determination is practically impossible, technical losses usually involve the assessed value of normal technical losses. So, for all practical purposes abnormal technical losses stay in quantum of the losses' unbalance, i.e. in quantum of commercial losses.

The primary objective of studies on energy loss in the distribution network, particularly in utilities with high loss level, is identification of most significant sources of losses, i.e. network areas with significantly high loss. Just these areas may be in a bad technical state or be equipped with a poor metering system. In these areas theft of electricity may take place as well.

For identification of loss sources, the network should be divided into so-called loss districts. For every district it is necessary to

- assess for a certain period, for example for a year, accounting losses on the basis of accounting values of incoming and outgoing energies $W_{I\,met}$ and $W_{O\,met}$ (2);
- evaluate the accuracy of the assessment results;
- calculate the value of technical losses ΔW_T in the district and evaluate its accuracy;
- determine the imbalance of losses, i.e. commercial losses ΔW_C (3);
- evaluate the toleration of commercial losses basing on evaluation accuracy of accounting and technical losses.

Such analysis allows to find out the network districts with relatively high loss levels which thereafter have to be subjected to a more thorough investigation including inspection of billing procedures, checking the state of metering systems, and/or direct measurements of actual technical losses.

The initial information for analysis of energy losses in a district of the distribution network

Accounting losses can be estimated knowing the amounts of energy having entered the loss district and left it. Amounts of incoming energy are metered by workers of the utility while the consumed energy is often (in low-voltage networks almost always) registered by customers. Energy accounts are registered usually monthly, enabling to determine the accounting losses for every month. However, to get more stable results, annual losses, calculated as the sum of monthly data, should be analyzed. Annual data characterize technical, managerial and economical efficiency of the utility.

The extent of information on varying state parameters is very distinct in different distribution systems and possible loss districts. For estimation of technical losses various other operational information can be used. Availability and character of the data determines the choice of calculation methods and trustiness of results.

The main operational parameters, which can be used for calculation of technical losses, are:

– energy amounts passed through substations' feeders or supplied to customers;
– readings of telemetry;
– checking measurements carried out during certain days of the year.

In the worldwide practice, in networks with high level of losses the metering system is usually poor – measurements are fairly inaccurate or they are missing at all. The situation is worst in small distribution substations which often lack any possibility of metering.

It is obvious that due to poor provision with information such utilities have to apply simplified methods for calculation of technical losses basing primarily on energy metering. The energy data are sometimes partially supported by measurements of currents in outgoing medium-voltage feeders.

The use of readings registered by customers for calculations of losses is rather problematic, as the results may be misrepresented due to accruals, prepayments, not reporting readings, and energy thefts. Therefore such data should be considered with high carefulness.

At choosing primary and fast measures of loss reduction, the most relevant thing is not high accuracy of loss calculations but realization of the importance of loss problems, preliminary arrangement of the metering system and rough loss analysis to discover districts with excessively high losses and to find out their reasons. This can be done by using calculation methods based on rather incomplete information.

Selection of loss districts

For location of losses a distribution network should be divided into smaller observable districts, after which relations of accounting, technical and commercial losses in every district should be analyzed.

Selection of such loss districts is inseparably related to the information needed for loss analysis. On the boundaries of every loss district at least data on incoming and outgoing or consumed energies $W_{I\,met}$ and $W_{O\,met}$ which allow assessing the accounting losses ΔW_A in the district must be available (Eq. 2). Possibility of calculation of technical losses ΔW_T is needed as well to determine the commercial losses ΔW_C by subtracting (Eq. 3).

At selecting loss districts, the following recommendations useful for loss analysis should be considered, if possible:

– the smaller are loss districts the more detailed will be the loss analysis in the whole network and the easier to establish sources of losses and prevent their occurrence in the future;
– it is advisable that the network in a loss district were as homogeneous as possible and linked to consumers of a character as similar as possible. This would guarantee the accuracy of calculation of technical losses.

A central but controversial problem is finding a reasonable compromise between the size and possibilities of the metering system. Aiming at a more detailed analysis, it is always possible to reduce a loss district, establishing additional measuring points. For example, if there are no watt-hour meters in distribution substations, the medium-voltage network under question together with low-voltage networks supplied by it have belong to the same loss district. The result is that it is impossible to find out whether the excessive losses occurred in the medium or low-voltage network.

A reasonable solution were metering the energy at every feeder going out from substations. In this case the medium-voltage feeder with its supply area would belong to one loss district. If the energy consumed in the area is accounted, all requirements and recommendations for selection of the loss district are practically fulfilled.

Often a way to overcome the contradiction between a large loss district and expensive metering system is the compromise at which larger districts are divided into smaller ones only in cases when provisional analysis leads to grounded doubts and to the necessity for a more detailed location of losses.

In principle there are numerous possibilities to select loss districts. However, in general the following main types of loss districts can be considered:

1. A low-voltage feeder with its service area – metering at least energies entering the feeder and supplied to customers must be ensured.
2. Several low-voltage feeders with their service areas – such an option is needed when there are no energy measurements by single feeders.
3. A medium-voltage feeder with all distribution substations and corresponding low-voltage service areas. The option is inevitable when energy

metering in distribution substations is lacking. Loss evaluation in such a district is very rough, and it is impossible to ascertain whether loss sources are at low- or medium-voltage level.
4. A substation – energies in all incoming and outgoing feeders have to be metered.
5. Busbar(s) of a substation – energies or at least power flows in all busbar connections must be recorded. This type and the previous one give, in essence, an opportunity to check the energy or power balance and so to assess the accuracy of measurement equipment in the substation.

Selection of loss districts depends on actual conditions of the network, on the existent system of metering and data acquisition, and its development possibilities. The selection should be accompanied by encoding of consumers and distribution substations to simplify their reconciliation with corresponding loss districts.

Soundness of the measured value

The analysis of energy losses is based on metered and calculated values. If the metering and accounting systems were ideal, all initial data available, the calculation methods exact and the network in good technical order, the commercial losses would be lacking.

$$\Delta W_C = \Delta W_A - \Delta W_T = 0 \tag{4}$$

In reality it is not so because of inaccuracy of accounting losses due to measurement errors and shortcomings in the billing system. Conscious distortion of metering results by customers may have occurred. Technical losses are determined on the basis of imperfect and inaccurate initial information by an approximate calculation method. As a result, the imbalance of accounting and technical losses, i.e. commercial losses, may prove rather considerable.

Figure 2 depicts a simplified diagram of analysis of an elementary loss district as well as disturbances affecting analysis accuracy.

When assessing accuracy of accounting losses, the accuracy of full measurement tracts (instrument transformers, measuring chains, counters) has to be considered. On the demand side, the exactness of accounting and data acquisition system must be taken into account as well.

Since the initial information and the values of accounting and technical losses determined on its basis are influenced by a number of random disturbances (Fig. 2), all terms in the equation (4) are of stochastic character, and the result will not equal to zero. From the practical point of view, the assumption of normal distribution of the terms is reasonable. The applied theory of errors is based on this assumption and enables to realize the analysis of uncertainty intervals of accounting and technical losses as well as tolerability of commercial losses.

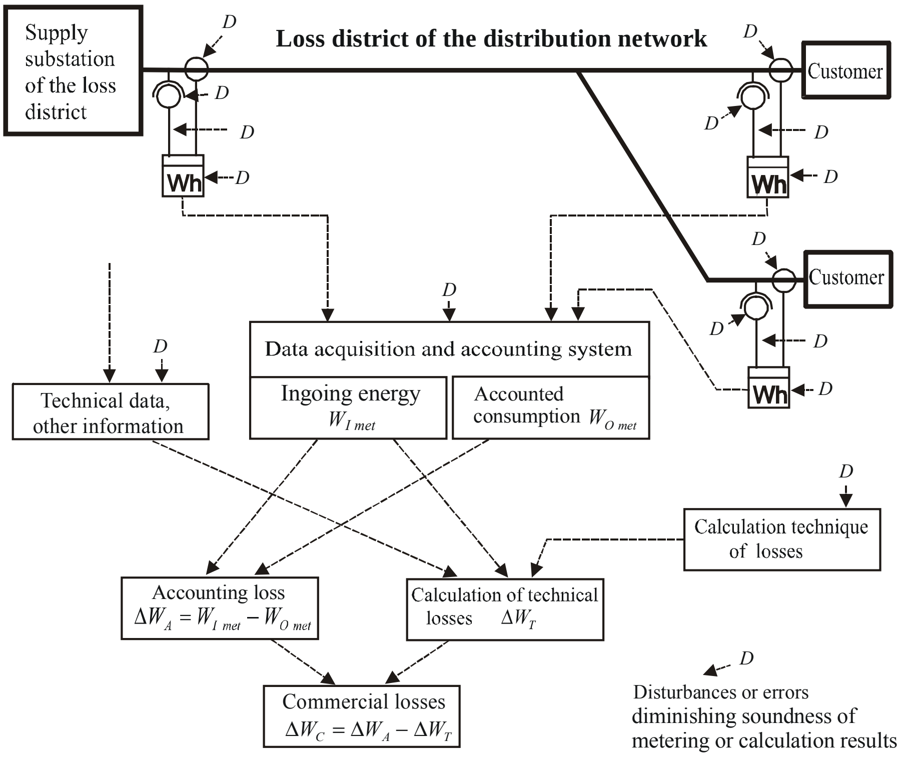

Fig. 2. Loss analysis and affecting disturbances.

Accounting losses in a loss district are determined as the difference of recorded values of incoming and outgoing energies. If considering the errors of the metering and accounting systems justifiable, one can estimate tolerable boundaries of commercial losses.

For evaluation of the loss situation in a loss district, it is practical to express losses and their intervals of uncertainty as percentage of the energy $W_{I\,met}$ entering the district:

$$\Delta W_{A\ \%} = \frac{\Delta W_A}{\Delta W_{I\,met}} 100 = \frac{W_{I\,met} - W_{O\,met}}{W_{I\,met}} 100 \tag{5}$$

$$\Delta W_{A\,\max\min\%} = \Delta W_{A\ \%} \pm \delta_A, \tag{6}$$

where δ_A is the error of accounting losses as percentage of incoming energy.

In principle the error of accounting losses can be evaluated basing on accuracy classes of the measuring equipment using, for example, the method presented in [2].

Evaluation of technical losses

In principle technical losses in power networks can be determined by calculations. Among different components of technical losses, calculation of load losses is the most complicated one. Choice of the calculation method depends on the character of the network and information available. The lower is the voltage level of a network, the bigger is the number of its elements, and the more deficient is operational information.

If the only currently available quantity is the energy entering the loss district, as quite common in medium- and low-voltage networks, the most suitable methods for calculation of load losses are those in which the loss district network is presented by an equivalent resistance R_{eq} loaded by the power entering the district and having losses equal to load losses in the district:

$$R_{eq} = \frac{\Delta P}{3{I_{fm}}^2}, \tag{7}$$

where ΔP – power losses in the loss district;
I_{fm} – feeder current or the total current of feeders, if the loss district comprises the service area of several feeders.

To differentiate between load losses in electric lines and distribution transformers, it is practical to express equivalent resistance as the sum of two equivalent resistances R_{eq}^{L} and R_{eq}^{T} in series.

The methods of equivalent resistance base on average load of the district and utilization time of power losses during the period under consideration. An overview of the methods can be found, for example, in [2, 3].

One of the simplest formulas for load loss calculation is

$$\Delta W_{load} = \frac{W_P^2 \circ k_f^2 \circ (1 + \tan^2 \varphi)}{U_{eq}^2 \circ T} R_{eq}, \tag{8}$$

where W_P – actual power entering the loss district during a period T (usually a year);
k_f – form factor of the load curve:

$$k_f = \frac{1090}{T_{\max}} + 0.876, \tag{9}$$

$tan\varphi$ – power factor at the peak load;
U_{eq} – equivalent voltage of the feeder (loss district), which considers the actual voltage changes with time as well as along the feeder [2]. One can take $U_{eq} \approx U_N$, where U_N is the nominal voltage;
T_{max} – peak load hours.

If there is lack of data for determination power factor and form factor, one can take approximately

$$\Delta W_{load} = \frac{1.63 W_P^2}{U_{eq}^2 T} R_{eq} . \quad (10)$$

When the actual power W_P is not measured but the peak load current I_{max} of the feeder(s) is known,

$$\Delta W_{load} = 4.1 I_{\max}^2 \tau^\circ R_{eqv} , \quad (11)$$

where τ is utilization time of power losses:

$$\tau = (0.124 + \frac{T_{\max}}{10000})^2 \cdot 8760 . \quad (12)$$

Simplest methods for calculation of load losses in low-voltage networks are based on maximal voltage drop [2] or load density [4].

No-load losses can be approximately estimated, multiplying the total no-load losses of transformers by average service hours. The other components of technical loss are negligible.

After calculation of total technical losses in the loss district, interval of uncertainty as percentage of the energy $W_{I\,met}$ entering the district can be calculated as

$$\Delta W_{T\max\min\%} = \frac{\Delta W_T}{\Delta_{I^\circ met}} 100 \pm \delta_T = \Delta W_{T\%} \pm \delta_T , \quad (13)$$

where δ_T is the calculation error of technical losses as percentage of incoming energy, which depends on the calculation method used [2].

Analysis of evaluation results

The answer to the question whether in the loss district there exist excessive commercial losses gives commercial losses as percentage of the incoming energy $W_{I\,met}$ (Fig. 3):

$$\Delta W_{C\%} = \Delta W_{A\%} - \Delta W_{T\%} . \quad (14)$$

For final analysis of commercial losses three main ways are recommended which can be used separately and combined.

1. For a loss district only accounting and calculated technical losses are known. At that the uncertainty intervals are not evaluated due to lack of sufficient information or time. In this case loss components can be compared only mutually. Although the analysis is rather intuitive and subjective, an experienced specialist can deduce substantial conclusions.

2. It is possible to compare losses in several loss districts of more or less similar character. The approach is relatively simple and often quite productive, giving a good overview of the loss situation in the network and helping to find loss sources.

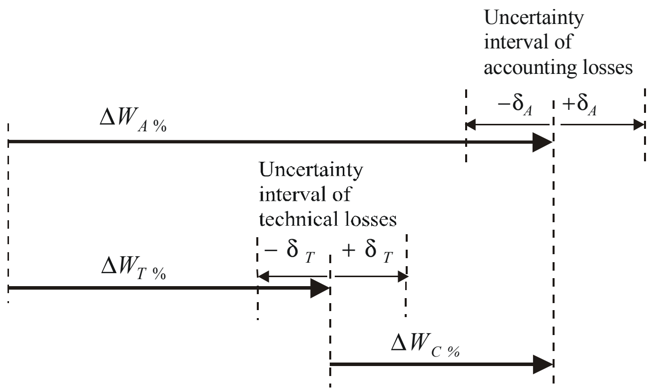

Fig. 3. Uncertainty intervals of losses.

3. In addition of accounting and technical losses, their intervals of uncertainty δ_A and δ_T are estimated. Assuming the errors of accounting and technical losses to be independent, the error of commercial losses is expressed as

$$\delta_C = \sqrt{\delta_A^2 + \delta_T^2} = \delta_{C°tol}\,. \tag{15}$$

In essence the error δ_C is just the tolerable commercial loss. So, the criterion of tolerability of commercial losses can be considered inequality

$$\left|\Delta W_{C\%}\right| \le \delta_{C°tol}\,, \tag{16}$$

or

$$\left|\frac{\Delta W_A - \Delta W_T}{\Delta W_A}100\right| \le \sqrt{\delta_A^2 + \delta_T^2}\,, \tag{17}$$

and excessive commercial losses

$$\Delta W_{C°exc\%} = \Delta W_{C°\%} - \delta_{C°tol}\,. \tag{18}$$

A positive value of $\Delta W_{C\ exc\%}$ refers to the presence of loss sources in the loss district in question.

The third approach is the most objective and informative one, but it needs sophisticated calculations of uncertainty intervals of accounting and technical losses.

After detecting loss districts with excessive commercial losses, a further more detailed investigation of loss reasons must follow.

Conclusions

Reduction of losses of power distribution networks is an ultimate objective of any electrical utility, but particularly of ones with high loss level.

The first stage of effective treatment of losses is a thorough specification of the loss situation in the network. As main steps of the specification, the following ones can be considered:

- division of the distribution network into so-called loss districts where a more or less accurate loss evaluation is possible;
- calculation of technical losses in every district;
- assessment of commercial losses as imbalance of accounting and technical losses;
- estimation of the accuracy of calculations and metering systems as well as of tolerable values of commercial losses;
- finding out the districts with excessive values of commercial losses;
- the detected districts should be subjected to a subsequent more detailed investigation with the aim to establish concrete reasons of excessive losses;
- ascertainment of the necessity to improve metering and billing systems and implementation of corresponding means;
- ascertainment of the necessity to improve the technical state of the network;
- evaluation of the effectiveness of loss reduction means and eduction of their implementation priorities.

By systematic analysis and effective implementation of corresponding measures, the Estonian Power Company managed to reduce losses in distribution networks from 19.5% to 9.8% during five years [5].

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